Charting Sustainable Seas: An Alternative Fuel Impact Model for Retrofitting Sailing Superyachts

MSc. Thesis

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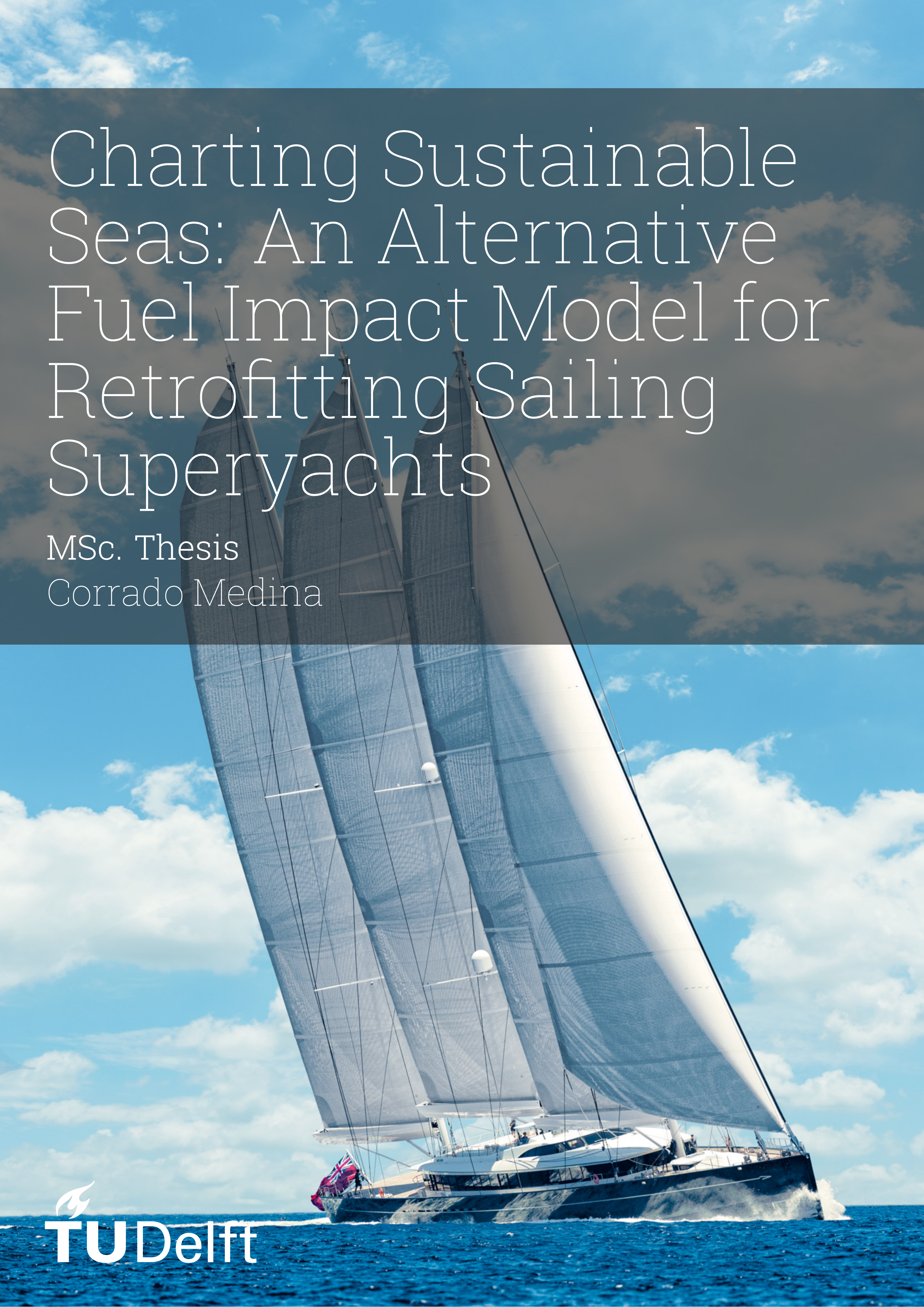

TU Delft

Charting Sustainable Seas: An Alternative Fuel Impact Model for Retrofitting Sailing Superyachts

by

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Cover image: Sea Eagle II Royal Huisman

Abstract

To reduce the environmental impact of the maritime sector, the International Maritime Organization (IMO) has established emission limits and ambitious sustainability targets. While superyachts are currently exempt from many of these regulations, they must align with IMO's objectives to establish the yachting industry as a responsible sector and adapt to the increasing application of these emission limits. Focusing only on new builds is not sufficient to meet ambitious targets, and sustainable refit of existing yachts is also essential. This applies not only to motor yachts but also to sailing yachts, which face unique challenges due to limited space which further complicates integrating alternative fuels like methanol or hydrogen, given their lower energy density. Despite various studies exploring alternative energy solutions, there remains a research gap in understanding the trade-offs associated with different energy configurations installable in a refit to minimize energy demand and emissions. To address this, an assessment model that evaluate technical feasibility, emissions, docking time, and Total Cost of Ownership (TCO) for different energy configurations is developed. Results from the assessment model, applied to two Royal Huisman sailing yachts of different size across various owner profiles, reveal that integrating alternative energy solutions requires significant reductions in energy demand. Feasible configurations range from using a single fuel HVO configuration for conservative owners to hybrid solutions involving HVO and methanol for more open to changes owners. Ultimately, owners willing to implement various energy reduction methods can achieve several feasible and sustainable configurations.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN WRITING

During the preparation of this work the author used ChatGPT in order to improve sentence fluency. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Preface

This thesis concludes my university journey divided between Italy and the Netherlands. After obtaining the Bachelor's degree in Naval Architecture and Marine Engineering at the University of Genoa, continuing my studies with a Master in Marine Technology at TU Delft was an immense opportunity. During the first year of my master, I had the chance to meet Professor Austin Kana, who immediately showed himself to be very helpful and brilliant when I asked if I could write my thesis with him in collaboration with a yachting company on the hot topic of alternative fuels. This led to the opportunity to spend 8 months exploring ways to reduce emissions from the magnificent Royal Huisman sailing yachts, widely regarded as the most beautiful sailing yachts in the world. It was very interesting and stimulating to work on such a current and central topic, especially while working from a desk with a window overlooking the yachts in the shipyard for refit projects.

I am confident that the results obtained from my thesis can contribute to reducing the environmental impact of the maritime sector, allowing yacht owners and their teams to make informed decisions when evaluating different sustainable refit options. A big thank you to Austin, a professor of exceptional brilliance and pragmatism, with a rare problem-solving ability. I also thank my company supervisor Jidde, very knowledgeable and helpful, who followed me step by step in these months, always offering interesting and not at all taken-for-granted insights. Thanks to Professor Jaap Gelling for the valuable feedback at the end of the literature review and green light meeting. It is always fascinating to hear from someone as knowledgeable as you with unique experience.

However, all this would not have been possible without my family, who have always supported me since the first day I expressed my desire to continue my studies in Delft, far from home. A special thanks to my girlfriend Matilde for always being there for me despite the distance, never making me feel it, supporting me in the most challenging moments, and celebrating with me in the happiest ones. Finally, thanks to my friends Andrea, Davide, and Jacopo with whom I was fortunate to share this beautiful experience and who have made me grow so much. I am sure you will go far and we will never lose touch.

Corrado Medina
Amsterdam, June 2024

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List of Abbreviations

- IMO: International Maritime Organization
- GHG: Greenhouse gas
- CO_2: Carbon dioxide
- MARPOL: International Convention for the Prevention of Pollution from Ships
- ECA: Emission Control Area
- NO_x: Nitrogen oxides
- SO_x: Sulfur oxides
- HVO: Hydrotreated Vegetable Oil
- PM: Particulate Matter
- CH_4: Methane
- NECA: NO_x Emissions Control Area
- SECA: SO_x Emissions Control Area
- ULSD: Ultra Low Sulfur Diesel
- MEPC: Marine Environment Protection Committee
- GT: Gross Tonnage
- COP UAE: United Nations Climate Change Conference
- EU ETS: European Union Emissions Trading System
- ICE: Internal Combustion Engine
- nm: nautical miles
- YETI: Yacht Environmental Transparency Index
- HVAC: Heating, Ventilation, Air-Conditioning
- MARIN: Maritime Research Institute Netherlands
- TRL: Technology Readiness Level
- TTW: Tank to Wake
- WTW: Well to Wake
- WTT: Well to Tank
- OpEx: Operational Expense
- CapEx: Capital Expense
- MGO: Marine gasoil
- DME: DiMethylEther
- ABS: American Bureau of Shipping
- SPS: Sandwich Plate System
- HT-PEMFC: High Temperature Proton Exchange Membrane Fuel Cell
- LT-PEMFC: Low Temperature Proton Exchange Membrane Fuel Cell
- FAME: Fatty Acid Methyl Ester
- BTL: biomass to liquid fuels
- TBN: Total Base Number
- NMC: Lithium nickel manganese cobalt oxide
- LFP: Lithium iron phosphate
- DSOC: delta state of charge
- AFC: alkaline fuel cell
- PAFC: phosphoric acid fuel cell
- MCFC: molten carbonate fuel cell

- SOFC: solid oxide fuel cells
- CO: carbon monoxide
- MSR: Methanol Steam Reforming
- DX: Direct Expansion
- Fr: Froude number
- HAZID: Hazard Identification
- HAZOP: Hazard and Operability study
- EEXI: Energy Efficiency Existing Ship
- EEDI: Energy Efficiency Design Index
- CII: Carbon Intensity Indicator
- GloMEEP: Global Maritime Energy Efficiency Partnerships
- SPEC: Ship Power and Energy Concepts
- TCO: Total Cost of the Ownership

1
Introduction

1.1. Background

While maritime transport plays an essential role in the world economy and is one of the most energy-efficient modes of transport, it is also a large and growing source of greenhouse gas (GHG) emissions. In 2018, global shipping emissions represented 1.076 million tonnes of carbon dioxide (CO_2), and were responsible for around 2.9% of global emissions caused by human activities [1]. The GHG emissions have been a central concern for the International Maritime Organization (IMO) continuously since the adoption of Conference Resolution 8 on *CO_2 emissions from ships* in September 1997, with the *2023 IMO Strategy on Reduction of GHG Emissions from Ships* adopted in July 2023 representing the last update [2]. Furthermore, with regulation 13 of the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI, the IMO has established Emissions Control Areas (ECAs) which include the Baltic Sea, the North Sea, the North American area, and the United States Caribbean Sea [3]. In these four areas, there are stringent limits for both Nitrogen oxides (NO_x) and Sulfur oxides (SO_x) emissions [4], and if vessels do not comply with these stricter regulations, they are not allowed into the ECAs.

Superyachts, which include pleasure vessels surpassing 30 meters in length, constitute a minor segment within the extensive maritime industry, and despite their exemptions from various energy efficiency and GHG reduction regulations, it is evident that the yacht sector must adhere to the ambitions outlined by the IMO to establish itself as a responsible industry [5]. Most energy is still converted from diesel engines with global and local emissions which are harmful for the environment and human health, but also local discomfort in the form of vibrations, noise, and fumes [6]. To decrease the negative impact on environment and climate and increase the comfort on board, there are several opportunities to reduce the energy demand and make energy conversion more sustainable and less harmful. Developing solutions to create an exceptionally energy-efficient yacht, minimizing emissions to ensure future sustainability is certainly of fundamental importance for new yachts, but it is also crucial for the refit of already existing yachts if it is considered the entire marine sector's goal of achieving net zero emissions by 2050 [7]. In fact, despite some of the companies in the sector being committed to reducing emissions in their new constructions [8, 7], it is still far from the possibility of every new yacht being emission-free. To move towards a decrease in the quantity of emissions and enable existing yachts to continue sailing in the future without regulation constraints, it is essential to optimize their efficiency and employ alternative energy carriers and converters through refit projects.

1.2. Company introduction

This project is performed in collaboration with Royal Huisman, a Dutch shipbuilding company that specializes in the newbuild and refit of sailing and motor yachts. Founded in 1884 Royal Huisman has evolved from "local builder of wooden workboats" to being the multiple award-winning creator of some of the finest custom superyachts in the world. The company's headquarters is located in Vollenhove, in the northern part of the Netherlands, while Huisfit, the division dedicated to refits, is situated in the

Amsterdam region. The company has always paid attention to innovation and the introduction of sustainable solutions, taking real action and avoiding greenwashing. An example is Project 384, Ethereal, the world's first hybrid superyacht incorporating 400 kWh of stored energy in her Li-ion battery bank, which was launched by Royal Huisman in 2008 [9]. Today, alternative fuels are at the forefront of attention, with a particular focus on methanol and hydrogen, as well as Hydrotreated Vegetable Oil (HVO) [8].

1.3. Emission limits

In response to the challenge of air pollution caused by international shipping, the IMO has implemented various regulations on both a global and regional scale [10]. The organization is dedicated to minimizing local emissions of NO_x, SO_x, and particulate matter (PM), as well as GHG emissions, with a primary focus on CO_2, but also including methane (CH_4). This commitment is demonstrated through the establishment of the NO_x Emissions Control Area (NECA) and the SO_x and PM Emissions Control Area (SECA), along with the setting of future percentage reduction targets for CO_2 emissions relative to 2008 levels. However, at the moment, the only limitations for yachts are local, namely the ECAs [11]. IMO Tier III standards on NO_x emissions [12] should be carefully considered as they are stringent, while limits on sulfur content [13] for yachts are not a problem since they typically use Ultra Low Sulfur Diesel (ULSD) [14]. Regarding PM emissions, however, the effects on human health are severe, with long-term exposure causing premature mortality and cardiovascular and respiratory hospital admissions [15].

On the other hand, the IMO's strategy to reduce GHG emissions to zero by 2050 [2] currently applies only to the shipping industry and not to yachts. Nevertheless, the overall direction that the maritime sector is taking towards emission reduction could soon officially extend these goals to the yachting sector, which cannot afford to be caught unprepared [7]. It is a widely held opinion within Royal Huisman engineers that being compliant with these standards is the minimum the company can do in the coming years to move towards a more sustainable direction. For this reason, the main existing regulations on emission reduction are listed below.

1.3.1. Local emissions

PM

The introduction of sulphur and particulate limits by the IMO occurred through Annex VI, regulation 14 of the MARPOL in 1997 [13]. To achieve these limits, the IMO established a global sulphur cap (GSC) and designated ECAs with more stringent sulphur limits [10]. Appendix VII of MARPOL Annex VI has identified four international ECAs for both SO_x, PM and NO_x, namely:

- Baltic Sea area
- North Sea area
- North American area
- United States Caribbean Sea area [13]

Furthermore, there is an upcoming Mediterranean Sea SECA that will be applied on 1 May, 2025 [11]. There are then three other potential ECAs that were announced during the Marine Environment Protection Committee (MEPC) 80 in July 2023. These include Canadian coast, North-East Atlantic Ocean, and also an extension of the already existing Norwegian coast ECA. While the incoming Mediterranean SECA covers only SO_x and PM, the other three zones should be complete ECAs, including limits on NO_x [11]. As previously stated, the sulfur content limits for yachts pose no issue as they commonly employ ULSD [13, 14]. Nevertheless, concerning PM emissions, the impact on human health is significant, leading to severe consequences such as premature mortality and admissions to cardiovascular and respiratory hospitals [15]. Therefore, careful consideration of these emissions is imperative.

Figure 1.1: Current ECAs [16]

NO_x

A gradual decrease of NO_x emissions is envisaged by regulation 13 of MARPOL Annex VI, that introduces ECAs where more stringent emission limits for air pollutants should be applied [12]. The first NECA was adopted in 2011, followed by the United States Caribbean Sea NECA in 2013 [17]. In 2021, the SECA in the Baltic Sea, the North Sea and the English Channel was extended with a NECA [12], and therefore all these four areas have today limits on both NO_x and SO_x, as can be seen in Figure 1.1.

The NO_x control requirements of Annex VI apply to installed marine diesel engine of over 130 kW output power, therefore covering the whole Royal Huisman fleet of sailing superyacht. Different levels (Tiers) of control apply based on the ship construction date, and within any particular Tier the actual limit value is determined from the engine's rated speed. Tier I applies to ships built on or after 2000, Tier II from 2011 and Tier III from 2016. Furthermore, Tier I and Tier II limits are global, while the Tier III standards apply only in NO_x ECAs. A marine diesel engine that is installed on a ship constructed on or after the following dates and operating in the following ECAs shall comply with the Tier III NO_x standard:

- 1 January 2016 and operating in the North American and the United States Caribbean Sea ECAs
- 1 January 2021 and operating in the Baltic Sea or the North Sea ECAs

Figure 1.2 represents a diagram showing NO_x emission limits in g/kWh at varying revolutions per minute (RPM) of the engine for all three Tiers.

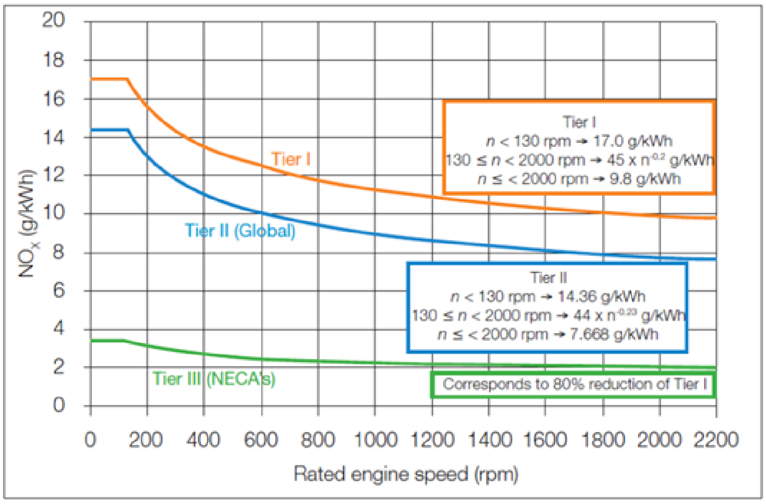

Figure 1.2: IMO NO_x control Tiers [18]

As for possible future NECA, the Mediterranean Sea area will only be a SECA, while those of Canada, the North-East Atlantic Ocean, and Norway will include both SO_x and NO_x emission limits [11].

1.3.2. Global emissions

GHG

The GHG emissions have been a central concern for the IMO for years, with the last update which is the revised Strategy on Reduction of GHG Emissions from Ships. This strategy was adopted at MEPC 80 in July 2023 and includes an enhanced common ambition to reach net-zero GHG emissions from international shipping in 2050. Furthermore it comprises a commitment to ensure an uptake of alternative zero and near-zero GHG fuels by 2030, as well as indicative check-points for international shipping considering 2008 as the baseline to reach net-zero GHG emissions for 2030 (by at least 20%, striving for 30%) and 2040 (by at least 70%, striving for 80%) [19]. This is done in order to effectively promote the energy transition of shipping and provide the world fleet with an incentive while contributing to a level playing field and a just and equitable transition [2]. Despite the fact mentioned earlier that these limits do not specifically pertain to yachts, several Royal Huisman engineers holds the belief that they serve as a benchmark. Ensuring compliance with these standards is considered the minimum commitment the company can make in the upcoming years to transition toward a more sustainable direction.

Although there are various GHG, including CH_4, the IMO focus is primarily on CO_2 since it is the main one that is emitted by ships [20]. In Figure 1.3, a line chart is depicted illustrating the millions of tons of CO_2 emitted per year from 2012 to 2050. With only the data from the IMO Fourth Greenhouse Gas Study 2020 [21] available, this study plotted the trend-line based on the projected trend using data available between 2012 and 2018. The calculation does not factor in emission reductions during the COVID period or improvements in the efficiency of new yachts, leading to an overestimation of emissions during that timeframe. Conversely, it underestimates emissions by excluding shore power consumption and its carbon intensity. In the end, the author of the graph, Malcolm Jacotine, a Master Mariner with an engineering background and a self-proclaimed sustainability advocate for the superyacht industry [22], deems the overall trend to be trustworthy.

Although 2008 serves as the baseline for the shipping industry, in this study, Malcolm Jacotine used a variation of the GHG strategy, considering the year 2018 for yachts due to emission data availability constraints for yacht emissions. Even with this choice, it is evident that if a 20% reduction is to be achieved by 2030, there is a necessity to reach the peak of emissions as soon as possible, at least not after 2027 [23].

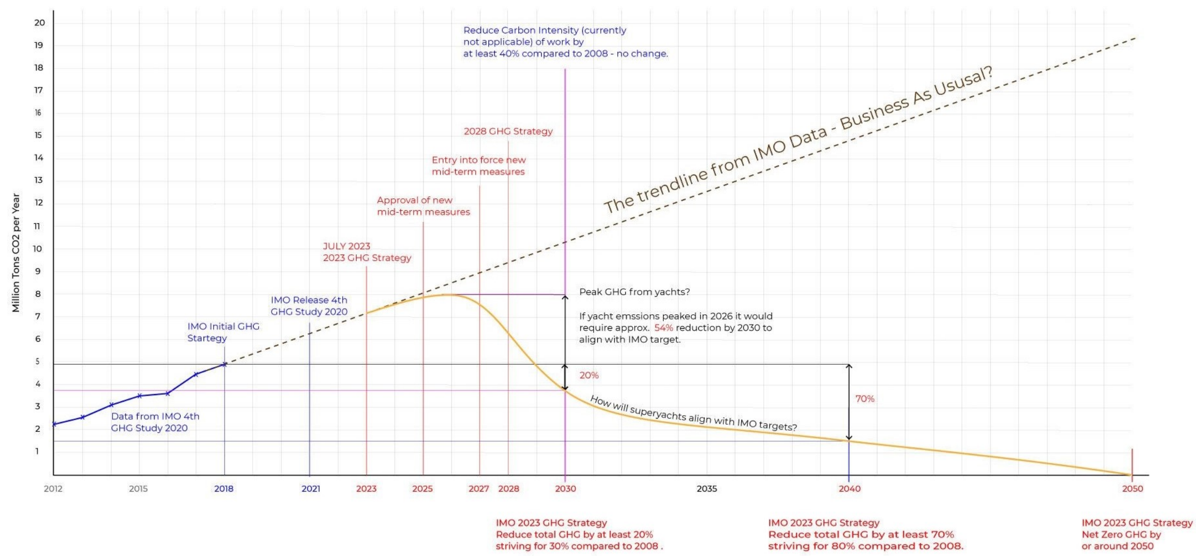

Figure 1.3: Trend-line of CO_2 emissions for the yachting industry up to 2050 [23]

1.4. Refits relevance to maritime enhancement

This section outlines the importance of yacht refit projects, initially examining the ongoing growth of the superyacht fleet, then introducing the reasons why and how often refit projects are typically carried out on yachts, and finally illustrating the significance of a sustainable refit.

1.4.1. Continued growth of the superyacht fleet

The global fleet of superyacht exceeding 30 meters is experiencing ongoing expansion. Since 2012, the average annual growth rate of the fleet has been 3.1%, as illustrated in Figure 1.4 [24]. From 1987 to the end of 2022, the fleet has surged in size more than sixfold, escalating from 917 yachts to 5.555 yachts. This phenomenon is intricately linked to the ascent of the refit market, which is assuming an increasingly pivotal role. The refit market is essential for incorporating the latest technology on board, ensuring continual adaptation of interior and exterior designs to accommodate changes in ownership or evolving personal tastes. Moreover, Royal Huisman anticipates a growing trend in refits during these years, aimed at incorporating emission reduction solutions essential for allowing ships over 30 years old to navigate in protected areas and be compliant in the event of the extension to yachting of all regulations currently applicable to commercial vessels.

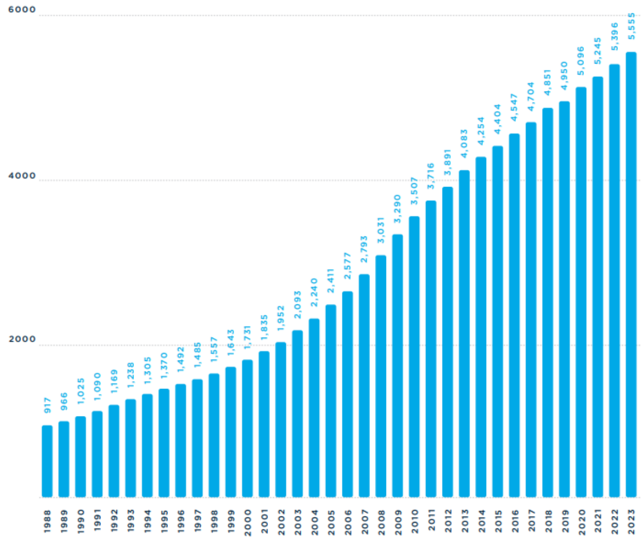

Figure 1.4: Evolution of superyacht Fleet exceeding 30 meters from 1988 to 2023 [24]

1.4.2. Refit background

Before delving into the need for sustainable refits, it is nice to introduce what is meant by refit and on which occasions is it generally carried out. According to Cambridge dictionary, a refit consist of *the process of putting a ship or a building, etc., especially a public or industrial building, back into good condition by repairing it or adding new parts* [25]. In the realm of maritime vessels, specifically within the yachting industry, it is essential to differentiate between necessary maintenance and a proper refit project. Essential maintenance adheres to the guidelines set by the classification society and is conducted through systematic surveys. This routine maintenance is crucial for ensuring the yacht's functionality and safety. On the other hand, refit projects are undertaken to enhance the vessel's luxury features and cater to the owner's pleasure, going beyond the necessities of basic maintenance [26]. Despite this distinction, project managers at Huisfit have stated that mandatory maintenance and a refit are often carried out simultaneously. This allows for taking advantage of the period during which the yacht must be in dry dock for classification society surveys to address additional owner requests, thereby reducing overall costs and the time that a subsequent docking would require.

The majority of Royal Huisman yachts follow the Rules and Regulations for the Classification of Ships by Lloyd's Register [27], which include the following surveys:

- Annual survey: held every year on board, so no dry docking required;
- Intermediate survey: done every 2 to 3 years, dry docking usually required to inspect the outside of the ship's bottom;
- Special survey: performed every 5 years, dry docking required.

Without dwelling on these mandatory surveys, refit projects typically take place concurrently with Intermediate and Special surveys, and the duration varies depending on the extent of the refit. Generally, it ranges from 3 months for minor refits to 9-12 months for major refits. However, a Huisfit project manager with over 20 years of experience in yacht refits has stated that exceptionally, it can even extend to two years in the case of true rebuilds, with approximately 15% of projects exceeding the one-year mark. Hull repainting typically occurs every 2.5 years, while major refits depend on various parameters but are often undertaken in the event of a new owner. It is possible to identify the following types of services, although often a refit project covers several areas [28]:

- Hull and superstructure extensions and remodelling: involve adding or altering yacht spaces to meet changing owner preferences, with options like guest bedroom additions but also new technologies integration;
- Interior rebuild and redecoration: address outdated designs or changing tastes, often requiring a complete overhaul and incorporation of modern materials;
- Technical refits and maintenance: focus on the engine room and systems, with major overhauls needed every five to ten years;
- System updates: involve replacing outdated electronic and communication systems;
- Exterior reconditioning: includes regular maintenance of teak decks, hardware, and repainting to combat saltwater exposure.

In further discussions with Royal Huisman engineers with more than 10 years of experience in the yacht building sector, it has been revealed that with the ongoing rise in prices for new-build yachts and, notably, the total construction time often exceeding 3 years, an increasing number of owners prefer to purchase an existing yacht and customize it to their liking through a major refit. Typically, a superyacht has a lifespan of around 20 years. After this period, all components, except the hull and superstructure, have reached the end of their operational life. Nevertheless, the yacht's longevity can be extended through the process of a refit [26].

1.4.3. Sustainable refit

A refit need not be exclusively aimed at prolonging the yacht's lifecycle, but can also involve incorporating components to enhance energy efficiency. This may include integrating energy converters capable of harnessing wind, water, and solar energy on board, such as hydro generation and solar panels. Additionally, refit activities might involve updating energy converters with various combinations of hydrogen or methanol fuel cells, battery packs, or methanol internal combustion engines.

There are several reasons why a refit integrating solutions to reduce emissions is becoming increasingly crucial. Primarily, this includes compliance with IMO emission limits and the necessity to demonstrate the yachting industry's responsibility in light of growing social pressure. Furthermore, from a shipyard point of view, embracing the opportunity to pioneer the implementation of new sustainable technologies contributes to achieving a favorable market position. From the owner point of view, a more sustainable yacht enhances its economic value, since in terms of chartering or reselling being able to sail around the world without constraints is certainly a great advantage [28]. In this context, it is pivotal to recognize the significance of responsible and motivated owners who are willing to invest in the ”green premium”, a term coined by Bill Gates in his book ”How to Avoid A Climate Disaster” [29]. This premium is essential for effectively reducing emissions and decarbonizing the yachting industry [30].

However, Posthuma de Boer, former director refit and services and current sales director at Feadship suggests that the decision to invest in significant sustainable upgrades for vessels is largely contingent on regulatory factors [7]. Speaking on behalf of shipyards, he advocates for eco-friendly solutions, advising owners to prioritize energy efficiency during refits. While endorsing comprehensive shifts to non-diesel systems, he acknowledges the associated high costs and extensive nature of such upgrades. Changes in the regulatory landscape could prompt a rapid shift in the refit sector, transitioning from minimal retrofits for future fuels to a more extensive approach. Giedo Loeff, head of research and development at Feadship adds that the EU's Fit for 55 initiative is expanding, requiring vessels over 5.000 GT to report emissions from January 2024, with a potential expansion to 400 GT vessels after 2026 [7]. Factors such as increasing fuel prices due to taxation, the phase-out of fossil fuel subsidies discussed at the United Nations Climate Change Conference (COP28 UAE) [31], and the introduction of the European Union Emissions Trading System (EU ETS) [32] for superyachts will have downstream effects. Simultaneously, efforts in the energy market to boost non-fossil fuel production and distribution will strengthen the business case for efficiency upgrade refits, aiming to reduce operating costs and potentially shift to alternative fuel-chemicals like methanol [7].

The Lloyd's Register Engine Retrofit Report [33], published in October 2023, sheds light on the shipping industry's decarbonization goals by 2050, emphasizing the impact of sustainable scaling of biofuels. Challenges in implementing future fuel technologies include yard capacity, conversion capability, and system integration. The report notes that the limited number of existing alternative-fuelled vessels hampers repair yards' ability to handle such projects [7]. In Figure 1.5 the growth of retrofit to alternative fuels is predicted for the shipping sector assuming zero-emission newbuilding starts in 2030, with a maximum retrofit age of 15 years. Even though it doesn't specifically address superyachts, it still serves as a reference, anticipating significant expansion in the refit market in the coming years, reaching its peak in 2036, with methanol emerging as the most popular solution.

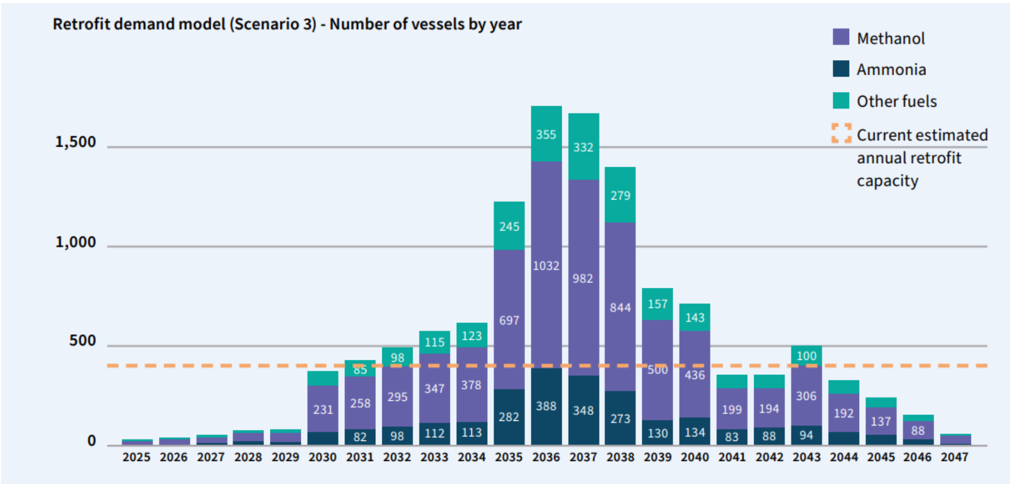

Figure 1.5: Retrofit to alternative energy carrier demand model (Scenario 3) - Number of vessels by year [33]

The sustainable refit of a yacht is a sector poised for significant growth [33], and although emission regulations for this category of vessels are currently not as stringent as those for commercial vessels, they may become more stringent soon [7]. Therefore, it is advisable for shipyards to be prepared. Even though, currently, the cost of alternative solutions is higher than that of established ones, and there are challenges in on-board integration, it is important to be open to alternative solutions for not only a limited number of owners but also a broader audience.

1.5. Research gap

Various studies exploring alternative energy carriers and converters were identified during the literature review. However, each of these studies has its own limitations. There is a notable absence of information on how these options can be combined and integrated together on-board, and what is their respective impact on internal volumes, weights, emissions, refit timeframe and costs of existing yachts. This knowledge is crucial for yacht owners and their teams to assess the feasibility of integrating sustainable technologies and to make informed decisions regarding the substantial changes such a refit would bring to their vessels. As a result, there exists a research gap concerning the trade-offs associated with different combinations of energy carriers and converters that can be installed when refitting sailing yachts to reduce energy demand and minimize emissions for future sustainability. This thesis aims to fill the gap by addressing critical aspects.

1.6. Research objective

The thesis goal can be summarized in a research question, which is expressed as follows:

"What trade-offs are made by the different combinations of energy carriers and energy converters that can be installed when refitting a sailing yacht by reducing energy demand and minimising emissions in order to ensure future sustainability?"

To answer this question comprehensively, the following subquestions have been formulated and will be examined and addressed in this thesis:

- *"What are the peculiarities of a sailing yacht in terms of interior space, operational profile, and energy demand?"* (Chapter 2)
- *"Which are the most promising alternative energy carriers? What alternative energy converters hold the most potential?"* (Chapter 3)
- *"Which are the opportunities to reduce the energy demand in design and operation?"* (Chapter 3)
- *"What is the structure of the assessment model used to evaluate the technical and economic feasibility of integrating sustainable solutions on already-built sailing yachts to reduce emissions?"* (Chapter 4)
- *"How do the volumes and weights of alternative energy carriers and converters vary in sailing yachts compared to the current energy configuration considering possible energy demand reduction? How do emissions and costs change?"* (Chapter 5)
- *"How can the assessment model developed to analyze the impact of sustainable solutions on sailing yachts be validated and verified?"* (Chapter 6)

1.6.1. Scoping

The thesis goal is to have a comprehensive overview of potential possible combinations of alternative energy carriers and converters for sustainable refits, considering both the technical feasibility of such energy configurations, the associated emissions, the refit timeframe, and finally the costs. This will help yacht owners and their teams to make a more informed decision in this regard. Indeed, in the face of numerous initiatives and pilot projects in place, the current landscape makes it challenging for them to discern suitable options for their vessels.

At the beginning attention will be directed towards the peculiarities of a sailing yacht in terms of operational profile and energy demand aiming to understand how energy consumption can be reduced and whether current operational requirements (particularly range and design speed) are genuinely necessary or can be minimized. Emphasis will then be placed on alternative energy carriers which are considered the most promising options for Royal Huisman sailing yachts. Simultaneously, hydro generation, solar panels, and other alternative energy converters as fuel cells will be examined. In order to assess the trade-offs associated with onboard integration of sustainable technologies, an assessment model is built. All the steps that constitute it and the results obtained will be presented, along with the model verification and validation to ensure its correctness and reliability.

2
Sailing yacht uniqueness

Sailing yachts represent a niche within the broader yachting sector, which is itself a niche within the entire maritime sector. This chapter analyzes the peculiarities that distinguish a sailing yacht, focusing in particular on the operational profile of Royal Huisman sailing yachts and their energy demand. This chapter attempts to answer the following subquestion:

"What are the peculiarities of a sailing yacht in terms of interior space, operational profile, and energy demand?"

2.1. Royal Huisman sailing yacht specifics

The main characteristic that distinguishes sailing yachts is their sails, which, when deployed, allow them to derive propulsion force from the action of the wind against them. This possibility significantly reduces the overall energy required by the yacht to be provided by the engines, compared to cases where propulsion power is provided by an engine. Additionally, another peculiarity when a yacht sails under wind power is the ability to harness kinetic energy from the flowing water through a hydrogenerator. This energy can be used to meet part of the hotel load energy requirement. Furthermore, if solar panels are also installed to harness solar power, the energy required would be further reduced, requiring energy converters (such as ICE or fuel cells) to supply only the remaining energy requirement. As for emission reduction, the energy demand reduction facilitates the technical feasibility of integrating alternative energy carriers and converters on board, since they require extra volume and weight for the same energy demand due to lower volumetric and gravimetric energy density.

Regarding dimensions, while the majority of Royal Huisman sailing yachts typically fall within the 40 to 60-meter range, the current norm in their business includes vessels exceeding 80 meters, exemplified by superyachts like Sea Eagle II, Project 410 and Project 411 [34]. Despite their considerable size, the available interior space on board is limited compared to a motor yacht of the same length, with the GT that is approximatly half [35, 36]. This is to be attributed to the stringent aesthetic standards and the performance requirements while sailing under sail that Royal Huisman yachts have. Tight spaces on board limit even more compared to a motor yacht the integration of alternative energy carriers and converters on board, as in terms of technical feasibility, they face the issue of extra volume and weight for the same energy demand due to lower volumetric and gravimetric energy density. To assess the energy demand of these yachts, it is crucial to initially scrutinize their operational profile, enabling a comprehension of the distribution over time among the five primary operational modes: motoring, sails only, motor sailing, anchor, and moored. Figure 2.1 shows the side view and the lower deck arrangement of the 47-metre and 282 GT sailing yacht Nilaya, delivered by Royal Huisman in 2023.

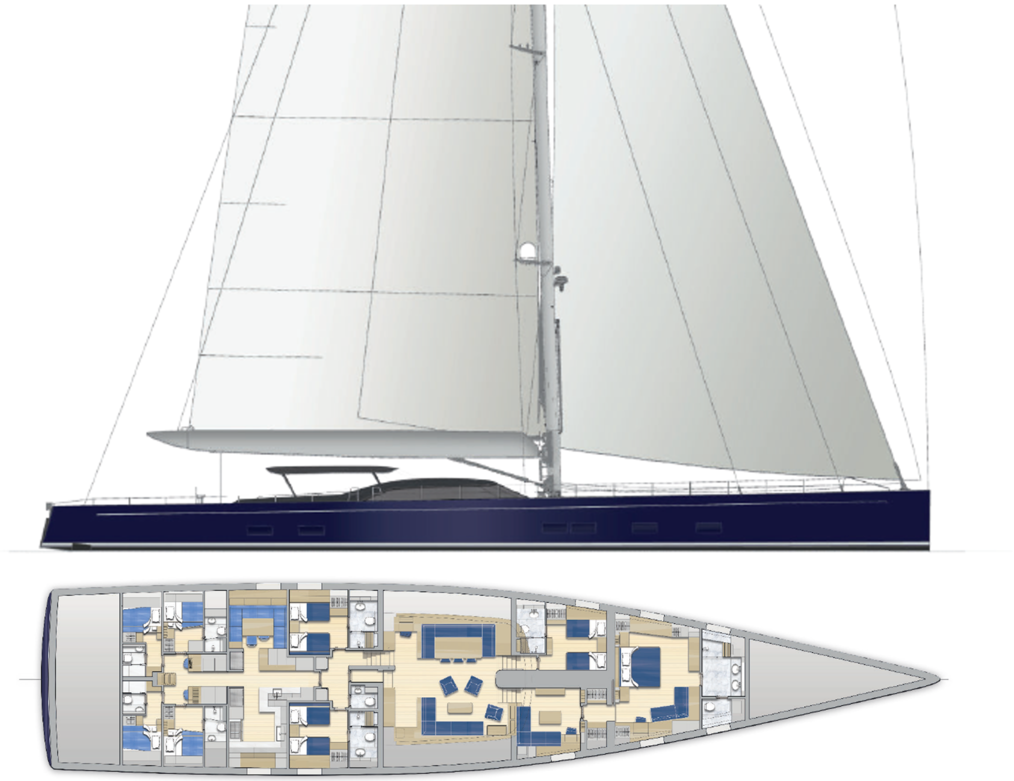

Figure 2.1: 47-metre and 282 GT high-performance cruiser sloop "NILAYA" external side and lower deck view [37]

2.1.1. Operational profile

As Royal Huisman specializes in building full custom sailing yachts of diverse lengths and operational profiles, providing a definitive 'typical' operational profile for a standard Royal Huisman yacht proves challenging. Consequently, the operational profile outlined in this section should be viewed as an average and not tied to any specific yacht. The analysis involves scrutinizing AIS data combined with data provided by yacht crews. From this dataset, five primary modes of operation are identified:

- Motoring
- Sails only
- Motor sailing
- Anchor
- Moored

The temporal distribution of these activities is examined using AIS data, where location and speed reveal whether a yacht is sailing, anchored, or moored. Notably, the AIS data doesn't distinguish if a yacht is sailing under engine, a combination of engine and sails, or solely under sail. To address this, the breakdown between sailing under engine and sailing under only sail is determined through insights from the crew. In particular, chief engineers of the two Royal Huisman sailing yachts Ngoni and Sarissa specified that this division depends on weather conditions and wind strength, which vary constantly depending on the geographical area and the time of year. Nonetheless, yachts aim to use sails as much as possible, but always with the main objective of arriving on time, safely, and without any damage. Specifically, a significant portion of the time, yachts typically do motor sailing. This approach offers numerous advantages, such as the ability to sail at a higher speed or reduce fuel consumption. Additionally, it provides more stability and reduces rolling, thus improving onboard comfort. The proportional distribution among these main activities on a yearly base is depicted in Figure 2.2 below:

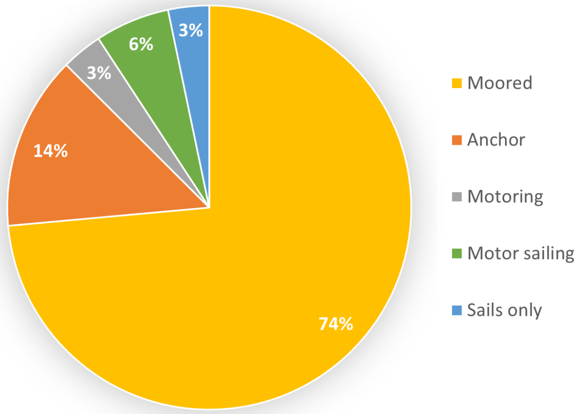

Figure 2.2: Typical operational profile of Royal Huisman sailing yachts on a yearly base

According to this pie chart, Royal Huisman yachts are moored most of the time and are sailing just under engine for 3% of the time based on a yearly average. The time spent at anchor is 14%, while sailing combining engine and sails occurs 6% of the time and sailing under sails is only 3% of the time. Considering that Royal Huisman yachts are primarily sailing yachts, it's somewhat unfortunate that the duration dedicated to sailing experiences seems to be comparatively limited. Having sails is indeed a rare feature for superyachts, which allows for a significant reduction in the energy required by the engine and also enables the generation of electricity through hydro generation [38].

From a geographical perspective, Figure 2.3 reveals distinct patterns collected by AIS data. Notably, a significant number of yachts undertaking journeys from Europe to the Caribbean at least once within the four-year dataset. The distance in nautical miles, for example, between Palma de Mallorca and the Caribbean islands, is approximately 4000 nautical miles (nm), which is indeed within the typical range required by most Royal Huisman yachts. However, during these crossings the majority of yachts made at least one stop at the Azores or at the Canary island, whose distance from the Caribbean is respectively 2400 nm and 2800 nm. Many yachts exhibit extended stays in specific harbors, with Palma de Mallorca emerging as the most popular location. Additionally, Barcelona and certain Caribbean islands are frequently chosen as mooring sites.

While the precise mooring locations may vary, it is reasonable to assume that a majority of these sites are equipped with shore power, and some even offer renewable electricity. In harbors with infrequent visits, shore power for vessels with power requirements of 100 kW or more is often not consistently available [39]. Using data from 33 superyachts' load balances provided by shipyards collaborating with the Yacht Environmental Transparency Index (YETI), it can be inferred that shore power is available for approximately 64% of the time when yachts are moored [40]. This percentage may be higher for smaller yachts and lower for larger ones, since for the latter the shore power is more likely to be not enough to support all the hotel load [40].

The sailing patterns, depicted in Figure 2.3 below with a focus on the Atlantic Ocean, highlight that although some yachts venture beyond this map scope, the majority of distances are covered within this region. The red areas indicate locations with a higher concentration of AIS data points.

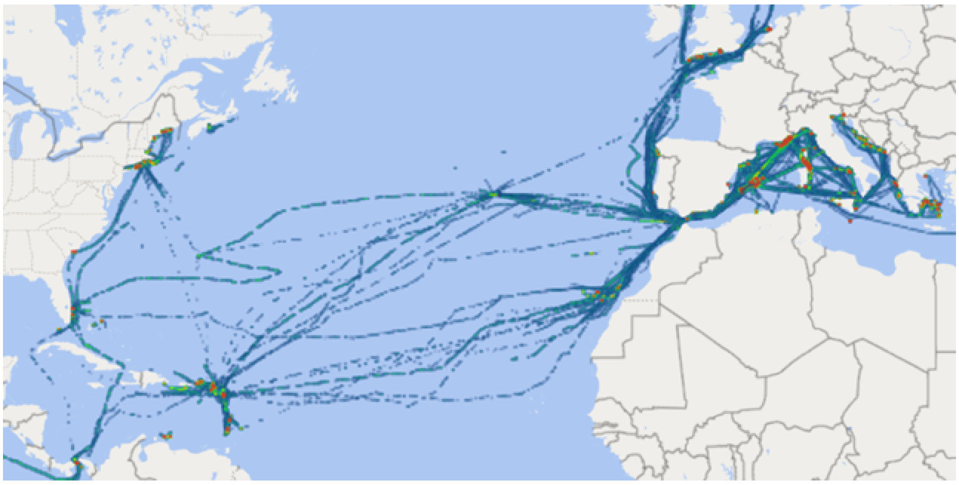

Figure 2.3: Royal Huisman yachts sailing pattern from AIS data

2.1.2. Energy demand

In general, a yacht necessitates energy for both propulsion and the operation of all other essential on-board systems collectively referred to as the hotel load. Derived from the operational profile collected by AIS data of a Royal Huisman sailing yacht below 500 GT and with a length between 50 and 60 meters, engine fuel consumption, and discussions with the crew, it is approximated that around 35% of the annual energy consumption is allocated for propulsion. This estimation is based on an average distance of 10.000 nm per year, and the energy required for the hotel load during sailing under engine is not factored into this percentage. Therefore, the majority of the energy demand is required by the hotel load. In particular, this remaining 65% of hotel load energy demand is generated approximately half onboard and half obtained from shore power, as can be observed in Figure 2.4. In terms of absolute figures, the overall energy needs of yachts depends on their size, systems, and operational activities. As an illustration, it has been computed that the Royal Huisman sailing yacht under analysis necessitates approximately 680.000 kWh per year, which are distributed as shown in Figure 2.4.

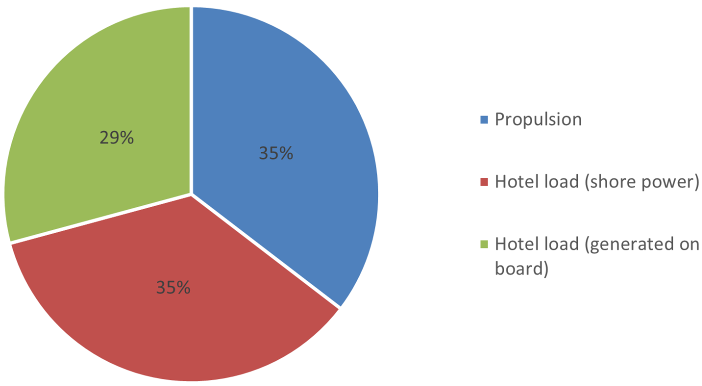

Figure 2.4: Yearly energy demand breakdown for a Royal Huisman sailing yacht below 500 GT and with a length between 50 and 60 meters

Based on data from Royal Huisman yachts, a core set of systems consistently requires energy irrespective of the operational mode. Examples of such systems include the seawater cooling system, refrigeration, communications, and lighting. Among these, the HVAC (Heating, Ventilation, Air-Conditioning) system stands out as the primary consumer in all activities, featuring a base load and demanding additional energy with an increased number of people on board. An example of the contribution that each subgroup of the hotel load makes to the energy demand is illustrated in Figure 2.5, referring to a Royal Huisman sailing yacht below 500 GT and with a length between 50 and 60 meters during anchoring in the evening.

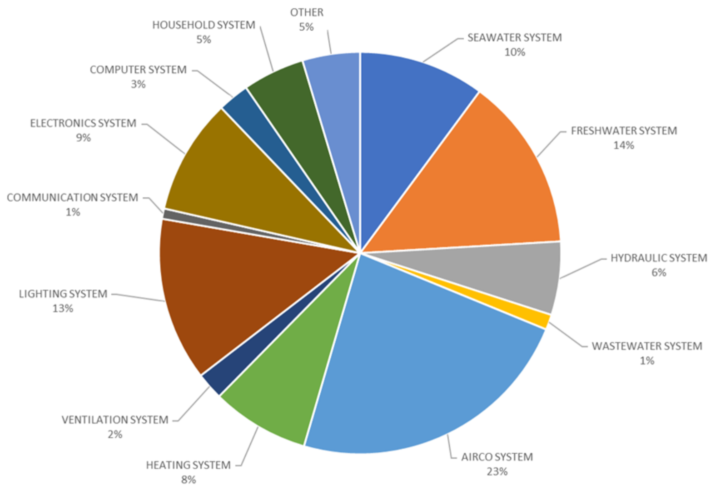

Figure 2.5: Breakdown of the hotel load for a Royal Huisman sailing yacht below 500 GT and with a length between 50 and 60 meters during anchoring in the evening

2.2. Chapter conclusion

In conclusion of this chapter, a succinct answer to the following subquestion is provided:

"What are the peculiarities of a sailing yacht in terms of interior space, operational profile, and energy demand?"

Sailing yachts represent a niche within the yachting industry. They have unique characteristics, foremost among them the ability to harness propulsion through sails, although unfortunately, the times when sailing superyachts navigate solely under sail are in the minority. In order to reduce ship emissions in general, scientific research and shipyards are focusing on alternative energy carriers and converters. However, these face significant challenges in terms of technical feasibility due to the increased volume and weight required because of their lower energy density. The onboard spaces of a sailing yacht are limited and even more optimized compared to a motor yacht, further complicating the integration of sustainable technologies onboard. Nevertheless, if the time dedicated to sailing under sail only or motor sailing were increased, especially during long crossings as they represent challenging scenarios in terms of energy demand, the required energy would be reduced. By reducing the energy demand, also the impact of integrating onboard alternative energy carriers and converters would be lower.

For a generic Royal Huisman sailing yacht, five operational modes can be identified: motoring, motor sailing, sails only, anchoring, and mooring. Based on AIS data cross-verified with input from the crew, the temporal distribution analysis reveals that yachts are moored for approximately 3/4 of the time, and the time spent sailing under only engine is similar to that of sailing only with sails, but more often yachts do motor sailing, combining sails with the propulsion engine. Finally, the time spent at anchor is 14%. The typical range required by most Royal Huisman yachts is 4000 nautical miles, corresponding to an Atlantic Ocean crossing. However, during these crossings, the majority of yachts make at least one stop at the Azores or the Canary Islands, which are approximately 2400 nm and 2800 nm away from the Caribbean, respectively. This means that even by reducing the storage fuel tank capacity, sailing yachts with a range of 4000 nm could still cross the Atlantic, and therefore, the compromise that the owner would have to make would not excessively impact the operational profile of their yacht.

Regarding energy demand, considering a Royal Huisman study that assumes an average distance of 10.000 nm per year for the yacht, it emerges that the energy required for hotel load is higher than the energy required for propulsion. Within the hotel load, the HVAC system stands out as the primary consumer. Furthermore, in the five primary modes of operation, the energy for the hotel load is derived from various sources—a specificity contingent on the yacht's energy concept and can vary for each vessel. It is noteworthy to observe that a distinctive characteristic of sailing yachts is the capability to produce electricity for the hotel load through hydrogenerators while actively sailing under sail.

3
Investigation into emission reduction

There are various methods to decrease emissions in the current fleet of Royal Huisman sailing yachts. A first important and simple step would be to sail under sail for a longer duration and use the engine less. Furthermore, a refit can be undertaken to enhance efficiency by replacing outdated systems without compromising on luxury, size, freedom, and other fundamental aspects of yacht construction. However, a technological limit exists that cannot be exceeded. Therefore, to achieve further emission reduction, a shift in fuel sources becomes imperative. Alongside alternative energy carriers, there are several possibilities for alternative energy converters, the most promising of which will be explored in this chapter. The two subquestions addressed in this chapter are as follows:

- *"Which are the most promising alternative energy carriers? What alternative energy converters hold the most potential?"*
- *"Which are the opportunities to reduce the energy demand in design and operation?"*

The focus will initially be directed towards alternative energy carriers, followed by alternative energy converters, and ultimately, energy demand reduction.

3.1. Alternative energy carriers

In this section, alternative energy carriers will be examined, providing a broad overview of those garnering significant attention within the maritime sector. Subsequently, the focus will narrow down to those that are practical for Royal Huisman yachts. This approach aims to address this first part of the second subquestion:

"Which are the most promising alternative energy carriers?"

Numerous energy carriers hold the potential to substitute fossil fuels. A continuously updated list of alternative fuels for the maritime sector is provided by the Maritime Research Institute Netherlands (MARIN) [41]. In Table 3.1, an excerpt from the comprehensive and intricate MARIN fuel list is provided.

Table 3.1: Alternative fuels characteristics [41]

Energy carrier	Energy density		Storage condition	
	Volumetric	Gravimetric	Pressure	Temperature
	[MJ/L]	[MJ/kg]	BAR	[C°]
MGO	36.6	42.7	1	Ambient
Biodiesel (HVO)	34.4	44	1	Ambient
Synthetic diesel	34.4	43	1	Ambient
Li-ion battery	0.62	0.40	1	Ambient
Hydrogen: compressed	2.6	120	300	Ambient
Hydrogen: liquified	7.5	120	1	-253
Ethanol	21.3	28	1	Ambient
Methanol	15.6	19.7	1	Ambient
Ammonia	12.7	18.6	1	-35
DiMethylEther (DME)	19	28	1	Ambient
Methane	9	48	250	Ambient

Royal Huisman has not focused on all the energy carriers listed in the table, but solely on specific ones, deeming others currently unfeasible for their yachts. Indeed, synthetic diesel will not be considered among the possible energy carriers to be integrated on board for this thesis despite it has very similar characteristics to fossil diesel. It can be considered as a potential future fuel due to its dual qualities of renewability and absence of WTW GHG emissions [42, 43]. Synthetic diesel is made by reconfiguring another hydrocarbon fuel, created from hydrogen and captured CO_2 [42, 44]. On the other side, however, the production costs are elevated as the process demands a substantial amount of renewable energy [42]. At present, the TRL remains relatively low, and large-scale industrial production is yet to be realized [43, 45]. While the high OpEx might be justifiable for superyacht owners, given its minimal impact on internal volume and CapEx, its feasibility for commercial ship owners is in question. A limited global demand would likely constrain the global supply of synthetic diesel.

The investigation into ammonia has been halted due to its significant toxicity to both humans and the environment [46]. Nonetheless, Lloyd's Register has indicated that ammonia is projected to account for 20% to 60% of total shipping fuels by 2050 [47]. Despite its higher volumetric energy density compared to alternative fuels like compressed hydrogen and relatively low production costs, vessels using ammonia may encounter limitations on the range of harbors they can access, possibly being restricted to industrial ports [48]. Liquefied hydrogen offers higher volumetric density than compressed hydrogen, but the limited holding time, large cryogenic tanks, and complex infrastructure are significant challenges associated with it. For large vessels, including large yachts, liquefied hydrogen can have a benefit of scale, since large tanks with large quantities can keep the hydrogen cool [49]. However this solution is not considered feasible for Royal Huisman sailing yacht, at least until smaller and with a longer holding time storage tanks will be developed. Also DME has a higher energy density than other alternative fuels like hydrogen (both liquefied and compressed) and methanol. Nevertheless, being gaseous at atmospheric pressure, DME necessitates storage at a minimum pressure of 5.1 bar. Synthetic DME, with the chemical formula C_2H_6O, is derived from liquid methanol (CH_3OH) [50]. This implies that synthetic DME incurs higher production costs and less favorable storage conditions compared to methanol. On the other hand, Bio DME boasts lower production costs, albeit with storage requirements less favorable than, for instance, biodiesel [51, 52]. In conclusion, it will not be considered as a possible solution for the Royal Huisman yacht fleet.

Methane requires compression or liquefaction for storage as it is a gas under atmospheric conditions [53]. Furthermore, it is a greenhouse gas, and so poses the risk of entering the atmosphere as methane slip when not entirely burned during energy conversion [54]. Both compressed and liquefied methane necessitate large, heavy, and complex storage tanks [53]. Given the limited available volume for yachts, and being the production process of bio methane similar to that of liquid biofuels, Royal Huisman agrees that it is more convenient to use liquid biofuels in this context. In synthetic production, the energy consumption for methanol production is only slightly higher than that of methane, yet methanol is liquid and easier to store [55]. Consequently, methane is not regarded as a viable solution for Royal Huisman yachts. Ethanol, characterized by the chemical formula C_2H_6O, exists in liquid form under atmospheric conditions and boasts a relatively high energy density for an alternative fuel, albeit approximately half that of diesel [56]. Indeed, as can be seen in Table 3.1, it is equal to 21.3 MJ/L as opposed to 36.6

MJ/L of diesel, requiring larger storage tanks. Volume-wise, ethanol storage tanks need to be 53% larger than a diesel tank containing the same amount of energy. The synthetic production of ethanol consumes more energy compared to methanol production, making methanol more favorably viewed as a promising synthetic fuel [56]. However, when derived from biomass, ethanol production is comparatively straightforward. Bioethanol is extensively used as a blend-in fuel, particularly in road vehicles (E10 fuel) [56]. A significant disadvantage of bioethanol compared to HVO is that to run on 100% ethanol, engines require modifications [57]. Ultimately, while its energy density surpasses that of other renewable fuels, it still falls short of biodiesel. Given that both are derived from biomass, it is probable that among biofuels, biodiesel will be the preferred choice for yachts.

Apart from these alternative fuels, there are several others in which Royal Huisman is interested and that are included in Table 3.1. They are methanol, compressed hydrogen, biodiesel (HVO), and batteries.

3.1.1. Methanol

Methanol, with the chemical formula CH_3OH, stands as the simplest alcohol. It exhibits characteristics of being a light, volatile, colorless, and flammable liquid under ambient conditions [58]. Despite its relatively high volumetric energy density of 15.6 MJ/L, which is noteworthy for an alternative fuel, it still has half of the energy density of diesel, that is equal to 36.6 MJ/L [41]. Large ship-owners have shown interest in methanol due to its versatile storage capabilities in various tank shapes, its superior volumetric energy density compared to hydrogen and ammonia, and the mature technology associated with methanol fuel production [59]. Notably, in 2015 Stena Germanica became the world's first RoPax vessel powered by methanol [60], and in 2021 Maersk has ordered 12 new container vessels of 16.000 TEU with dual-fuel engines that can operate on methanol or on low sulphur fuel oil [58]. These developments could contribute to the expansion of (green) methanol bunker stations on a global scale.

Various types of methanol energy converters are currently in the developmental phase, but these will be deepened in the next section 3.2. When methanol undergoes combustion, it produces carbon dioxide and water, but noxious emissions from burning fossil-derived methanol in ship engines are much lower than those of diesel [59]. Despite pure methanol lacking sulfur, in case of ICE the presence of diesel pilot ignition means that SO_x emissions are not entirely eliminated [58]. Nevertheless, methanol demonstrates the capability to reduce SO_x and PM emissions by over 95%, and NO_x by up to 80% compared to conventional marine fuels [61].

Methanol can be produced from numerous sources, including carbon-containing feedstocks, biomass, and non-bio renewable energy. However, it is currently predominantly produced through carbon-intensive processes, such as natural gas reforming and coal gasification. For methanol to become a sustainable alternative in a low-carbon future, there is a need to shift production towards cleaner methods [62]. The emissions of carbon from green methanol are considered climate-neutral since the combustion process does not introduce more CO_2 into the environment than was previously extracted from it. Further enhancement of the carbon balance could be achieved by adopting more sustainable feedstocks or capturing the emitted CO_2 for reuse in the production of green fuels [59].

Storage & Safety

Beyond the challenge posed by energy density, the use of methanol as fuel introduces an additional concern pertaining to stringent safety regulations governing the storage of flammable, explosive, and/or toxic substances [63]. In addressing this matter, the IMO IGF Code incorporates imperative guidelines encompassing the arrangement, installation, oversight, and monitoring of machinery, apparatus, and systems using low-flash fuels [64]. Spaces involved in methanol handling necessitate thorough ventilation and other safety precautions [63]. Additionally, detection systems are mandated in specific locations, and in areas where methanol is pressurized, double-walled piping is deemed essential. A nitrogen system is also required for purging [65]. For Royal Huisman, the corrosive nature of methanol is of particular concern, affecting metals such as aluminum and steel. When methanol tanks are integrated into a steel vessel construction, applying a coating is deemed sufficient. However, for standalone methanol tanks, it is recommended to use stainless steel or composite tanks, although coating should still be applied [66]. There is a lack of specific studies addressing the feasibility of storing methanol in an integrated aluminum tank.

Compared to a diesel configuration, the planned changes primarily involve adjusting layouts for fuel preparation, ventilation, and storage tank to meet specific requirements. Nevertheless, the most significant effect will be associated with the storage part, specifically concerning cofferdams [67]. Cofferdam is defined as a structural space surrounding a fuel tank which provides an added layer of gas and liquid tightness protection against external fire, and toxic and flammable vapours between the fuel tank and other areas of the ship [64]. As defined again within the IMO Interim guidelines, cofferdam removal is allowed if the tanks are bound by shell plating under the lowest possible waterline, other fuel tanks (containing methyl/ethyl alcohol), or fuel preparation space [64].

Regarding cofferdam dimensions, IMO Interim guidelines states that cofferdams should have a minimum clear opening of 600 x 600 mm and for access through vertical openings providing main passage through the length and breadth within fuel tanks and cofferdams, the minimum clear opening should not be less than 600 x 800 mm at a height of not more than 600 mm from bottom plating unless gratings or footholds are provided [7]. The sizing of cofferdams is influenced by their accessibility for inspection, a criterion demanding human entry. Moreover, to accommodate openings within the cofferdam structure measuring 600 x 600 mm horizontally and 600 x 800 mm vertically, the cofferdam's overall dimensions must surpass these specified measurements [64]. Since the tank volumes for Royal Huisman yachts are relatively small compared to other (commercial) ships, the impact of cofferdams is too large.

The rules of the IGF code are important for designing a safe and reliable system, but they are not mandatory for most Royal Huisman yachts. They apply to ships subject to Part G of SOLAS Chapter II-1, which is applicable to vessels with a GT exceeding 500 [64]. However, the American Bureau of Shipping (ABS) applies the IGF code to all vessels, regardless of size, including those with less than 500 GT [68]. The majority of Royal Huisman yachts are classified by the Lloyd's Register, that in November 2023 has introduced a novel concept involving the use of ballast water tanks instead of cofferdams around methanol tanks [69]. However, Royal Huisman sailing yachts lack ballast water tanks, so this solution is not feasible.

Since IMO rules in this regard are conservative when applied to yachts, often a risk-based approach is applied to get an approval from the classification society, demonstrating that new technologies are possible at a safety level equivalent to existing technologies. In this respect, for example in a recent thesis performed for Feadship it was also concluded that cofferdams currently required will result in a significant reduction of interior space, which was not acceptable. Alternative cofferdams of 100 mm were suggested, with additional sensors and ventilation systems [67]. This proves that risk-based design procedures might lead to smaller cofferdams. Using the same principle, a solution featuring a sandwich arrangement with a 25 mm polymer layer between two steel panels has received an approval in principle [70]. However, it must be specified that the application of this solution to aluminum hulls and not steel requires further studies, given that without electrical isolation between the steel external plates and the aluminum hull, the aluminum could act as an anode to the steel, resulting in galvanic corrosion [71]. Isolating the metals with non-conductive barriers, using sacrificial anodes, or applying protective coatings are all solutions that need further investigation and could solve such complications that might arise when applying this Sandwich Plate System (SPS) technology to Royal Huisman sailing yachts. Despite this, the solution appears promising and would address many of the issues related to installing cofferdams around the relatively small tanks of Royal Huisman sailing yachts. For this reason, this thesis has chosen to adopt this promising solution.

3.1.2. Hydrogen

Hydrogen is a colorless, odorless, and non-toxic gas [72]. Due to its low volumetric energy density, it requires compression or liquefaction for use as a fuel. In this thesis, the focus will be solely on compressed hydrogen, as the liquefied form has been excluded for the previously stated reasons. The volumetric energy density of 300 bar compressed hydrogen is 2.6 MJ/L, which is less than 20% of methanol and only 7% of MGO [41]. Hydrogen does not generate TTW emissions. However, when considering the WTW process, which includes the entire fuel production, emissions can vary significantly based on the production methods employed [73]. If generated using renewable energy, WTW

CO_2 emissions can be reduced by more than 80%, compared to conventional diesel. Nevertheless, it is crucial to note that, at present, 95% of hydrogen is derived from fossil fuels [74]. The storage of compressed hydrogen is more intricate compared to methanol, requiring pressurized heavy cylindrical tanks and resulting in a reduced volume effectively available for hydrogen storage [75]. In terms of energy conversion, hydrogen can be used in ICE. However, hydrogen's true potential is realized through the application of Proton Exchange Membrane Fuel Cells (PEM FC) [73].

Hydrogen supply poses a challenge for maritime vessels, especially as significant ports currently lack extensive infrastructure [76]. Yachts face an even greater hurdle since they often sail in remote areas where (renewable) hydrogen availability is scarce. While compressed hydrogen delivery via truck is feasible in certain regions, it appears an impractical solution for addressing hydrogen supply issues. Onboard production of renewable hydrogen is a potential alternative through water electrolysis, a process using clean water and electricity to generate hydrogen and oxygen. Although the technology is not overly complex, implementation necessitates a watermaker with a purifier, a compressor, and a sizable electrolyzer, typically not designed for marine applications. Nevertheless, there are instances of vessels employing this technology. The Energy Observer, a French research vessel, serves as an example where renewable hydrogen is generated onboard. This vessel obtains the required electricity from solar panels and extracts water from seawater. Furthermore, it has the capability to use electricity directly and store it in a battery pack [77]. A comparable energy concept is expected to be implemented in a 19-meter pleasure catamaran scheduled for delivery in 2024 [78]. However, the extended production times for hydrogen using water electrolysis, along with high costs, low efficiency, and the substantial size of the components, currently make it not convenient [79].

Storage & Safety

Compressed hydrogen storage tanks, which typically operate within the pressure range of 250 to 500 bar, are available, featuring cylindrical shapes and constructed from composites to minimize weight [80, 75]. As the pressure in the tanks increases, the occupied volume decreases, but concurrently, the weight and potential hydrogen leakage increase [81]. Royal Huisman expresses a particular interest in the 350-bar variant for two primary reasons: first, it provides greater flexibility in design, allowing for slightly larger but more efficient tanks, and second, it offers flexibility in supply. Indeed, this solution is advantageous when employing the balancing method to fill hydrogen tanks, as the shore supply, typically a truck, necessitates a higher pressure than the onboard storage system. Currently, the standard pressure for trucks ranges up to 500 bar, often settling at 350 bar [82].

Hydrogen safety regulations concern detection, alarms, ignition control, ventilation, leak control, safety distances and hazardous zones [83]. Although classification societies are beginning to publish guidelines [84, 85], IMO guidelines for hydrogen-fueled vessels do not yet exist and are expected to be released in January 2025 [86]. The IGF code, in fact, does not currently provide guidelines for the safety of ships using hydrogen as fuel [85]. Nevertheless, similar to methanol, Royal Huisman considers a risk-based approach as the most suitable method for designing a class-approved system.

3.1.3. Biodiesel

Biodiesel is a fuel obtained by processing biomass, and can be derived from various sources such as soy, sugarcane, corn, algae, or plant dry matter (including trees, bushes, corn stalks, etc.) [73]. Its characteristics are similar to diesel and is capable to be used in currently existing diesel engine with little or no need for engine modification [87]. Among the three main types of biodiesel, namely FAME (fatty acid methyl ester), BTL (biomass to liquid fuels), and HVO [88], Royal Huisman and in general the yachting industry are focusing on HVO. Indeed, despite being analysed in various research projects exploring potential alternative fuels for the maritime sector [83, 89], FAME is not the preferred alternative. It is produced from vegetable oils, animal fats or waste cooking oils by transesterification, where various oils (triglycerides) are converted to methyl esters. This is the most widely available type of biodiesel in the industry and is often blended with regular marine diesel [88]. However, FAME tends to attract water and is consequently susceptible to bacterial growth in storage tanks [90].

HVO is derived from the same biomass as FAME but can also be produced from residual crops and industrial waste. Produced through hydrocracking, it forms paraffinic hydrocarbons similar to those in petroleum-based diesel [90]. A diesel engine can run on neat HVO, but marine vessels may need fuel treatment system adjustments due to low fuel density [90]. Unlike FAME, HVO is not prone to microbial growth. It lacks aromatics and sulfur, burning cleaner with minimal soot formation and limited ash content, leading to longer lubrication oil quality [90]. As can be seen in Figure 3.1, HVO allows for substantial WTW CO_2 emission reduction thanks to its production process. However, the density difference between HVO and residual fuels poses risks during fuel changeover.

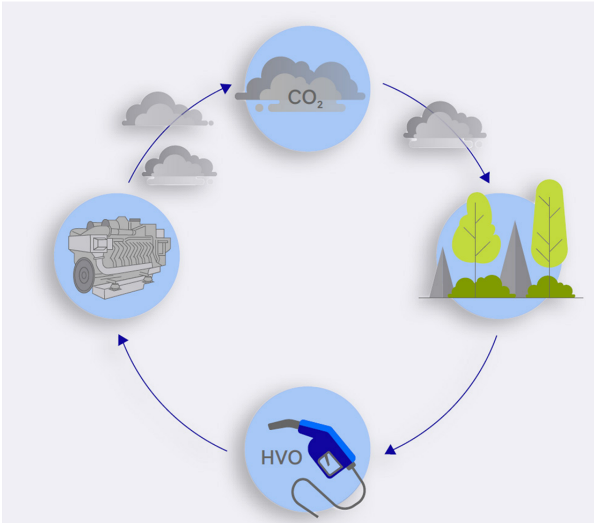

Figure 3.1: Full life cycle emissions of HVO [38]

Biodiesel can emit more particulate matter than fossil diesel, although this depends on the bio stock that is used [91]. Furthermore, global HVO production falls short of meeting the shipping industry's growing demands, but traditional oil refineries have been converted to HVO production and this has led to the increase of more than 40% capacity in the last five years [83]. The primary drawback of HVO lies in its comparatively inferior lubrication properties when compared to the benchmark value of F76. However, it still falls within the ranges specified by STANAG-1385 [89]. If HVO will spread, lubrication oil producers must adapt to its absence of sulfur, requiring oils with low total base number (TBN) and high detergency for efficient engine lubrication and prevention of scuffing [90]. From a safety and regulations point of view, due to the fact that HVO has a similar chemical structure as MGO fuel, there are no safety issues, extra rules or extra crew qualifications for the application compared to MGO [83].

Regarding the diesel engines currently installed in Royal Huisman yachts, almost all of them are compatible with HVO. Both MTU [92] and Caterpillar [93], as well as Scania [94], which are the main manufacturers of engines installed, have officially confirmed this information.

3.1.4. Batteries

In recent years, interest in batteries as an energy carrier on board ships has been growing. This can be attributed to the increased power densities, lower costs, and longer lifetime that batteries are experiencing [83]. While the advancements are promising, the energy density still remains low compared to all other alternative fuels. Energy density values vary depending on the type of batteries, with the most promising ones that according to Royal Huisman and other sailing yacht companies are the Li-ion type [95, 96]. The majority of those currently installed on Royal Huisman yachts are of the Lithium nickel manganese cobalt oxide (NMC) type, but they are also currently considering Lithium iron phosphate (LFP) batteries. The primary benefits of the latter include durability, a long life cycle, safety, and lower cost, but on the other hand, they have a slightly lower average energy density as can be seen in Figure 3.2, although it depends on the manufacturer [97].

This analysis will focus on LFP batteries, specifically with a volumetric energy density of 0.62 MJ/L and a gravimetric of 0.40 MJ/kg as can be seen in Table 3.1. It is essential to clarify that, given the recommendation against fully discharging the batteries, these values have been calculated based on using only 80% of the battery capacity. Lithium Cobalt Oxide (LCO) batteries where not chosen due to unstable operation at increasing cell sizes and high capital costs, despite similar energy density to NMC batteries [83]. The performance of batteries is influenced by volumetric and gravimetric energy density. Additionally, charging time, discharging time, and delta state of charge (DSOC) play crucial roles. DSOC represents the percentage of the total battery capacity used during discharge. Charging time is measured in C-rate, with a 1C battery charging in 30 minutes. Lower battery density typically corresponds to a charging class of 4C or higher. A higher DSOC and shorter discharging time are associated with a lower battery lifetime [83].

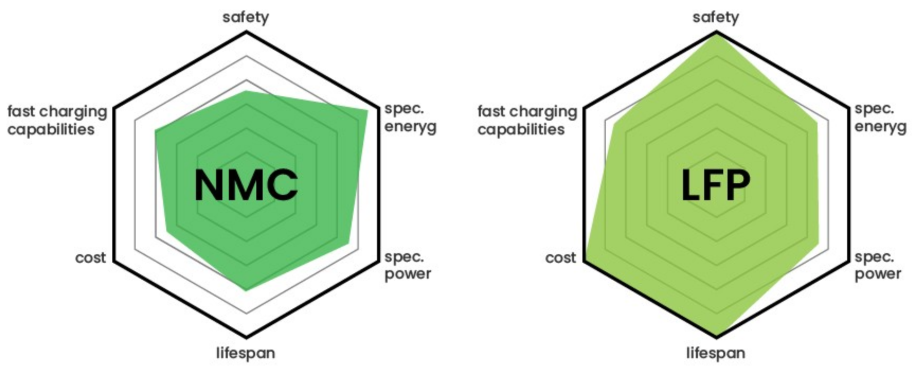

Figure 3.2: Comparison between NMC and LFP batteries [98]

Batteries have the potential to achieve zero emissions. However, their use in the maritime sector is considered promising for vessels with a restricted operational range and predictable routes, featuring a limited day endurance or range [99]. Yachts, on the other hand, typically lack limited operational ranges or predictable routes. Nevertheless, for sailing yachts, the ability to harness wind power for propulsion and enable hydrogenerators to come into play offers the prospect of minimizing the necessary stored energy. This makes the use of batteries more appealing, but in any case, it does limit the operational profile, making it dependent on weather conditions and requiring an owner willing to sail under sail more frequently.

Safety and Regulations aspects

The safety considerations and potential issues demanding heightened attention include internal cell failure, internal or external short circuits, overcharging, and overtemperature. These issues may manifest as gas development, fire hazards, explosion risks, and notably, thermal runaway—a rapid temperature increase of 20°C per minute [83]. The internal rise in pressure and temperature could lead to the melting of the separator, causing an internal short circuit. This, in turn, results in the evaporation of battery fluids, leading to increased pressure in the cell [100]. The resulting fumes could cause an explosion if ignited by an external source. The exothermic reaction of a runaway quickly spreads to other cells and is challenging to halt. Therefore, it is essential to store batteries in a closed, well-ventilated environment [101]. To mitigate the consequences of a thermal runaway in a cell, a dedicated foam installation must be implemented. This system continuously monitors the temperature of each cell and can inject foam rapidly and in large quantities [102]. These advanced systems contribute to making batteries a promising and secure application [83].

3.1.5. Conclusion on alternative energy carriers

In conclusion of this section, a concise and effective response to the following subquestion is provided:

"Which are the most promising alternative energy carriers?"

There are several promising alternative fuels that allow for the reduction of emissions from Royal Huisman sailing yachts, but it is difficult to identify one as more promising because of their trade-offs between associated emissions, energy density and TRL. Indeed, as shown in Table 3.1, except for biodiesel and synthetic diesel, both methanol and hydrogen, as well as batteries, have a volumetric energy density that is lower than traditional diesel currently used in yachts. The sustainable pathway that would have the least impact on design and operational profile without the need for additional storage volume is with biofuels or synthetic diesel. However, this pathway still has local emissions, and future availability is uncertain.

Batteries are too heavy and have too low energy density to replace diesel, but they are still crucial for peak shaving. Furthermore, they can ensure silent periods by allowing diesel generators to be turned off, for example, while anchoring. They can also be combined with other alternative energy converters powered by methanol or hydrogen, or hydrogenerators for the storage of generated electricity. As for methanol and hydrogen, they are the most promising for emission reduction and are indeed at the centre of attention from the maritime industry. However, the TRL is still not high, and they face challenges related to availability, high costs, safety, and, as mentioned earlier, low volumetric energy density. In the end, combining HVO with methanol or hydrogen or batteries seems the most promising option, but this will be analyzed further in the course of the thesis. It is therefore not considered possible to refit a Royal Huisman sailing yacht to a single alternative fuel, apart from HVO, without modifying the operational profile, reorganizing internal spaces, altering the hull shape or installing extra fuel tanks on the main deck, with the last two possibility which is not considered feasible for sailing yachts given their hull shape and high aesthetic standards.

3.2. Alternative energy converters

This section centers on alternative energy converters, spanning from Internal Combustion Engines (ICEs) to fuel cells, hydrogeneration, and solar panels. This approach will address the second part of the second subquestion:

"What alternative energy converters hold the most potential?"

The predominant power sources for marine propulsion and auxiliary systems on yachts are currently ICEs fueled by diesel. While these engines have demonstrated reliability and diesel is easy to store and has a high specific energy and energy density, the future direction of propulsion systems appears to be moving away from exclusive reliance on diesel ICEs. Consequently, there is an anticipation that diesel engines will be replaced within a foreseeable timeframe [83]. The research, studies, and experiments conducted to develop new energy converters have significantly advanced the TRL of a system [103]. These advancements have prompted discussions about various alternatives to diesel ICE energy converters. In this context, fuel cells emerge as a noteworthy alternative due to their promising characteristics. Despite being relatively new, fuel cells have gained attention for their high efficiencies and the ability to operate without emitting CO_2, leading to their application on vessels [83].

Moreover, the yacht is surrounded by an abundant reserve of energy in the form of wind, solar power, heat, and waves. However, converting these resources into usable energy in an efficient and reliable way is a challenging endeavor. Many energy consumers on board rely on electrical energy, making the possibility of converting various energy sources directly into electricity promising. In the case of a sailing yacht, wind is already harnessed to propel the yacht forward using sails. Furthermore, this kinetic energy can be transformed into electricity through a propeller, or more efficiently, a turbine submerged underwater, a process known as hydro generation [38]. Also solar energy can be converted into electricity through the use of solar panels [104]. Presently, there isn't a suitable technology available for yachts to harness energy from waves or heat in seawater for practical use. The conversion of natural energy sources has its limitations. Hydro generation is effective only when the yacht is sailing, solar power is limited to daylight hours, and wind power relies on sufficient wind conditions. Additionally, the realistically attainable size of turbines and solar panels is often restricted. Despite these challenges, the key advantage of renewable sources lies in their consistent reduction of emissions, even if the impact is relatively small.

3.2.1. ICEs

ICEs serve as the predominant energy converters across all types of ships. While ICEs are known for their efficiency and reliability, the combustion process inherently gives rise to noise, vibration, and emissions, including local emissions that are inevitably generated [89]. In the combustion process, nitrogen and oxygen combine to form NO_x, which are regulated as local emissions in Europe and America, as discussed in subsection 1.3.1. Additionally, combustion-related emissions such as PM contribute to smog and pose health concerns [105]. The effective efficiency of an ICE installable on a superyacht is 50% [106], with values that can reach up to 55% for slow-speed two-stroke diesel engines [107]. One drawback of ICEs is their varying efficiency levels across different loads [89]. The degree of efficiency fluctuates depending on the engine manufacturer and type. Typically, high-speed and medium-speed marine engines achieve their peak efficiency at relatively high loads, often reaching 70% of the maximum load or even higher. In the case of large marine engines, this efficiency threshold is frequently elevated, reaching up to 85% [108]. Major engine manufacturers are developing ICEs that can operate on alternative fuels, especially on methanol [109, 110]. As a result, ICEs could remain the predominant energy converters over the next 20 to 30 years if alternative fuels such as HVO or methanol are used instead of conventional diesel [83]. Below are the suggested alternative fuel types suitable for ICEs.

HVO

The engines of the Royal Huisman fleet, like the vast majority of existing yachts, are compatible with biodiesel. Within this category of alternative fuels, HVO is considered the most promising, as explained in subsection 3.1.3. The main engine manufacturers for Royal Huisman yachts, including MTU [92], Caterpillar [93], and Scania [94], have officially verified their compatibility with HVO.

Methanol

Modified conventional marine engines are compatible with methanol. In the past decade, numerous engine manufacturers have designed their engines to be ”retrofit ready”, facilitating future modular retrofits at a limited cost [83]. The primary challenge associated with using methanol fuel in existing diesel engines lies in the fact that diesel engines operate on compression ignition, while methanol is a spark ignition fuel with a high octane number. In dual fuel engines, methanol is used as the primary fuel, and a small amount of diesel, known as the pilot fuel, is employed to initiate combustion [111, 112, 113]. Today, several engines running on 100% methanol are available for ships [114, 115].

Hydrogen

The development of hydrogen-fueled ICEs demands significant attention from manufacturers [83]. While some projections suggest readiness for installing hydrogen engines by 2030 [116] or even as early as 2025 [117], the predominant trend in hydrogen-powered vessels leans towards the use of fuel cells. This preference is attributed to the advantages of fuel cells over engines, including minimal noise, absence of vibrations, higher efficiency, and no local emissions. The avoidance of local emissions is particularly noteworthy, as burning hydrogen in engines can generate very high temperatures, leading to increased NO_x emissions [118].

3.2.2. Fuel Cells

Fuel cells are electrochemical devices that directly convert chemical energy into electrical energy, bypassing the indirect thermal energy route in combustion engines. The absence of expansive, high-temperature combustion results in reduced NO_x formation, noise, and vibrations, while still achieving high efficiencies [118]. However, the drawbacks include the high production costs, directly linked to the still too small-scale production and technical characteristics [119]. Fuel cells operate on pure hydrogen, which can be derived from sources such as ethanol, methanol, or ammonia. Some fuel cells can internally reform methanol into hydrogen on the anode side, but this internal reforming can lead to reliability issues. Hence, it is common to perform the reforming of the fuel before it enters the fuel cell [83]. Depending on the electrolyte type, fuel cells can be categorized into alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), proton exchange membrane fuel cells (PEMFC), and solid oxide fuel cells (SOFC). Currently, the latter two types of fuel cells are the focus of marine research and are increasingly being commercially used [119]. As a result, the analysis will be centered on these two types.

PEMFC

PEM fuel cells can be divided into HT-PEMFC (high-temperature) and LT-PEMFC (low-temperature), and the only appropriate fuel for this fuel cell types is pure hydrogen [118].

- LT-PEMFC: This fuel cell type has experienced significant development, achieving a high TRL with commendable power densities and transient performance [118]. Notably, these fuel cells offer rapid start-up times and also possess a high energy density, allowing for compact installations [120]. However, their operational temperature range of 65-85°C complicates the use of hydrogen reformed from methanol [118]. LT-PEMFCs require high-purity hydrogen due to their low tolerance for impurities, especially carbon monoxide (CO) [121]. While challenges such as CO sensitivity have hindered widespread commercial adoption, studies suggest the potential for advancing a Methanol Steam Reforming (MSR) system for on-site hydrogen production and supply to LT-PEMFCs [122, 121, 123]. To meet LT-PEMFC requirements, reformate products' CO concentration must be processed to be below 10 ppm [122]. Element 1 specializes in methanol reformer systems, featuring a design with a hydrogen purifier based on a membrane [124]. This reformer efficiently separates hydrogen, yielding a remarkably pure stream suitable for LT-PEMFC applications, with less than 0.2 ppm of CO and CO_2.

  The PowerCellution Marine System 200 (MS200) stands out as a promising high energy-dense system with an efficiency reaching up to 60% [125]. Its power-to-volume ratio is 159 kW/m^3. However, its dimensions and weight reported in Table 3.2, shows that on-board sailing yachts integration would be challenging. Also marinized automotive fuel cells prove suitable. An illustrative example is the RexH2 from EODev [126]. Dimensions and weight of this fuel cell are reported in Table 3.2. It integrates sensors and firefighting equipment and holds an approval in principle from Bureau Veritas [127]. Also the HyMove H2FC is a promising option [128]. There are three versions, whose peak power are 30, 45 and 60 kW, and frame dimensions and weight are also reported in Table 3.2. Although only 70% of the hydrogen produced by the reformer is pure enough for LT-PEMFC, when considering the footprint of the Element 1 reformer, the H2FC 60kW - M13 combination proves the best option for LT-PEMFC [123]. The combined power-to-volume ratio remains significantly higher.

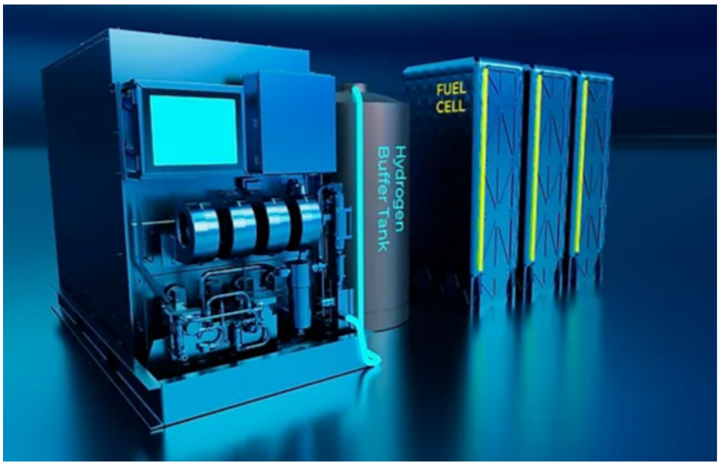

Figure 3.3: 'Element 1' methanol reformer system (on the left), hydrogen buffer tank (in the middle) and LT-PEMFCs (on the right) [124]

- HT-PEMFC: This type of fuel cells exhibit a longer startup time compared to LT-PEM fuel cells. Additionally, they face a disadvantage in handling rapid power demands, as a LT-PEMFC can adjust its load from 0% to 100% in 10 seconds, whereas an HT-PEMFC requires approximately 15 minutes [83]. The output is constrained due to the relatively large size of fuel cells, and their response time to load fluctuations is comparatively extended. However, an advantage lies in the higher operating temperature range of 140-200°C, which enhances tolerance to less pure hydrogen, allowing other fuels to be reformed into pure hydrogen to supply the fuel cell in a less complicated manner than LT-PEMFC [118].

For instance, methanol can be converted into hydrogen using a reformer that is successfully integrated within HT-PEMFC systems [118], and not separated as for mentioned LT-PEMFC. However, also for HT-PEMFC, the reforming part is an additional step that may potentially decrease overall efficiency compared to an ICE configuration. In any case it brings other benefits, such as the low noise and vibrations characteristic of fuel cells. A promising HT-PEMFC that has been recently developed is the Serene U-5G4 [129], that is designed in a way where methanol is reformed on site to hydrogen. The unit dimensions are weight are reported in Table 3.2. The system produces up to 5 kW and as it is modular, multiple cells can be interconnected. Sanlorenzo is using this type of fuel cells on a 50 meters yacht, developed by the shipyard in collaboration with Siemens Energy [130].

Superyacht shipyard Lürssen is presently constructing a yacht equipped with this technology [131]. Nonetheless, it's important to note that high-temperature fuel cell technology is less mature, more expensive, and has a shorter lifespan compared to LT-PEMFCs [118].

In the following table, power, dimension and weight of the mentioned PEMFCs are summarized.

Table 3.2: Considered PEMFC summary [125, 128, 126, 129]

Name	Type	Max power [kW]	Dimension [m]	Weight [kg]	Power-to-volume [kW/m^3]
PC MS 200	LT-PEMFC	200	0.7 x 0.9 x 2.0	1070	159
H2FC-30 kW	LT-PEMFC	33	1.4 x 0.8 x 0.5	440	59
H2FC-45 kW	LT-PEMFC	48	1.4 x 0.8 x 0.6	470	71
H2FC-60 kW	LT-PEMFC	72	1.4 x 0.8 x 0.7	490	92
RexH2	LT-PEMFC	70	1.0 x 1.7 x 1.0	540	41
Serene U-5 G4	HT-PEMFC	5	0.3 x 0.5 x 0.9	77	37

SOFC
SOFCs represent a highly promising category of fuel cells that has undergone extensive exploration in recent decades [118]. They belong to the high-temperature fuel cell family, capable of operating at temperatures reaching up to 1000 °C [120]. These cells exhibit impressive electrical efficiencies, reaching up to 60% in stand-alone fuel cell products [118]. Despite these advancements, there remain hurdles to the commercialization of SOFCs, including various thermochemical technical challenges such as prolonged start-up times, rapid performance degradation, sealing issues, and dynamic instabilities when exposed to ship motions [132, 133]. Consequently, the TRL of SOFCs is currently low. Nevertheless, in the next decade, there is potential for these fuel cell types to evolve into efficient and dependable energy converters when coupled with effective energy carriers.

3.2.3. Hydro generation

Hydro generation proves to be an efficient technique for transforming the kinetic energy from flowing water into electricity. Recently, there has been a surge in the popularity of hydro generation, especially with the increasing adoption of hybrid propulsion systems [38]. Each vessel that drives the shaft with an electric motor can theoretically generate electric energy using the propeller and electric motor. Various options and configurations exist for hydro generation, with a key distinction being the integration within the propulsion system or the use of a dedicated hydro generation turbine. From an efficiency standpoint, separating the propulsion and generation systems proves advantageous, allowing optimization for their respective purposes [38]. Achieving maximum efficiency for both generation and propulsion on a single propeller is unattainable, given the inherent compromise in a dual-purpose design.

Optimal hydro generation efficiency requires a dedicated turbine design where leading edge, camber, and blade characteristics can be optimized [38]. Although smaller sailing vessels have embraced dedicated hydrogenerators [134], large sailing yachts have yet to adopt them widely. Royal Huisman and Rondal have developed a hydrogenerator in collaboration with an electric pod specialist. This compact pod, significantly smaller than typical propulsion pods for superyachts, has a maximum output of 17 kW, with a hub diameter of 12 cm [135]. The design allows minimal drag and speed loss, making it appealing for continuous hydrogenerator use during sailing. By splitting tasks between two propellers, higher efficiencies are achieved. Of particular importance for refits is that it can be integrated into yachts with conventional propulsion systems, since it is a stand-alone system that works independetly. Therefore, there is no need for a complex refit to the propulsion system during crossings. The e-motor is located inide the hub and therefore there are no mechanical parts inside the yachts hull. To install the hydrogenerator, the yacht should be outside the water. However, when the bracket is placed, the hydrogenerator can be removed and replaced while inside the water by a diver, for example for a regatta.

However, since hydro generation during sailing is only feasible for sailing yachts, this has been a niche. Anyway, ongoing development indicates potential growth in this technology. Successfully harnessing this technology to its maximum potential and combining it with reduced energy demand, along with other energy converters such as solar panels, batteries, and PEMFC, would be a significant goal in achieving a substantial reduction in emissions and, consequently, a more sustainable future.

3.2.4. Solar panels

Solar panels have not been widely used on ships, primarily due to their low power output, low efficiency, limited available space on board, and also the variability of weather conditions, which are often unfavorable in certain areas. However, from an operational profile standpoint, yachts represent an exception, as they are frequently located in areas with high solar exposure. Therefore, they could contribute to meeting the energy demand of yachts. The operational principle involves when the sun illuminates a solar panel, photons striking the thin layer of silicon on the panel's surface cause electrons to be dislodged from the silicon atoms. The resulting charge generates an electric current, which is then captured by the wiring within the solar panels [83].

The most suitable solar energy converters are thin, flexible PV panels, which have been applied on smaller yachts for several years, including racing yachts enduring extreme conditions [136]. Royal Huisman created prototypes and tested the performance of three applications: PV panels integrated into a carbon mast, PV in an aluminum superstructure, and PV on canvas (e.g., bimini covers). An alternative being considered is also to install them on the deck. However, the excessively high temperatures that the deck would reach could limit its usability from passengers, and, above all, the same aesthetic level that Royal Huisman sailing yachts have might not be maintained, which is a compromise that owners are unlikely to accept if present on a large part of the deck.

Figure 3.4: Flexible solar panels from Solbian [137]

Monocrystalline silicon cells are the most efficient and widely employed for maritime applications [83]. However, as mentioned earlier, the output of PV panels is modest, around 185 W/m^2 with an efficiency of 24% [136]. In the Mediterranean during the summer, the available sunlight yields an average of slightly over 1 kWh per square meter per day [138]. Consequently, achieving a substantial contribution requires covering a large area with PV panels, considering potential shadow effects from rigging. Even if extensive areas, such as all bimini covers, some sections of the rigging, and parts of the superstructure, are covered, the contribution to daily energy consumption remains a relatively small percentage. Nonetheless, a notable advantage of PV panels is their role as a passive energy converter, providing electricity without manual intervention. This enhances the total yearly output, as PV panels contribute in every mode of operation, including periods with reduced crew or when the owner is not on board.

3.2.5. Conclusion on alternative energy converters

In conclusion of this section, a concise and effective response to the following subquestion is provided:

"What alternative energy converters hold the most potential?"

Replacing the current ICE engines using MGO with a single type of energy converter powered by alternative fuel is very complex unless the energy demand of the yacht is significantly reduced. The solution that would have less impact on technical feasibility would be to maintain ICE engines but powered by HVO. However, by considering which of the other possible alternative energy converters is the most promising, it can be concluded that currently the most promising one is LT-PEMFC with methanol stored onboard and reformed to hydrogen before feeding the fuel cell. This type of fuel cell has undergone significant and rapid development in recent decades, reaching a high TRL [118]. They do not have noise and vibrations compared to ICE, and boast a quick start-up time and exhibit a high efficiency [120]. However, they require hydrogen, which can be stored directly in special tanks or instead reformed from stored methanol. Although methanol storage is more easily achievable than hydrogen storage, it still presents more complications than traditional diesel, or even HVO, and therefore LT-PEMFCs feasibility depends on the combination of energy requirement, energy converters and energy carriers.

HT-PEMFCs are beginning to be applied, but at present, the only real advantage they have over low-temperature ones is the better tolerance to hydrogen impurities resulting from reformed methanol. The TRL of SOFC is still too low at the moment, but progress is being made. Regarding ICEs, thanks to biodiesel, they will likely continue to be used for several years. Hydro generation is a crucial aspect for sailing yachts, allowing the production of energy that can be used for the hotel load while sailing. If done with a separate turbine, it is also easily achievable for refit projects, as the propulsion does not require changes. Solar panels can also contribute to meeting the energy demand of yachts, especially since they are often navigating in areas with strong sunlight exposure. However, power output and efficiency are limited.

In conclusion, replacing the current energy configuration composed of MGO ICE with LT-PEMFCs and no other energy converters without reducing the energy demand is an option that would have a significant impact on the design and operational profile of the yacht, and consequently, it would be feasible only if the client is particularly motivated in having a sustainable yacht. For this reason, possible combinations of ICE with HVO, LT-PEMFCs, batteries, and also hydrogenerator, solar panels could be the most feasible sustainable solutions, and they will be analyzed in this thesis.

3.3. Energy demand reduction

One of the main issues related to the use of alternative fuels is the lower volumetric energy density, resulting in a larger volume required for on-board fuel storage. Reducing energy demand is the first step toward emissions reduction and can simplify the integration of alternative energy carriers and converters by decreasing the amount of fuel required on board to meet the yacht's energy demand. There are primarily two ways to reduce energy demand: opportunities in design and opportunities in operational use. This section will address the third subquestion:

"Which are the opportunities to reduce the energy demand in design and operation?"

3.3.1. Opportunities in design

Given the uniqueness of each yacht owner, the design focus for each yacht is specific, driven by factors such as aesthetics, performance, or comfort. Royal Huisman has established design standards to guarantee a consistently high level of quality and comfort across all yachts. Ensuring a yacht's design minimizes energy demand is important, but this should not come at the expense of compromising Royal Huisman's established standards for comfort and net interior volume. In this section, hull design will not be considered since it is already optimized and furthermore, for sailing yachts sailing performance under sail is more important than cruise speed.

Power and propulsion

An aspect to be considered for increasing energy efficiency is engine dimension. Indeed, many superyachts are overpowered, with engines and generators that exceed necessary capacity, consuming an excessive amount of fuel [7]. However, Royal Huisman sailing yachts are already optimized for design speed rather than maximum speed, so the maximum power output that energy converters can provide will not be altered.

Furthermore, a sailing superyacht equipped with traditional sails often resorts to using its engine for propulsion due to the challenges associated with raising the sails, which may include time constraints, difficulty and damage risk. A sailing system that is straightforward and secure for operation by a small crew is likely to see more frequent use, thereby reducing energy requirements for propulsion. Set-up time is a key consideration when comparing different sailing systems. Factors such as complexity, performance, power usage, ease of use, and set-up time are all taken into account. The analysis focuses on three main types of sailing systems: Dynarigs, wing sails, and the conventional sail system but with delivery sails.

Wing sails offer a notable advantage in their superior lift-to-drag ratio compared to conventional sails and Dynarigs. However, challenges arise with stability issues if installed on existing monohulls, necessitating substantial reductions in sail area, which diminishes driving force. While promising, the extensive hull design changes currently required make wing sails as a not preferred option in this thesis. Dynarigs boast the advantage of a rapid setup, with the entire system ready within 7 minutes as the sails roll out automatically from the mast, requiring only a small crew for operation. Nonetheless, two significant drawbacks hinder its feasibility. Firstly, Dynarigs are limited to downwind sailing, and secondly, implementing them would necessitate extensive local modifications to the hull structure, resulting in a prolonged, delicate, and high costly refit project for existing yachts. Thus, Dynarigs are also not explored further in this thesis.

The optimal solution for a sailing yacht refit, which will be further explored in this project, involves the use of the conventional sailing system, but with delivery sails. This type of sails, designed for ease of handling and durability during long passages, could lead to an increase in the time the yacht spends sailing under wind power. Delivery sails are constructed with materials prioritizing longevity over high-performance racing materials and make it easier for a smaller crew to manage the sails. The costs and implementation times of this modification are manageable, and it could also reduce the risk of damage to the sailing system, encouraging the crew to sail under sail more frequently.

Also, acting on the propeller design and thus optimizing dimensions and RPMs is a way to increase efficiency [83], but it will not be explored in this thesis as it is considered already optimized. Additionally, energy saving devices as pre-swirl, ducts, post-swirl fins–propeller boss cap fins, wheels–grim vane wheel, bulbs, and twisted rudder will not be considered since they are not efficient for sailing superyachts [139].

HVAC

An examination of the energy usage in Royal Huisman's yachts revealed that, among all hotel load energy consumers, the majority of energy is needed for HVAC. The efficiency of HVAC systems depends on system type and capacity [140]. In the last yachts built, Royal Huisman has adopted a direct expansion (DX) system, that could also be installed onboard an existing yacht through a refit. This system uses a gaseous medium for cold transport, proving more efficient than employing chilled water as a transport fluid [141]. The power input required for this system is lower also because less equipment is used that is always turned on, and there is only one energy conversion compared to the chilled water system. Furthermore, similar to engines, HVAC systems use more energy at part loads. Systems designed for extreme conditions may run sub-optimally in common environments. Extreme conditions occur infrequently in a yacht's lifespan. Designing the HVAC system for optimal operation in common conditions is recommended.

Reducing the absorbed heat is also a central topic related to HVAC and to energy demand reduction [140]. Heat enters yacht internal spaces either through incoming fresh air or solar radiation through structures and windows. Minimum air change regulations in vessels are stricter than in buildings, making it challenging to achieve savings in this aspect. Solar radiation increases the load on air conditioning systems, and while structural insulation standards are high, glass surfaces, especially transparent ones, pose a significant challenge due to their heat absorption. Mitigation strategies involve improving glass properties for insulation and solar protection or increasing external shading to reduce solar radiation reaching glazing surfaces [140]. However, this thesis does not delve into mitigation strategies for solar radiation, focusing instead on examining the impact of transitioning from an HVAC chilled water system to a DX system on the energy demand of the yacht.

3.3.2. Opportunities in operations

To further reduce the energy demand of a yacht, in addition to opportunities in design, there are also opportunities in how it is operated. In the case of yachts, saving energy is crucial, while minimizing the impact on comfort for the owner and guests, and performance. A significant operational energy efficiency measure with considerable potential is the practice of slow steaming [142]. Given the approximately cubic relationship between ship speed and fuel consumption per unit time, even a slight reduction in speed can lead to a substantial impact on fuel consumption. Weather routing and voyage planning are also very important [143], especially for sailing vessels. Indeed, it is not only crucial to avoid rough seas, which cause increased resistance to motion, but for sailing yachts, it can also mean favorable winds, eliminating the need for propulsion engines and even allowing the use of hydrogenerators for the hotel load. Leveraging the greatest advantage that sailing yachts have over motor yachts, namely the use of sails as propulsion power, would significantly reduce the energy demand that onboard engines must meet. If even the main sail is used, the engines onboard only need to provide power to the hotel load, whereas if only the head sail is used (motor sailing), the power they must provide is still reduced by over 50% compared to the absence of sails [144]. Also by reducing the design range of the yacht, the energy demand for that route can be substantially reduced. This energy demand represents the most critical situation, as the fuel tanks are sized to ensure this nautical miles autonomy at the design speed.

Also the availability of information, coupled with user-friendly features, is a crucial factor in diminishing energy demand. Being aware in real-time of how the energy demand, especially for hotel load, increases compared to the ”default mode” (the primary mode when owners and guests are not on board) can influence passengers, particularly the crew, to consume less energy—for instance, by maintaining a higher air conditioning temperature. Providing real-time information about the remaining battery life or energy consumption per nautical mile, along with guidance on reducing these metrics, could represent a straightforward yet promising approach in this context. Achieving this would necessitate more detailed logging of electronic consumption per consumer type and integrating this data with measurements from other systems. For instance, the on-board monitoring system could flag an open door or hatch in spaces where the air conditioning is operating. However, due to the difficulty of making a meaningful estimate of these reductions, for the purpose of this thesis, these possibilities will not be considered.

3.3.3. Conclusion on energy demand reduction

Concluding this section, a brief and efficient answer to the following subquestion is presented:

”Which are the opportunities to reduce the energy demand in design and operation?”

The starting point for preparing the transition to carbon-neutral fuels involves reducing the energy demand, that can yield decarbonization results immediately, while also contributing to future reductions in demand and price pressures [145]. Reducing energy demand can also simplify the integration of alternative energy carriers and converters by decreasing the amount of fuel required on board to meet the yacht's energy demand. In the short term, yachts can progress from straightforward, cost-effective options such as speed reduction, route optimization, range reduction and increased sailing time to updated HVAC DX systems and increasingly digitalized systems. Indeed, to achieve a genuinely efficient yacht where energy demand is minimized without compromising Royal Huisman's established standards for comfort and net interior volume, interventions must be made in both design and operations.

3.4. Sustainable refit paths

Refit projects that significantly increase efficiency by replacing obsolete systems without compromising on luxury, size, freedom, and other fundamental aspects of yacht construction are feasible, but there exists a technological limit that cannot be surpassed [7]. To achieve further emission reduction, a shift in fuel sources is imperative. However, even if shipyards advocate for greener solutions by encouraging owners to prioritize comprehensive upgrades to non-diesel systems, it remains a costly and extensive undertaking [7]. According to Posthuma de Boer, an owner with a 20-year-old Feadship facing a generator replacement is likely to opt for conventional updates unless future legislation mandates a different approach. The decision to invest in major sustainable-focused upgrades depends largely on these considerations [7].

Conducting a complete refit to alternative energy carriers is currently challenging due to high costs, increased volume requirements for storage (without modifying the operational profile), safety measures, and supply issues in the world's most remote areas. Giedo Loeff explains that, for instance, Feadship can retrofit methanol tanks large enough to support the base load of energy consumption using fuel cells 100 percent of the time while stationary, but it is required to supplement it with combustion engines (second-generation bio-fuel) while sailing [7]. Therefore, hybrid solutions that combine alternative energy carriers such as methanol, hydrogen, or batteries with ICEs powered by fuels like HVO and with other alternative energy converters like hydrogenerators are more suitable for refit projects, and combinations of these will be explored in this thesis. Once the trade-off of various combinations is made explicit, the owner and their team will have a clearer understanding of the implications in terms of space, emissions, docking timeframe, costs, and any potential modifications to the operational profile that these solutions require. To simplify and make this process more effective, an assessment model will be developed in this thesis, and different academic and research approaches for investigating and enhancing ship refit projects are outlined in subsection 3.4.1 that is following.

3.4.1. Ship refit methods

Various academic and research methods are employed to explore, guide, and optimize ship refit projects. Below are the most relevant methods and tools that can be used in ship design refit research:

Environmental Impact Assessment Tools

In cases where a refit project aims to enhance energy efficiency and reduce emissions, several tools are available for assessing the environmental impact of ships. The YETI offers a reliable tool to measure and compare the footprint of existing yachts, thus having the potential to guide sustainable yacht refit practices [146]. It takes into account the energy efficiency of the yacht, emissions, waste management, water usage and treatment, and finally, sustainable materials and construction. This structured scoring allows stakeholders to easily compare yachts and make informed decisions based on their environmental impact. However, even though it shares with the model intended to be developed the intention of enabling informed decisions and evaluating emissions, thereby contributing to assessing the trade-offs discussed in the research question, it differs from the overall scope of the thesis, and consequently will not be applied.

Other examples include the Energy Efficiency Existing Ship (EEXI) indicator, the Energy Efficiency Design Index (EEDI), and the Carbon Intensity Indicator (CII) [83]. These tools help evaluate overall sustainability and compliance with environmental regulations. However, the EEXI indicator is unsuitable for this study due to complexities in correction factors, and the EEDI is not chosen for its focus on new build vessels. The CII, measuring emissions per transport work, is also excluded [83]. An additional existing method is the Global Maritime Energy Efficiency Partnerships (GloMEEP) [147]. However, it refers to commercial ships, that have different operational profiles and designs, and it does not consider diverse power systems, consequently resulting not suitable for this project [28].

Parametric Design

Parametric design involves systematically varying specific design parameters to generate multiple ship designs [89]. This method has been widely used in theses focusing on design implications & performance assessment [148], and technical & economic feasibility [83]. The Ship Power and Energy Concepts (SPEC) tool developed by MARIN is an example [149], though not used in this thesis due to limitations in creating designs with more than one energy converter or carrier [83]. Nevertheless, as a parametric tool facilitates the swift modification of key parameters, with the goal of comprehending their influence on the overall performance and attributes of the ship [89], it is deemed suitable to be used in this thesis.

Multi-Objective Optimization

Ship design often requires balancing conflicting objectives [150]. Multi-objective optimization helps find optimal design solutions considering these factors [151]. Although relevant, the direct application of this methodology does not constitute the most suitable solution for this thesis. A parametric / tailor-made approach is preferred to address the thesis's objective, that will be presented in Chapter 4, allowing also increased flexibility, especially in challenges related to obtaining high-quality data.

Among all these different types of methods, the assessment model developed in this thesis can be regarded as a parametric design model. In fact, it relies on variable inputs to produce outputs, functions as a decision support tool, takes into account constraints and trade-offs, and involves an iterative process where adjustments are made in response to changing parameters. Regarding the other methods listed, they are not required for this thesis due to their application and scoping.

4 Assessment model

To address the research gap that has been identified in section 1.5, an assessment model has been developed. This model aims to evaluate the technical and economic feasibility of a sustainable refit for Royal Huisman sailing yachts. It will also calculate polluting emissions and estimate the docking time required for each different solution. The proposed model is designed to be easily applicable to various sailing yachts, serving as a support tool for making informed decisions when assessing retrofit possibilities. This chapter attempts to answer the following subquestion:

"What is the structure of the assessment model used to evaluate the technical and economic feasibility of integrating sustainable solutions on already-built sailing yachts to reduce emissions?"

As can be seen in the top left part of the flow chart shown in Figure 4.1, the model considers four main variable inputs: ship dimensions, operational profile, energy demand reduction methods, and the selection of energy carriers and converters. By leveraging the first three inputs, the model determines the required stored energy. In order to do so, the model takes into account ship resistance, power requirements, and the efficiency of transmission, reformer, and converter. The fourth input involves selecting energy carriers and converters to calculate the required volume and weight. The use of alternative energy carriers and converters may lead to potential iterations in ship design due to lower energy densities and safety requirements for storage compared to the current MGO energy configuration.

The simplest way to address the issue of increased space requirements for alternative energy carriers and converters is to increase the percentage of time the yacht sails under sail rather than using the engine. The model will analyze how this affects the volume required by the various configurations under consideration. In addition to avoiding the consumption of fuel for propulsion, hydrogenerators can be used to generate electricity for onboard hotel loads, making it a highly promising and eco-friendly solution. Continuing with regard to acting on the operational profile, limiting the range or cruising speed are also options that are considered in the model. Indeed, sometimes the range or cruising speed for which the yacht was designed differs from its actual usage in recent years. This could be due to a change in ownership or simply an overestimation of the yacht's real usage.

Alternatively, the necessary volume can be achieved through the reconfiguration of internal spaces. While this may be met with resistance from the owner if it results in a reduction of luxury areas, gaining internal space near the engine room and fuel tanks could be obtained by reducing the crew thanks to a simplified sailing system, and consequently converting a crew cabin in technical space for energy carriers and converters storage. To accommodate the extra required storage volume without reducing crew spaces or modifying the operational profile, yachts could be extended in length. However, aside from the fact that the CapEx would be very high, the hull shape of a sailing yacht is unique and lacks a cylindrical body. Therefore, adding a cylindrical body at the center of the ship is not considered feasible for the refit of a Royal Huisman sailing yacht. After discussions with experienced engineers from the company, it was concluded that the hull could be lengthened by adding space at the bow and stern. However, the gained volumes would be above the waterline and away from the center of the ship, making them unacceptable for accommodating extra fuel tank space or enlarging the engine room.

As depicted in the right part of Figure 4.1, if the new energy configuration is technically feasible, resulting emissions are also considered, along with an estimate of the time required to install the necessary modifications to the yacht while it is in the dock. Attention is then shifted to the economic feasibility of the analyzed power configuration. CapEx and OpEx are calculated to determine the total cost of ownership (TCO). The calculation of the latter can be considered a useful factor in better assessing the overall impact that alternative solutions have on a Royal Huisman sailing yacht. However, in the realm of superyachts, unlike in commercial shipping, the significance of client preferences surpasses that of TCO. The inclination of owners towards more sustainable yachts makes a big difference.

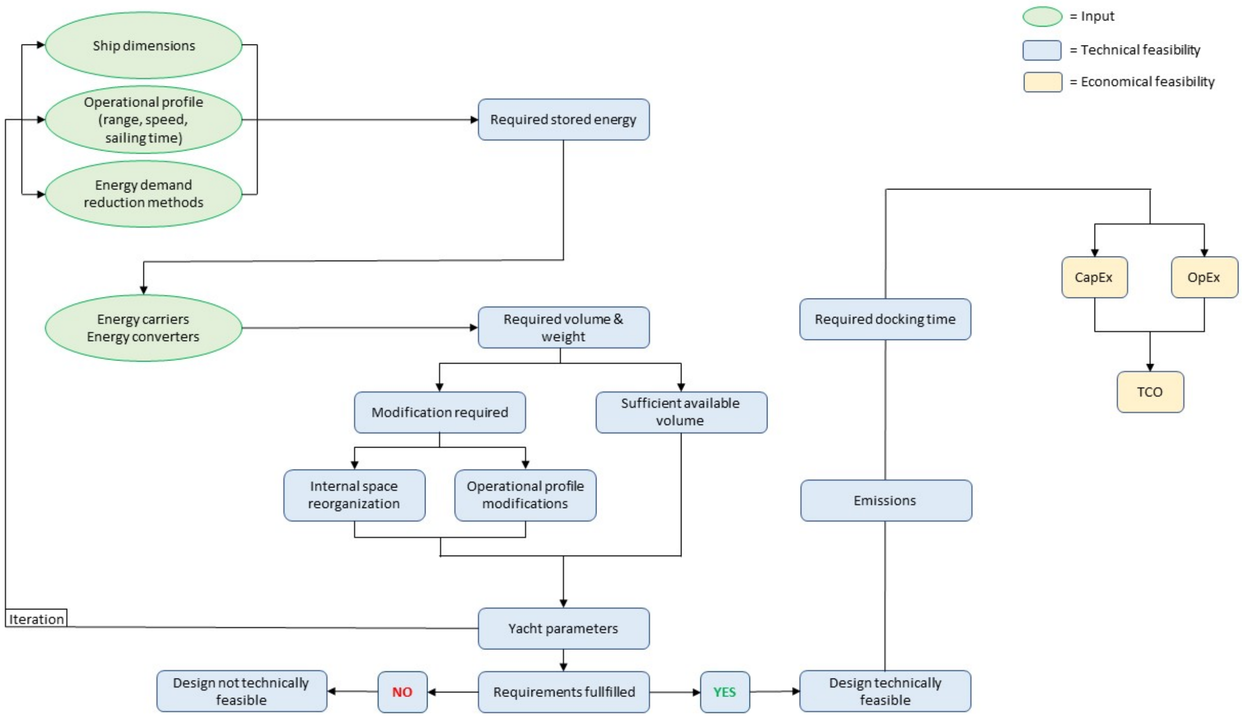

Figure 4.1: Overview of the assessment model

4.1. Technical feasibility

An explanation of the model is provided in this section, aiming to assess the technical feasibility of diverse configurations of energy carriers and converters.

Royal Huisman sailing yachts fuel tanks and engine room are sized with the requirement to cover a specific range at the design speed and to reach a maximum speed, all while navigating under engine power rather than sail. In order to assess the technical feasibility of a new combination of energy systems, it is necessary to calculate the volume and weight of the energy carriers and converters analyzed for that specific combination.

4.1.1. Required model inputs

The developed model process is automated as it contains all the information obtained from the literature review and the corresponding equations that link them. The inputs required to observe the impact variations of the various configurations can be grouped into the following categories:

- Yacht dimensions
- Operational profile

- Range
- Design speed
- Maximum speed
- Sailing under sail time

- Energy demand reduction method selection
- Energy carrier selection
- Energy converter selection

So simply with this selection of inputs based on the specific case and the configuration one wants to analyze, the model is able to provide the impact on volumes and weights, emissions, refit times, and ultimately costs, that are the outputs.

4.1.2. Required volume & weight energy carrier

The procedure for calculating the volume and weight of energy carriers is the same for both propulsive power and auxiliary power, with the exception of how brake power and hotel load power are obtained. Regarding the required propulsive power, for each Royal Huisman yacht already built, the company possess graphs like the one shown in Figure 4.2 that depict how hull resistance and brake power vary with sailing speed. This line chart refers to a >50 meters Royal Huisman sailing yacht, and already consider the sea margin for an increased resistance caused by wind, sea state, fouling of hull and propeller. This approach avoids the use of resistance estimation methods such as Holtrop and Mennen's method, which is widely employed in academic research to obtain the required brake power at varying ship speeds [152, 67, 83]. The advantage lies in obtaining more precise values, ensuring greater reliability of the results.

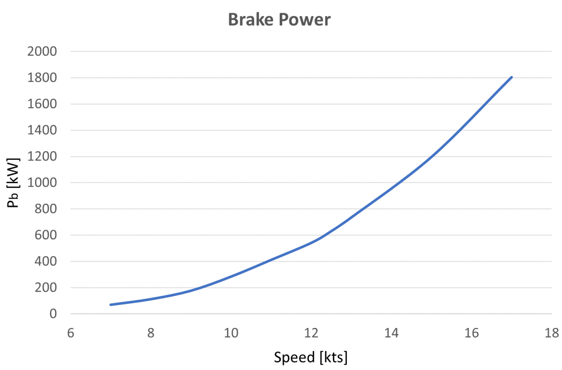

Figure 4.2: Brake power over speed of a >50 meters Royal Huisman sailing yacht obtained from internal company data

In this manner, with knowledge of the yacht's design speed, one can determine the associated brake power. In case the variation of brake power with speed is not available for a specific yacht, it is still possible to estimate the brake power at a certain Froude number, defined as follows.

$$F_r = \frac{V}{\sqrt{g \cdot L_{wl}}} \tag{4.1}$$

Where:

- F_r: Froude number [-]
- V: Yacht speed [m/s]
- g: Gravitational acceleration [m/s^2]
- L_{wl}: Waterline length [m]

After discussions with Royal Huisman naval architect with more than 10 years of experience, it has been decided to categorize sailing superyachts into more performance-oriented and more cruising-oriented types to obtain a realistic approximation of the brake power. In fact, for each of these categories, the hull shape is similar, so it will be sufficient to use displacement and velocity as parameters to obtain a good approximation of power [153]. Consequently, if in addition to fixing the hull shape, the yacht's speed is also a set parameter at this stage, linear interpolation between displacements and brake power can be carried out to estimate the brake power of the specific yacht [154], as expressed in Equation 4.2.

$$P = P_0 + (\Delta - \Delta_0)\frac{P_1 - P_0}{\Delta_1 - \Delta_0} \tag{4.2}$$

Where:

- P: Brake power of the analysed yacht [kW]
- P_0: Brake power of the lower limit yacht [kW]
- P_1: Brake power of the upper limit yacht [kW]
- Δ: Displacement of the analysed yacht [t]
- Δ_0: Displacement of the lower limit yacht [t]
- Δ_1: Displacement of the upper limit yacht [t]

Figure 4.3 and Figure 4.4 each represent two lines referring to the variation of brake power with Froude number for the sailing yacht with the lowest and highest displacement analyzed in that category. These lines represent the lower and upper limits, and Equation 4.2 can be applied throughout the area between them. Naturally, in this way, the obtained value of brake power is an estimate, and comparing this value with the actual values of other yachts within the area for which the entire variation of brake power with speed is available, the error is less than 22%, thus providing a good indication of this value. This percentage was obtained considering the yacht for which the brake power estimation is less precise. Applying Equation 4.2 with the reference values as reported in Equation 4.3, taken for a Froude number equal to 0.27, which on average for Royal Huisman sailing yachts corresponds to the design conditions, for a yacht with a displacement of 381 tonnes, a brake power of 399 kW is obtained, while in reality, the exact value of required brake power obtained from the data provided by the naval architects involved in the design of such yacht is 325 kW.

$$P = 186 + (381 - 220)\frac{(449 - 186)}{(419 - 220)} = 399[kW] \tag{4.3}$$

The resulting percentage error can be calculated with Equation 4.4.

$$\%error = \frac{(399 - 325)}{(325)} = 22\% \tag{4.4}$$

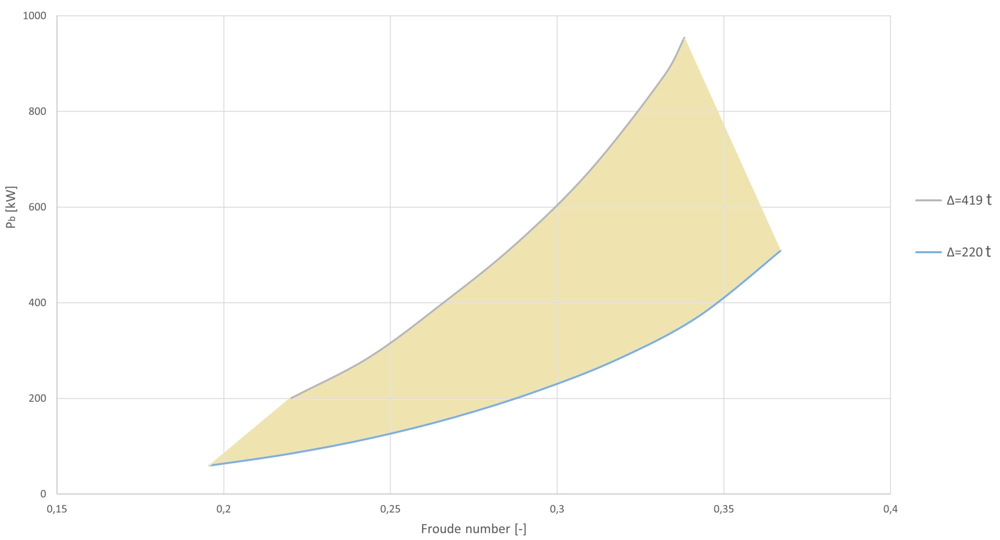

Figure 4.3: Brake power over Froude number for performance sailing superyachts obtained from internal company data

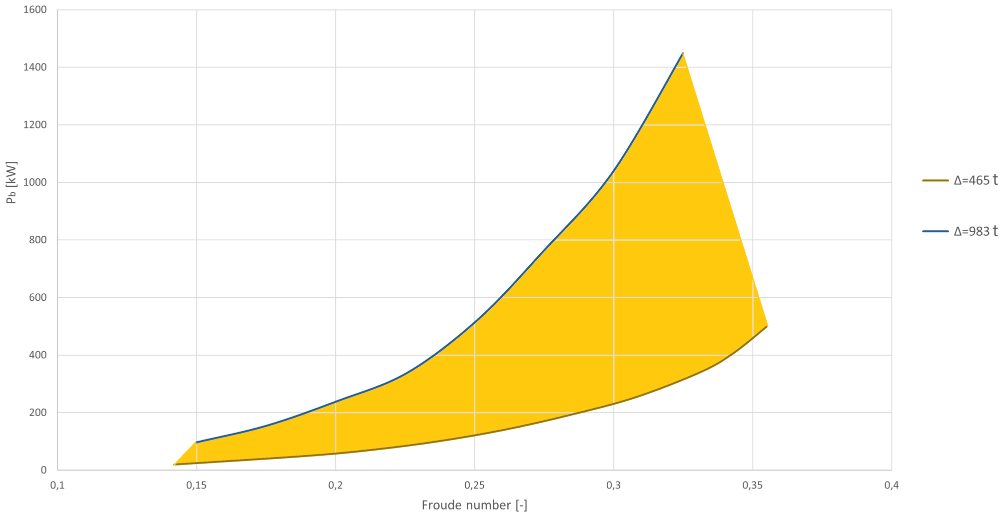

Figure 4.4: Brake power over Froude number for cruising sailing superyachts obtained from internal company data

Given the known range, the time taken to traverse that route at the design speed can be calculated with the following equation:

$$T = \frac{Range}{V_{design}} \tag{4.5}$$

The power required by the hotel load varies slightly depending on the operational mode, and depending on the one analysed, an average kilowatt value is taken into account, derived from the analysis of historical data for each yacht. At this point, the energy required for propulsion and hotel load is calculated separately, and to do so the efficiency of the selected energy converter for that configuration is requested, and these values are summarized in Table 4.1:

Table 4.1: Energy converters efficiencies [128, 129, 124, 155]

Energy converter	η
ICE diesel	0.45
ICE HVO	0.45
ICE methanol	0.46
LT-PEMFC methanol	0.46
HT-PEMFC methanol	0.42
LT-PEMFC hydrogen	0.56

All the types of PEM-FC mentioned are fueled by hydrogen. If ”methanol” is specified alongside PEM-FC, it indicates that methanol is stored as fuel and is reformed into hydrogen onboard. The conversion efficiency is already included in the values presented in the table. Subsequently, the energy required for propulsion and hotel load can be calculated using the equations below:

$$E_{prop} = \frac{P_b \cdot T}{\eta_{conv}} \tag{4.6}$$

$$E_{hotel} = \frac{P_{hotel} \cdot T}{\eta_{conv}} \tag{4.7}$$

$$E_{req} = E_{prop} + E_{hotel} \tag{4.8}$$

Where:

- E_{req}: Required energy [kWh]
- E_{prop}: Required energy for propulsion [kWh]
- E_{hotel}: Required energy for hotel load [kWh]

- P_b: Brake power [kW]
- T: Time [h]
- η_{conv}: Converter efficiency [-]

Once energy carriers and converters are selected, to obtain the volume and weight corresponding to that energy, it will be sufficient to divide the required energy by the volumetric and gravimetric energy density reported in Table 3.1. Certainly, in the case of adopting hybrid solutions with more than one energy carrier, it will be necessary to divide the energy required by the specific energy carrier and divide it by its energy density. To obtain the final volume and weight, it will be sufficient to sum the results after this step.

$$V_{req} = \frac{E_{req}}{\rho_{vol}} \tag{4.9}$$

$$W_{req} = \frac{E_{req}}{\rho_{grav}} \tag{4.10}$$

Where:

- V_{req}: Required volume [L]
- W_{req}: Required weight [t]
- E_{req}: Required energy [MJ]
- ρ_{vol}: Volumetric energy density [MJ/L]
- ρ_{grav}: Gravimetric energy density [MJ/t]

Furthermore, a 10% precautionary margin is then added to these values. Additionally, for methanol the requirement of the cofferdams as reported in subsection 3.1.1 is taken into account, and its impact on the fuel tanks of a Royal Huisman sailing yacht below 500 GT is represented in green as an example in Figure 4.5 and Figure 4.6. As can be seen in the drawings, the impact of the cofferdams consisting of only a 25 mm polymer layer between two steel panels is minimal, resulting in a reduction of the volume that can still be used for fuel storage by 9%.

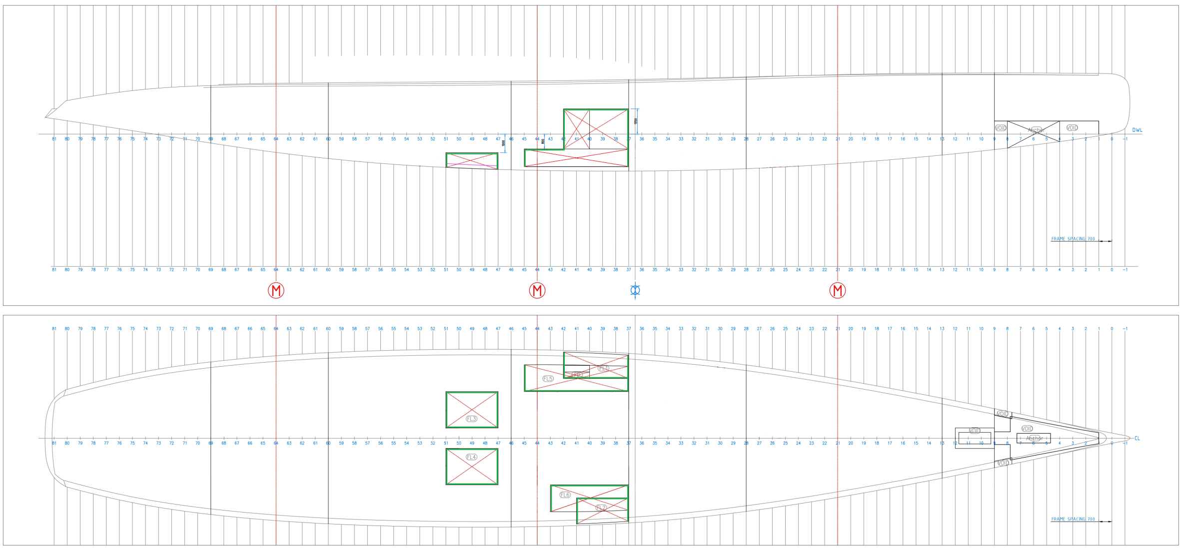

Figure 4.5: Royal Huisman sailing yacht below 500 GT top and side view of fuel tank location including 25 mm cofferdams

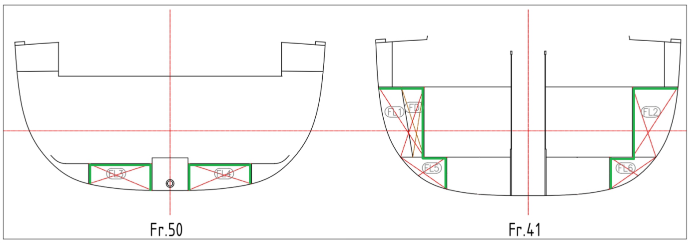

Figure 4.6: Royal Huisman sailing yacht below 500 GT front view of fuel tank location including 25 mm cofferdams

Considering hydrogen, the cylindrical shape and weight depending on the pressure of the fuel tanks as reported in subsection 3.1.2 are taken into account, which cause an increase in volumes and weights required by the energy carrier. The results obtained can then be compared with the volume and weight of the current configuration of the yacht, which uses diesel as the energy carrier. This information is available in the technical specifications of the yachts or, as a double check, it can also be obtained by setting diesel as the energy carrier in the model.

The impact of batteries

Batteries have also been considered as energy carriers, but due to their particular characteristics and not requiring energy converters like ICE and fuel cells needed for diesel, HVO, methanol, and hydrogen, they are analyzed separately in the model. For the specific LFP battery considered in the model, dimensions, weight, and the energy they can provide are known [156]. From these data, it is possible to calculate the volume and weight of the batteries relative to the energy they can provide, and the results obtained are reported in Table 4.2.

Table 4.2: Relative volume and weight of LFP batteries [156, 157]

Batteries	
[m³/kWh]	[t/kWh]
0.0058	0.0081

It is important to specify that these values also include the volume and weight of the necessary safety and control unit [157]. In order to calculate the total volume and weight occupied by the batteries needed to provide energy, the equations below are used:

$$V_{bat} = V_{rel} \cdot P_{bat} \cdot T \tag{4.11}$$

$$W_{bat} = W_{rel} \cdot P_{bat} \cdot T \tag{4.12}$$

Where:

- V_{bat}: Required batteries volume [m^3]
- V_{rel}: Batteries relative volume [m^3/kWh]
- W_{bat}: Required batteries weight [t]
- W_{rel}: Batteries relative weight [t/kWh]
- P_{bat}: Power batteries have to provide [kW]

4.1.3. Required volume & weight energy converter

Despite energy carriers being the most critical aspect regarding additional volume and weight required by alternative solutions, it is necessary to include the energy converters in the model as well. This allows for a comparison of the results obtained with the currently installed configuration on board.

The dimensions, weight, and power characteristics of the energy converters considered in this thesis are known [128, 129, 124, 155], allowing for the determination of the [m³/kW] and [t/kW] associated with each converter. Table 4.3 displays the volume and weight relative to kilowatts for each type of energy converter. Although these values may vary slightly for the currently installed diesel engines, the table includes an indicative example of a specific Royal Huisman sailing yacht. This example is representative of the entire fleet of the company.

Table 4.3: Energy converters relative volume and weight [128, 129, 124, 155]

Energy converter	[m^3/kW]	[t/kW]
ICE diesel	0.0037	0.0033
ICE HVO	0.0037	0.0033
ICE methanol	0.0059	0.0040
LT-PEMFC methanol	0.0241	0.0102
HT-PEMFC methanol	0.0270	0.0154
LT-PEMFC hydrogen	0.0117	0.0045

It is appropriate to specify that the fuel cell external box are already accounted for in these values, and for hydrogen PEMFCs for which methanol is stored, the dimensions and weight of the hydrogen reformer are included [124].

At this point, based on the amount of power they are required to provide, their volume and weight can be determined with the following equations:

$$V_{conv(i)} = V_{rel(i)} \cdot P_{req(i)} \tag{4.13}$$

$$W_{conv(i)} = W_{rel(i)} \cdot P_{req(i)} \tag{4.14}$$

Where:

- $V_{conv(i)}$: Converter type volume [m³]
- $W_{conv(i)}$: Converter type weight [t]
- $V_{rel(i)}$: Converter type relative volume [m³/kW]
- $W_{rel(i)}$: Converter type relative weight [t/kW]
- $P_{req(i)}$: Power that the energy converter type need to deliver [kW]

As new configurations may incorporate various energy converter types, each designed to deliver specific power, their volumes and weights can be combined for subsequent comparison with the existing on-board solution. This information, akin to energy carriers, is typically available in the technical specifications of different yachts or can be cross-verified using the [m³/kW] and [t/kW] values of diesel engines.

$$V_{conv} = \sum_{i=1}^{N} V_{conv(i)} \tag{4.15}$$

$$W_{conv} = \sum_{i=1}^{N} W_{conv(i)} \tag{4.16}$$

Where:

- V_{conv}: Total converters volume [m³]
- W_{conv}: Total converters weight [t]

In the end a comparison of the results obtained with the new solution and the currently installed configuration on board can be done.

Natural energy sources converters

In addition to ICEs and fuel cells, the model also considers solar panels and hydrogenerators, which are specific types of energy converters harnessing solar energy and kinetic energy from water, respectively. They do not pose the same volume and weight constraints as other converters, and for this reason, the power and energy they can provide are calculated differently.

Regarding solar panels, the first step involves calculating the usable deck area using the following equation:

$$A_{solar} = L_{oa} \cdot B_{max} \cdot C_{wl} \cdot a \tag{4.17}$$

Where:

- A_{solar}: Total solar panel area [m^2]
- L_{oa}: Length overall [m]
- B_{max}: Maximum beam [m]
- C_{wl}: Water line coefficient [-]
- a: parameter <1 indicating percentage of deck area available for solar panels [-]

Then considering that solar panels are able to provide 175 W/m^2 and that usually this power is available 8 hours per day in operational scenarios where yachts navigate, the energy provided can be calculated with the following equation:

$$E_{solar} = \frac{P_{solar} \cdot T}{3} \tag{4.18}$$

Where:

- E_{solar}: Energy provided by solar panels [kWh]
- P_{solar}: Power provided by solar panels [kW]
- $T/3$: Fraction of the analysed time in which E_{solar} is available [h]

If the decision is made to include solar panels in the considered configuration, the resulting outcome can be subtracted from the required energy for propulsion or hotel load, thereby reducing the volume and weight of the energy carriers. The equation to calculate it is provided below:

$$E_{prop/hotel} = \frac{P_{b/hotel} \cdot T - E_{solar}}{\eta_{conv}} \tag{4.19}$$

Then, the energy required for propulsion or hotel load can be summed up as it is reported in Equation 4.8.

Regarding the hydrogenerators, a 15 kW one has been chosen due to its properties described in subsection 3.2.3 and the suitable power it provides for Royal Huisman sailing superyachts. Figure 4.7 represents the electrical power it is capable of providing over sailing speed. As can be seen, the trend is approximately linear, as for speeds above 11 knots, the power is limited by the engine.

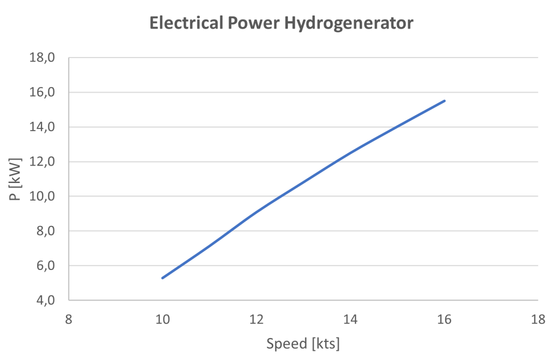

Figure 4.7: Electrical power over speed provided by Sea Drive POD hydrogenerator

However, the hydrogenerator introduces an increase in resistance, resulting in a reduction in sailing speed. Nevertheless, the speed loss diminishes with the rise in sailing speed. For this reason, at speeds exceeding 10 knots, which will be analyzed in this thesis when using the hydrogenerator, this loss can be neglected.

If the decision is made to include the hydrogenerator in the considered configuration, it is possible to calculate the energy it can provide by multiplying the provided power given in Figure 4.7 at a certain speed by the time the yacht is sailing under sail.

$$E_{hydro} = P_{hydro} \cdot T_{sailing} \tag{4.20}$$

Where:

- E_{hydro}: Energy provided by hydrogenerator [kWh]
- P_{hydro}: Power provided by hydrogenerator [kW]
- $T_{sailing}$: Time in which the yacht is sailing under sail [h]

At this point, it is necessary to subtract this value from the energy required by the hotel load while sailing under sail, as reported in the following equation:

$$E_{hotel} = \frac{P_{hotel} \cdot T - E_{hydro}}{\eta_{conv}} \tag{4.21}$$

Then, the energy required by the hotel load using the hydrogenerator can be summed up to the energy required for propulsion to obtain the total required energy, as reported in Equation 4.8.

4.1.4. Energy demand reduction

There are opportunities to reduce the energy demand both in operation and design, as it has been explained in section 3.3. From an operational point of view, the model analyzes how the yacht's energy demand would change if the percentage of time spent sailing under sail were increased, allowing for the avoidance of propulsive power from the engine and supplying energy for the hotel load through hydrogenerators and solar panels. Referring to Figure 2.2, it can be noted that on average, the time spent sailing, combining both motoring, motor sailing and only sail navigation, accounts for 12%. Of this, just a quarter is spent sailing under sail. Estimating together with Royal Huisman experts that approximately, on average in ocean crossings depicted in Figure 2.3, there are conditions where it is possible to efficiently sail for one-third of the time, it can be considered that by modifying the sail type as illustrated in subsection 3.3.1, the time spent sailing under sails only could increase from 25% to 33%. Additionally, the model considers how a change in required range or design speed would impact the volumes and weights required for energy carriers and converters.

Regarding opportunities in the design, it is essential to note that the calculations in subsection 4.1.3 are initially performed while keeping the installed power on board constant for both propulsion and hotel load. These values are limited by the requirement to achieve a certain maximum speed and to be able to use bow or stern thrusters at their maximum power output, respectively. However, there are no new calculations or equations to be added to the tool to obtain these variations. It is sufficient to modify the input parameters of the model, such as range, design speed, maximum speed, and auxiliary power.

As for HVAC, significant savings in its energy demand can be achieved by transitioning from the conventional chilled water system typically installed on Royal Huisman sailing yachts to a more efficient direct expansion system that uses a gaseous medium for cold transport [141]. The latter allows for a 50% reduction in HVAC energy demand. Since the percentage of energy it requires compared to the rest of the hotel load is known based on the operational mode, it is possible to calculate the decreased energy required by the hotel load with the following equation:

$$E_{hotel} = (P_{hotel} - P_{HVAC} \cdot b) \cdot T \tag{4.22}$$

Where:

- P_{HVAC}: Power required by conventional HVAC system [kW]

- b: Parameter <1 indicating the power reduction obtained with the new HVAC system [-]

Therefore, if this new HVAC system is installed on board, the obtained value of the new energy required by the hotel load must be substituted into Equation 4.8 to then obtain the advantages in terms of volume and space on board.

Sailing modes distribution & crew cabin conversion

The model thus provides the total volume and weight required for energy carriers storage and energy converters collocation in the engine room. In case volumes and weights are higher than those of the current energy configuration, despite applying methods and technologies capable of reducing the energy demand, some inputs can be modified and a new iteration can be performed. In particular, it can be observed how the volume and weights required would vary if the design range were not fully covered by sailing solely under engine power, but in line with the average real data on the operational profile provided by the crews of the analyzed yachts provided in Figure 2.2. This means that it is possible to calculate the volume and weight required by the energy carriers considered by dividing the design range that the yacht must be able to navigate in the following sailing modes:

- Motor sailing
- Motoring
- Sails only

For the brake power required for motor sailing compared to simple motoring at the same speed, a reduction percentage of 50% has been applied, considering a more conservative value compared to the 67% considered for Project ZERO [144], which was evaluated together with expert naval architect from Royal Huisman with more than 10 years of experience as overly optimistic, given that it also depends greatly on the specific situation considered. Considering the time distribution of the three sailing modes for the design range, Equation 4.6 and Equation 4.7 can be applied to obtain the required energy for each operational mode. Then, these energies can be summed up to obtain the associated volume and weight following the same procedure described in subsection 4.1.2. It should be noted that the brake power for motor sailing is indeed considered to be 50% of the case of motoring alone, while for sails only, it is null, and thus energy will only be required for hotel load. In addition to varying the distribution of the three sailing modes, it is also possible to reduce the design speed, and to decrease the maximum range that the yacht can currently navigate only under motor power without sails.

Regarding the possibility of modifying the internal layout, this proves to be very complicated for a Royal Huisman sailing yacht refit project due to the almost nonexistent availability of extra space on board. However, it could be feasible to convert into technical space a guest cabin or a crew cabin, as they typically border the engine room, as shown in Figure 4.8 for superyacht Twizzle.

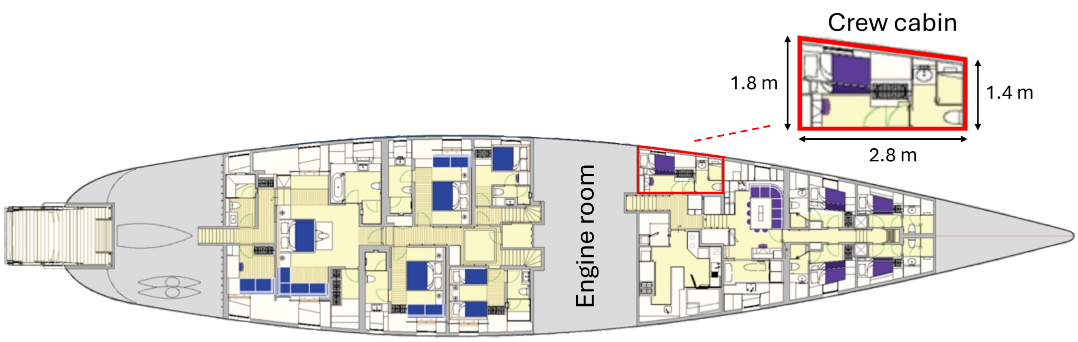

Figure 4.8: Superyacht Twizzle lower deck view with focus on crew cabin [158]

In particular, the model includes the possibility of converting a crew cabin into extra space that can be used for the storage of alternative energy carriers and converters. Indeed, the crew cabin shown in

Figure 4.8 is close to both the engine room and the fuel storage tanks, which are usually located at the bottom center of the ship, as previously shown in Figure 4.5. Regarding the exact calculation of the volume of the crew cabin, its shape can be approximated to a right prism with a rectangular trapezoid base. The base area will thus have two parallel sides of 1.4 m and 1.8 m, and a length of 2.8 m. The volume is then obtained by multiplying this area by the height of the crew cabin, which is 1.8 m, as shown in Equation 4.23.

$$V_{crewcabin} = (\frac{1,4+1,8}{2} \cdot 2,8) \cdot 1,8 = 8[m^3] \tag{4.23}$$

Consequently, the model allows for the addition of 8 [m^3] of volume that can be used for the storage of alternative energy carriers and converters. Although of lesser relevance, 0.5 tons of weight from the bed, sanitary facilities, and other interior cabin furnishings can also correspond to extra weight for alternative configurations. These values are assumed to be valid not only for the superyacht Twizzle but for all the superyachts considered in this study. Therefore, the impact of this space on the total available storage volume of a yacht is proportionally different, with a greater influence on yachts with lower GT.

However, all these solutions heavily depend on the owner's willingness to make compromises to reduce the emissions of their yacht. The solutions not included in chapter 5 were excluded because they would excessively alter the current characteristics of the yacht, but others may be considered feasible or not depending on the yacht owner. Since this thesis is not focused on a single case study of a specific yacht, different solutions will still be considered, and for these, emissions, refit time, and costs will also be evaluated to provide comprehensive information on how alternative solutions impact existing sailing yachts.

4.2. Emissions

After evaluating the technical feasibility of the most promising combinations of energy carriers and converters on board, the model provides the associated emissions on a yearly base. Considering only TTW emissions would have been limiting and would have provided only a partial indication of the complete emissions cycle represented in Figure 4.9, so WTT emissions preceding the fuel bunkering phase were also taken into account.

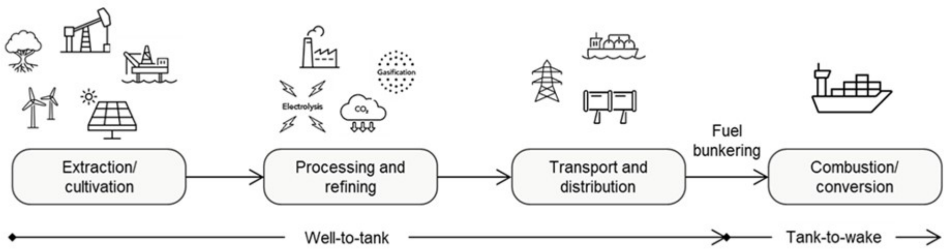

Figure 4.9: Well-to-Wake emission cycle

Regarding the types of emissions analyzed, they are CO_2, NO_x, and PM. Table 4.4 provides the emission values in [g/MJ] associated with the energy carriers linked to their respective energy converters, which for MGO, HVO, and methanol are ICE, while for hydrogen, they are PEMFC. For methanol, only ICEs are considered since when it is stored and the energy converter is a PEMFC, it is reformed to hydrogen onboard, and therefore the emissions are considered as hydrogen PEMFC. Furthermore, the expressions e-Methanol and e-Hydrogen indicate that the fuels are obtained from renewable sources, thus significantly reducing WTW emissions as they not only do not emit CO_2 in the WTT phase but also have the ability to absorb it.

Table 4.4: Tank-To-Wake emissions of considered energy configurations [41, 159, 160, 161]

	CO_2 [g/MJ]	NO_x [g/MJ]	PM [g/MJ]
MGO	75.1	1	0.043
HVO	70.3	0.9	0.026
Methanol ICE	69.66	0.4	0.004
Bio-Methanol ICE	69.66	0.4	0,004
e-Methanol ICE	69.66	0.4	0.004
Hydrogen PEMFC	0	0	0
e-Hydrogen PEMFC	0	0	0

Table 4.5: Tank-To-Wake and Well-To-Wake CO_2 emissions of considered energy configurations [41]

	CO_2 [g/MJ]	
	TTW	WTW
MGO	75.1	89.36
HVO	70.3	9.15
Grey Methanol ICE	69.66	97.01
Bio-Methanol ICE	69.66	37.62
e-Methanol ICE	69.66	2.16
Grey Hydrogen PEMFC	0	75.6
e-Hydrogen PEMFC	0	0

To obtain the total mass of emissions produced, it will simply be necessary to multiply the values reported in Table 4.4 and Table 4.5 by the required energy of the specific combination of energy carrier and converter analyzed.

4.3. Refit timeframe

To provide yacht owners with a more comprehensive understanding of what would be involved in refitting to alternative fuels to reduce emissions, it is essential to estimate the timelines required for the project. Predicting this accurately is challenging, particularly given the scarcity of similar projects executed to date. However, based on classification society requirements and ship designers' experience, it is possible to estimate the time required for project implementation depending on the alternative energy carriers and converters installed.

In general, for a fuel retrofit project, the following four stages can be identified [162]:

- Feasibility (6-12 months)
  This stage has the widest range of temporal variation, as it could take approximately between six and twelve months. Here the owner and the shipyard identify conversion options based on technology, fuel, commercial, and operational considerations. Additionally, Initial Design and Safety Statements are drafted by the shipyard and appraised by class, and areas for further investigation are identified. Finally, Approvals in Principle for system/equipment/component designs can be issued.

- Design & Engineering (5 months)
  This part includes risk assessments, HAZID (Hazard Identification), and further studies conducted to finalize initial designs, perform HAZOP (hazard and operability study), and complete safety action recommendations. Then consultation with the flag state begins to address certification requirements, detailed designs are sent to the class technical support office for plan approval before use of equipment and component fabricators. Additionally, equipment component certification begins, confirming that the equipment to be installed is built in accordance with designs. Moreover, time is allowed for the delivery of pre-fabricated equipment/components to the conversion site.

- Conversion (4-6 months)
  The actual retrofit project, intended as the conversion process, is likely to take between four and six months, depending on the size of the vessel, the technical solutions, and the level of preparation (such as prefabrication of equipment) that can be achieved. This can be broken down into several stages:
  – Removal of existing fuel system components, including installing new tanks or modifying existing tanks;
  – Modification of retained elements such as welding and drilling for pipe support;
  – Assembling and installing new components including the engine package and fuel supply
  – Electrical wiring.
- Adoption (1 week)
  The last phase consists of completing class and flag certification following successful commissioning and sea trials.

For the purpose of this thesis, the part that is most appropriate to focus on is the conversion phase, when the yacht must be in dry dock to undergo the selected modifications. Regarding the previous phases, an estimated timeframe has been indicated in the list above and will not be further elaborated. If the considered configuration does not involve the storage of methanol or hydrogen, the timeframe is significantly reduced. In the case of choosing HVO, for instance, the tanks and ICEs do not need substantial modifications. However, if a significant amount of batteries power is to be installed on board, modifications may be required to the existing fuel system components to accommodate the volume required by them and adjustments to the electrical wiring, although all Royal Huisman sailing yachts already have batteries on board, at least for peak shaving and starting diesel engines.

The time required to install the hydrogenerator is also minimal [135]. Even if the yacht must be out of the water, the turbine is independent of the propulsion system, with the e-motor located inside the hub, and therefore there are no mechanical parts inside the yacht's hull. Multiple cables connect the e-motor with the electronic system on the yacht, and the bracket can be attached to the hull with bolts. Solar panels integration on board requires more time than hydrogenerators, but is still limited. It is performed by simply fixing them in the chosen location and then connecting them to the onboard electrical system.

Since the model also includes the possibility of transitioning from a chilled water HVAC system to a DX system, resulting in a substantial reduction in the hotel load's energy demand, it is also included in the calculation of the refit timeframe. The DX system requires less complex piping and equipment installation, and no chilled water pumps are required, only a compressor [141]. Therefore, it requires not much time to be installed on board, with the main modifications required to the piping system and the installation of a compressor instead of chilled water pumps. However, if solutions involving the storage of methanol or hydrogen and consequently PEMFC or methanol ICE are considered, then all four points in the list above are required, and the estimated four to six months are deemed necessary for the conversion, depending on whether they are used for propulsion or hotel load or both.

4.4. Economical feasibility

In order to provide a more comprehensive picture regarding the impact of a sustainable refit on a Royal Huisman sailing yacht, it is essential to analyze the associated costs. After evaluating the impact in terms of ship design through technical feasibility analysis and calculating how emissions would vary and how much time would be required for such a refit project, the model is also capable of providing CapEx, OpEx, and thus the TCO associated with each different combination of alternative energy carriers and converters analyzed. Indeed, one of the major drawbacks related to alternative energy systems today, besides the increased weight and volume required, is the high cost of both energy converters and fuels.

4.4.1. CapEx

The CapEx associated with a sustainable refit include the cost of energy converters, control and safety systems, storage systems including tanks, bunkering, and piping systems, as well as energy demand reduction technologies. Furthermore, also installation costs, including wirings and electrical components, are part of this type of expenses. However, given the complexity of estimating all these expenses, it has been decided to analyze only the most significant and relevant ones for the purpose of this thesis, namely the cost of energy converters, storage systems and energy demand reduction solutions.

Table 4.6 shows the costs in [€/kW] and [€/kWh] associated with them.

Table 4.6: CapEx of considered sustainable solutions [41, 163, 135, 164, 141]

Systems	Cost	
LT-PEMFC	2000	[€/kW]
HT-PEMFC	3500	[€/kW]
ICE methanol	300	[€/kW]
Methanol storage system	0.40	[€/kWh]
Hydrogen storage system	16.45	[€/kWh]
Reformer meth-H2	1500	[€/kW]
Hydrogenerator	4000	[€/kW]
Batteries	600	[€/kWh]
Solar panels	9067	[€/kW]
DX HVAC system	4000	[€/kW]
Delivery sails	300	[€/m^2]

It should be specified that the cost of HT-PEMFC already includes the cost of the methanol-hydrogen reformer. At this point, in order to calculate the actual cost in euros, it will be necessary to apply Equation 4.24 and Equation 4.25, depending on whether the cost is expressed per unit of power or energy associated with each system.

$$Cost_{syst(i)} = Cost_{P-rel(i)} \cdot P_{req(i)} \tag{4.24}$$

$$Cost_{syst(i)} = Cost_{E-rel(i)} \cdot E_{req(i)} \tag{4.25}$$

Where:

- $Cost_{syst(i)}$: System cost [€]
- $Cost_{P-rel(i)}$: System power relative cost [€/kW]
- $Cost_{E-rel(i)}$: System energy relative cost [€/kWh]
- $P_{req(i)}$: Power that the system need to deliver [kW]
- $E_{req(i)}$: Energy that the system need to deliver [kWh]

To determine the total CapEx associated with the analyzed energy configuration, which combines various items from Table 4.6, it will therefore be necessary to sum them using Equation 4.26.

$$CapEx = \sum_{i=1}^{N} Cost_{syst(i)} \tag{4.26}$$

Where:

- $CapEx$: Total CapEx of analysed systems in the specific energy configuration [€]

Once the CapEx associated with the integration of a possible energy system combination into the refit project has been calculated, it is also important to consider their lifetime. Indeed, considering how long each system will need to be replaced influences the TCO of the yacht, thereby modifying the impact that a possible combination of energy systems has on the yacht costs. Although one might consider including this expenditure among OpEx, it has been deemed more appropriate to include these costs among CapEx, as they are not operational costs. Table 4.7 shows the lifetime of the systems considered.

Table 4.7: Lifetime of considered sustainable solutions [156, 165, 128, 136, 135, 141]

Systems	Lifetime [years]
LT-PEMFC	20
HT-PEMFC	20
ICE methanol	10
Reformer meth-H2	16
Hydrogenerator	20
Batteries	5
Solar panels	30
DX HVAC system	20
Delivery sails	5

The lifetime calculation of these systems depends on the number of hours they are in operation. The lifetime years of PEMFC systems are obtained by considering the 25.000 hours declared by the manufacturers [128] and integrating them with the average operating profile of a Royal Huisman sailing yacht described in Figure 2.2. For the methanol ICE engine, a value similar to diesel of 10.000 hours has been considered, as it is derived from it, and also reference was made to the typical operating profile, considering 10.000 nm at 10 knots. The methanol reformer has a manufacturer-declared lifespan of 20.000 hours [164], and the LFP batteries considered can perform 3.500 cycles before being replaced [156]. For all the systems considered, the values obtained are based on technical data provided by the manufacturer and the average operating profile described in Figure 2.2.

To be able to calculate the yearly TCO after also having analyzed the OpEx, it will be sufficient to divide the calculated CapEx using Equation 4.26 by their lifetime, as reported in Equation 4.27.

$$CapEx_{yearly} = \sum_{i=1}^{N} \frac{Cost_{syst(i)}}{T_{(i)}} \tag{4.27}$$

Where:

- $CapEx_{yearly}$: Yearly CapEx of analysed systems in the specific energy configuration [€/year]
- $T_{(i)}$: System lifetime [years]

4.4.2. OpEx

A sustainable refit also has a significant impact on the OpEx of a yacht. Specifically, both HVO, methanol, and hydrogen have an energy cost [€/MWh] significantly higher than the diesel currently used, as reported in Table 4.8. Depending on the chosen energy solution, the maintenance costs of the yacht may also undergo variations, and furthermore, the crew costs could vary since the crew will need to be adequately trained in new systems, fuel handling, and safety precautions [33]. However, for the purpose of this thesis, it is considered sufficient to consider only the fuel cost as OpEx, without taking into account the maintenance cost and crew cost. Speaking with Royal Huisman experts with more than 10 years of experience, it has been concluded that these latter two costs indeed vary much less compared to the current diesel configuration, and therefore focusing on the fuel cost is considered representative of the change that OpEx will undergo following the sustainable refit. Table 4.8 represents the current costs of the energy carriers analyzed in this thesis and also provides a prediction of their costs in the near future of 2030.

Table 4.8: Current and 2030 predicted energy carrier cost [166, 167, 168, 169, 170, 171]

Fuel	Cost [€/MWh]	
	2024	2030
MGO	47	51
HVO	94	103
Grey Methanol	97	91
Bio-Methanol	143	149
e-Methanol	220	176
Grey Hydrogen	119	112
e-Hydrogen	241	195

With e-Methanol and e-Hydrogen, it is meant that the fuels have been obtained from renewable sources, and as shown in Table 4.8, currently their costs are roughly double those of methanol and hydrogen obtained from non-renewable sources. Looking at the table, it can be seen that the cost of alternative fuels is expected to decrease on average, even reaching a reduction of 20% in the case of e-methanol [167]. This is primarily due to expected technological advancements, scale of production with increasing demand and more widespread adoption of these fuels, and market competition. As for biofuels, a slight cost increase is anticipated, justified by the challenging situation of a possible shortage of feedstock supply [171].

In order to calculate the yearly fuel cost depending on the energy configuration, it is necessary to analyze the operational profile of the yacht, an average value of which for a Royal Huisman sailing yacht is depicted in Figure 2.2. This allows determining the number of hours the yacht typically spends sailing under motor, sailing under sail, motor sailing and at anchor. The time spent moored is not considered as it is assumed that in this operational mode, the harbors provide sufficient shore power to satisfy the entire energy demand. To calculate the annual fuel cost associated with a specific converter for a specific operational mode, it will be necessary to apply the following equation. In case energy demand reduction technologies are applied, the energy required by the ICEs and fuel cells will be lower, as described in subsection 4.1.4.

$$Fuelcost_{(i)} = \frac{Fuelcost_{rel(i)} \cdot P_{(i)} \cdot T}{\eta_{conv}} \tag{4.28}$$

Where:

- $Fuelcost_{(i)}$: Yearly fuel cost for the converter (i) at specific operational mode [€]
- $Fuelcost_{rel(i)}$: Relative fuel cost [€/kWh]
- $P_{(i)}$: Average power [kW]
- T: Time [h]
- η_{conv}: Converter efficiency [-]

At this point, by summing up the fuel cost for each converter and each operational mode using Equation 4.29, the model provides the total cost in € required for the fuel for the specific yacht.

$$OpEx = \sum_{i=1}^{N} Fuelcost_{(i)} \tag{4.29}$$

Where:

- $OpEx$: Yearly OpEx [€]

Carbon pricing

A factor to consider when evaluating fuel costs is carbon pricing. Starting in 2024, the EU ETS will cover shipping activities within the European Economic Area (EEA), necessitating ship operators to monitor, report emissions, and surrender allowances for each ton of CO_2 emitted. Additionally, during the 80th session of the MEPC in July 2023, the IMO affirmed plans to implement global carbon pricing for the shipping industry, expected to enter into force in 2027. These initiatives currently target commercial vessels, leaving yachts unaffected for now, although this could change soon [7, 172]. Given the increasing transition to alternative fuels in yachts, the model also considers estimating the potential carbon tax based on the yacht's annual CO_2 emissions.

To calculate the annual CO_2 emissions from the yacht, it is necessary to consider the energy required when sailing under engine, sailing under sail, motor sailing, and at anchor (emissions generated when moored are excluded). This depends on the time spent in each operational mode, as shown in Figure 2.2, and the average power required in each scenario. Next, multiply the energy by the g_{CO_2}/MJ values reported in Table 4.5 of the selected energy combination and then by the carbon tax value, as outlined in Equation 4.30.

$$CO_2tax = t_{CO_2} \cdot d \tag{4.30}$$

Where:

- CO_2tax: Yearly carbon tax [€]
- t_{CO_2}: Yearly TTW CO_2 emissions [t]
- d: Relative carbon tax [€/t]

Possible future scenarios

Since there are many uncertainties regarding both the value of the 'd' parameter affecting the amount of carbon tax and the prices that alternative energy carriers will have in the near future, it has been chosen to analyze three different future scenarios for calculating OpEx:

1. No carbon tax and high fuel cost scenario [171]
2. 100 [€/t] carbon tax and low fuel cost scenario [33, 172]
3. 200 [€/t] carbon tax and low fuel cost scenario [173]

The high and low fuel cost scenarios are obtained by considering a 30% increase and a 30% reduction in the 2030 fuel cost. This decision was made because the cost of alternative fuels, especially methanol and hydrogen, has experienced various fluctuations in recent years [174, 175]. This approach allows to understand how OpEx impacts TCO in both a more pessimistic and more optimistic scenarios for alternative fuel integration. The following bar chart allows for the visualization of a comparison between the current cost of fuels and the projected cost for 2030, including a 30% upper and lower variation to account for future price forecast uncertainty.

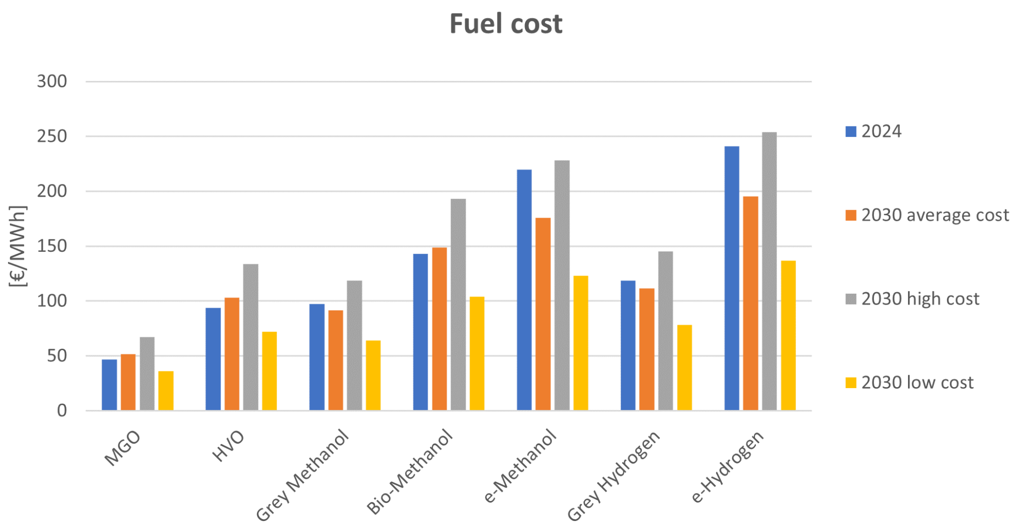

Figure 4.10: Current and 2030 predicted energy carrier cost

4.4.3. TCO

To complete the analysis of costs related to a sustainable refit, the model allows for the TCO calculation. It encompasses various expenses throughout the ship's lifecycle, including CapEx, OpEx, and yacht depreciation. A detailed calculation of it would therefore require a thorough technical analysis that is beyond the scope of this thesis. However, by calculating yearly CapEx and OpEx, it is possible to provide information on how they vary when conducting a sustainable refit, thus contributing to understanding how such a refit project impacts the overall costs of a yacht. The yearly TCO can therefore be calculated according to Equation 4.31.

$$TCO = CapEx + OpEx \tag{4.31}$$

The unit of measurement for OpEx is [€/year], and therefore the CapEx considered in this equation is also on a per-year basis, obtained from Equation 4.27 while taking into account the lifetime of the installed systems. This way, a yearly TCO can be obtained, which varies depending on which of the three OpEx scenarios is considered.

4.5. Conclusion on the assessment model

In conclusion of this section, a concise and effective response to the following subquestion is provided:

"What is the structure of the assessment model used to evaluate the technical and economic feasibility of integrating sustainable solutions on already-built sailing yachts to reduce emissions?"

The model described in this chapter has been designed to be easily applicable to various sailing yachts, serving as a supporting tool for making well-informed decisions when assessing retrofit possibilities. The developed model process is automated, incorporating all information obtained from the literature review and the corresponding equations developed to link them within the model. The inputs required to observe the impact variations of the various configurations relate to yacht dimensions, operational profile (including range, design speed, maximum speed, and deployment of sails), energy carrier and converter selection, and energy demand reduction method selection.

Firstly, the technical feasibility of each selected configuration is assessed by calculating the volume and weight associated with it and comparing them with the values of the current energy configuration of the yacht in question. In order to do so, the most critical scenario is considered, assuming that the requirements to travel a certain range at a certain speed, using only the engine without deploying any sails, remain unchanged. Subsequently, the impact of applying energy reduction methods, operational profile modifications based on the actual usage of the yacht in recent years, and internal space reorganization on the technical feasibility of the selected energy configuration is verified.

For configurations deemed technically feasible, emissions associated with them are calculated on an annual basis. Furthermore, an estimate of the time the yacht will need to stay in the dock for the installation of necessary modifications is provided. Since a significant factor hindering several owners from using alternative fuels is the high price compared to diesel, an economical feasibility analysis is also performed. Consequently, CapEx related to energy converters, storage systems, and energy demand reduction solutions is calculated based on the yacht and its configuration. Regarding OpEx, the focus is on fuel costs, and apart from the current scenario, three different future scenarios are analyzed to account for uncertainty regarding the cost that energy carriers will have in 2030 and the possibility of extending the carbon tax to yachts and its amount. To have a more comprehensive understanding of the economic impact of a sustainable refit for a yacht, the yearly TCO is also calculated. As it is derived from the sum of CapEx and OpEx, it considers not only the upfront investment costs but also the expenses related to the system's lifetime and yacht operation.

All the steps described allow structuring the assessment model to evaluate the technical and economic feasibility of integrating sustainable solutions on already-built sailing yachts to reduce emissions.

5
Results

This chapter presents the results obtained from the model described in Chapter 4. These results will provide information on the volume required by different combinations of energy carriers and converters, and the associated weight compared to the standard diesel configuration currently present on sailing superyachts. Only for technically feasible combinations, the reduction in emissions on a yearly basis will be evaluated compared to the current emissions of the yacht. The docking time required for the sustainable refit will be estimated and finally the variations in CapEx, OpEx, and TCO will be examined. Although the model is applicable to multiple yachts, as described in Chapter 4, results are proposed for two Royal Huisman sailing yachts of different sizes: one below 500 GT and one above 1000 GT, which will be called respectively Yacht A and Yacht B.

- Yacht A: GT < 500
- Yacht B: GT > 1000

Figure 5.1 and Figure 5.2 represent the side view and lower deck arrangement, respectively, of a Royal Huisman sailing yacht with a GT less than 500 and one with a GT greater than 1000. Specifically, the first represents Nilaya, with L_{oa}=47m and 282 GT [37], while the second represents Sea Eagle II, with L_{oa}=81m and 1104 GT [176]. It should be noted that these do not correspond to Yacht A and Yacht B, but clarify the sizes and internal spaces that such categories of sailing yachts have.

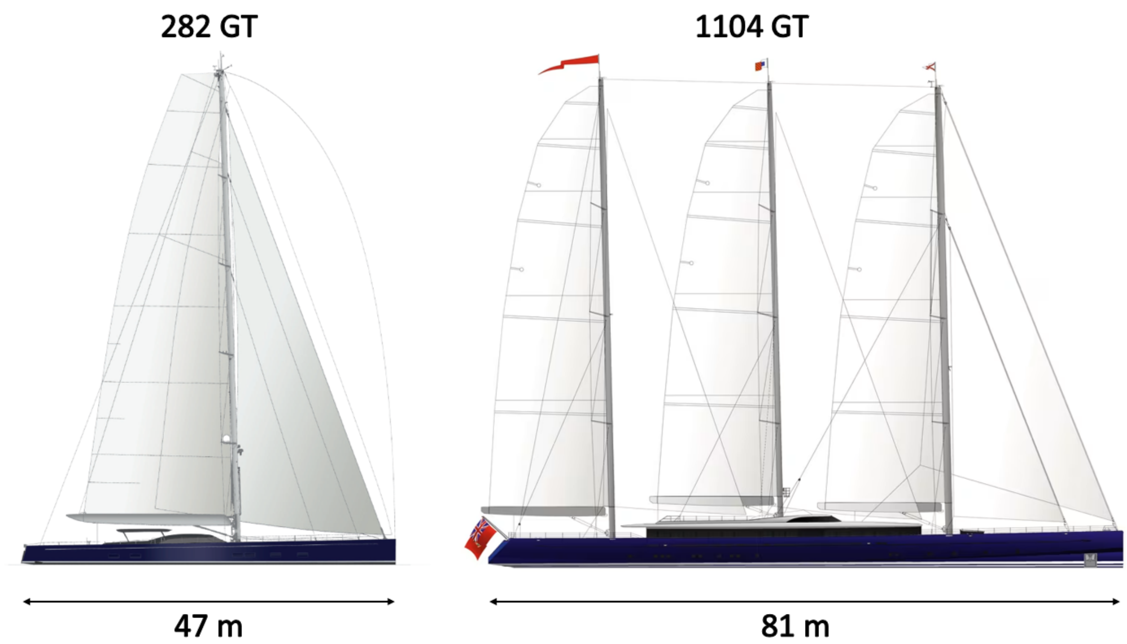

Figure 5.1: Representative examples of Royal Huisman sailing yachts below 500 GT (Nilaya on the left) [37] and above 1000 GT (Sea Eagle II on the right) [176]. They do not correspond to Yacht A and Yacht B.

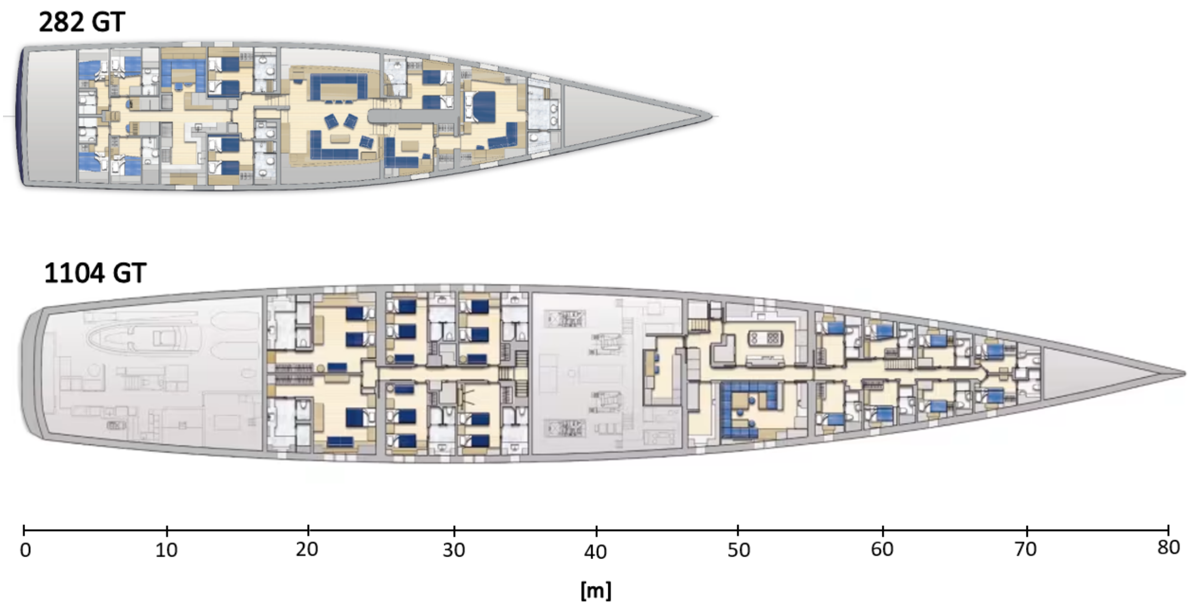

Figure 5.2: Lower deck representative examples of Royal Huisman sailing yachts below 500 GT (Nilaya above) [37] and above 1000 GT (Sea Eagle II below) [176]. They do not correspond to Yacht A and Yacht B.

The purpose of analyzing two sailing yachts of different sizes is to test the applicability of the model to several yachts of different sizes and to verify how the impact of integrating sustainable technologies varies depending on the yacht size, especially in terms of technical feasibility. For each yacht, four hypothetical owner profiles have been identified. These range from Owner 1, who is less inclined to make alterations to decrease onboard energy usage, to Owner 2, who is open to minor adjustments in design speed, range, and sailing time, and approves the installation of solar panels on a small section of the deck. Moving on to Owner 3, who is open to more substantial changes in range and sailing time, and is willing to install hydrogenerators, additional solar panels, and convert a crew cabin into technical space. Finally, there is Owner 4, who is the most willing to change the operational profile and to install more solar panels to significantly lower energy demand. Regarding a refit to alternative fuel, the reduction in required energy significantly influences the technical feasibility of various solutions, as evidenced by the results reported in this chapter. This chapter attempts to answer the following subquestion:

”How do the volumes and weights of alternative energy carriers and converters vary in sailing yachts compared to the current energy configuration considering possible energy demand reduction? How do emissions and costs change?”

Initially, the variations in energy demand of the 4 hypothetical owner profiles will be explained, and subsequently, the two sailing yachts will be analyzed separately, providing for each of them the values of volume occupied, associated weight, emissions, refit times, and costs.

5.1. Energy demand

All the possible alternative fuels considered have lower values of both volumetric and gravimetric energy density compared to the diesel currently used [41]. Consequently, to make a sustainable refit technically feasible, it is necessary to make some modifications aimed at reducing onboard energy demand or converting non-technical spaces into storage tanks or an engine room, since hull extension has not been considered a viable option for a sailing superyacht. The application or not of energy demand reduction possibilities depends on the owner’s willingness to accept some compromises to reduce emissions. For this reason, in consultation with a Royal Huisman manager with more than 10 years of experience, four hypothetical Owner profiles have been defined, each with different thresholds of compromise acceptability. As shown in Table 5.1, all four profiles are willing to replace the conventional HVAC chilled water system with a DX system. This is indeed a solution that reduces the energy requirement of the hotel load without technical complications related to volumes and weights.

Due to the negative aesthetic impact of solar panels, it is assumed that Owner 1 prefers not to install them, while Owners 2, 3, and 4 have them and cover a percentage of the deck area of 10%, 20%, and 30%, respectively. Hydrogenerators are accepted only by Owner profiles 3 and 4, while Owner 1 is not willing to modify the design speed. Owners 2 and 3 reduce it by 1 knot, and Owner 4 by 2 knots. The maximum range achievable by the yacht is not changed by Owner 1, while Owners 2, 3, and 4 accept a reduction of 5%, 10%, and 30%, respectively. Although a 30% reduction is significant, it would still allow both Yacht A and Yacht B to complete the Atlantic crossing, as the range would still be greater than the 2800 nm separating the Caribbean from the Canary Islands, where yachts typically stop, as noted in subsection 2.1.1. Regarding sails, Owners 1 and 2 will continue to install conventional sails, while Owners 3 and 4 will install delivery sails, with the benefits described in subsection 3.3.1. Furthermore, only Owners 3 and 4 are willing to modify the interior spaces, particularly by converting a 8 [m^3] crew cabin into technical space for energy carriers and converters. These characteristics are summarized in Table 5.1 below.

Table 5.1: Energy demand reduction options for the 4 owner profiles compared to the current configuration

		Current configuration	**Owner 1**	**Owner 2**	**Owner 3**	**Owner 4**
HVAC system	[-]	Chilled water	DX	DX	DX	DX
Hydrogenerator	[-]	No	No	No	Yes	Yes
Solar panels	[%]	0	0	10	20	30
Speed reduction	[kts]	0	0	1	1	2
Range reduction	[%]	0	0	5	10	30
Sails type	[-]	Current	Current	Current	Delivery	Delivery
Interior space conversion	[-]	No	No	No	8 m^3 crew cabin	8 m^3 crew cabin

As already explained in Chapter 4, the technical feasibility of an alternative fuel refit is evaluated by analyzing volumes and weights of energy carriers and converters sized to ensure a certain range under engine at a specific design speed. This operational requirement remains unchanged only for Owner profile 1, while it has been considered that the other Owners cover this distance also by motor sailing or sailing under sail, in accordance with real data provided by the captains and crews of Royal Huisman sailing yachts. These divisions are illustrated in the following pie charts.

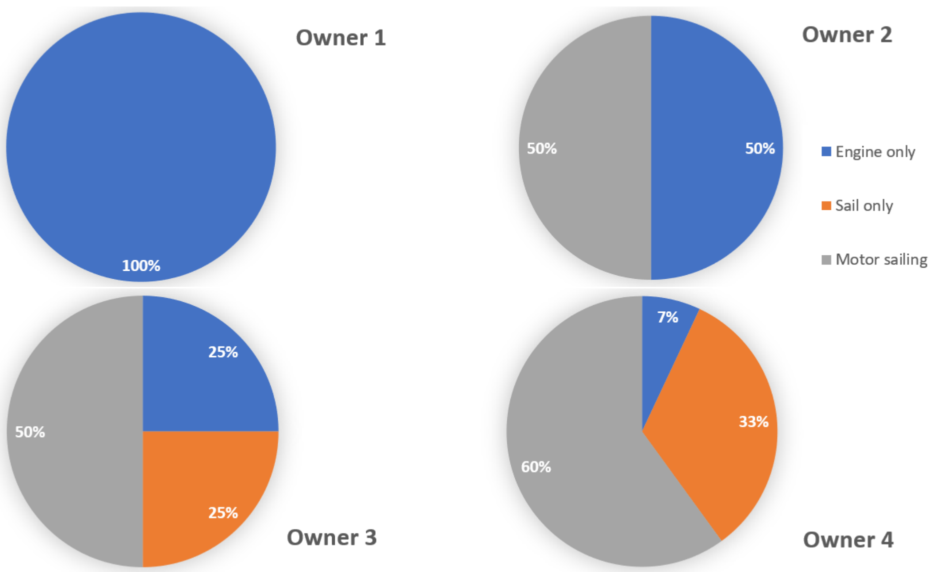

Figure 5.3: Sources of propulsive power for design range for the 4 Owner profiles

According to Table 5.1 and Figure 5.3, the energy demand for the same yacht varies significantly based on the owner profile. The values for Yacht A are listed in Table 5.2, which also includes the percentage reduction compared to the current configuration for both propulsion, hotel load, and total energy demand. These same results are also displayed in Figure 5.4.

Table 5.2: Yacht A changes in energy demand according to owner profile compared to current condition

	Current configuration	**Owner 1**		**Owner 2**		**Owner 3**		**Owner 4**	
	[MWh]	[MWh]	[%]	[MWh]	[%]	[MWh]	[%]	[MWh]	[%]
Propulsion	241	241	100%	139	58%	88	36%	40	17%
Hotel load	38	29	75%	26	69%	22	57%	17	44%
Total	279	269	97%	165	59%	109	39%	57	20%

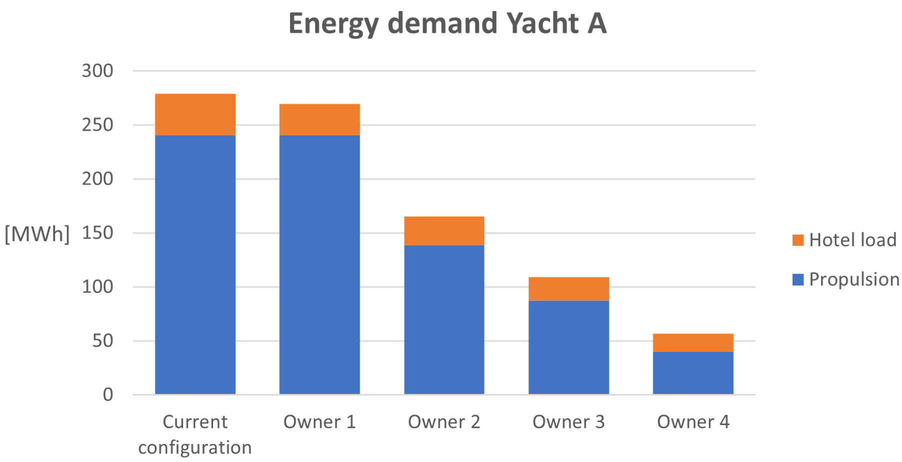

Figure 5.4: Yacht A changes in energy demand according to owner profile compared to current condition

Remarkably, there is a substantial reduction in energy demand for the hotel load even for Owner 1, achieved solely by replacing the HVAC chilled water system with the DX system. It is also noteworthy that the total energy demand for Owner 2 is only 59% of the current demand, achievable simply by reducing speed by 1 knot, reducing the range by 5%, motor sailing for 50% of the time, and having solar panels occupy only 10% of the deck.

As described in chapter 4 with Equation 4.6 and Equation 4.7, the energy required depends on the efficiency of the energy converter that are shown in Table 4.1. Although the model and therefore the results obtained take into account the differences in energy demand based on the converters considered, the values reported in this section refer to the case where an ICE with MGO is used for both propulsion and hotel load for every owner. The purpose of this section is indeed to show how the energy demand varies based on the owner profile and how it is distributed between propulsion and hotel load. Interestingly, regardless of the energy converter used, these proportions remain unchanged.

The same table and bar chart are also reported for Yacht B in Table 5.3 and Figure 5.5.

Table 5.3: Yacht B changes in energy demand according to owner profile compared to current condition

	Current configuration	**Owner 1**		**Owner 2**		**Owner 3**		**Owner 4**	
	[MWh]	[MWh]	[%]	[MWh]	[%]	[MWh]	[%]	[MWh]	[%]
Propulsion	652	652	100%	378	58%	239	37%	110	17%
Hotel load	129	97	75%	90	70%	78	61%	62	48%
Total	781	749	96%	468	60%	317	41%	172	22%

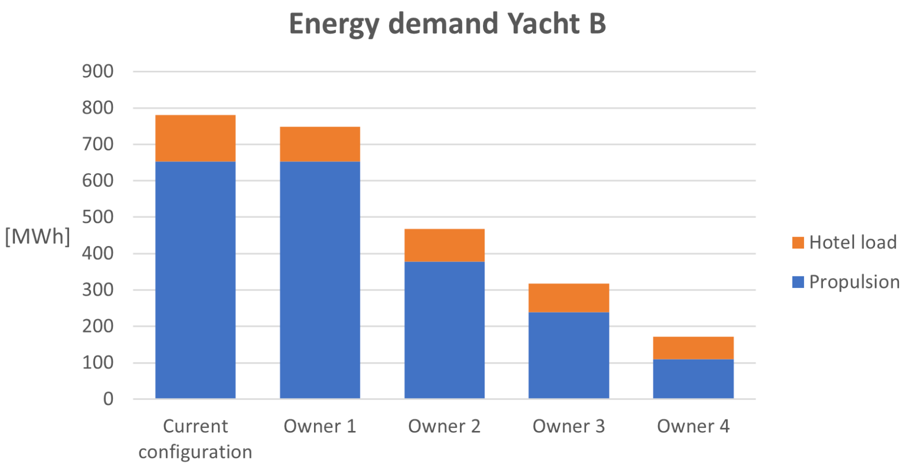

Figure 5.5: Yacht B changes in energy demand according to owner profile compared to current condition

5.1.1. Difference in energy demand reduction between the two yachts

From these results, it can be observed that for Yacht A the percentage reductions compared to the current configuration generally deviate by less than 1% for Owner 1 and 2 compared to Yacht B. However, the difference in energy demand reduction between Yacht A and Yacht B for Owner 3 and 4 is greater, namely 2%. Although 2% may seem like a slight difference, for Yacht B this corresponds to 15.623 [kWh], which is equivalent to, for example, an extra 1537 [L] of MGO that could have been saved. This is due to the fact that only these two owners have hydrogenerators, and the type of hydrogenerator installed is the same on both Yacht A and Yacht B. Therefore, with the same power provided, the impact is lower for Yacht B, which has a higher hotel load requirement. Furthermore, this difference can be justified by the varying impact that a 1 or 2 knots speed reduction has on different yachts with different power-to-speed curves.

Finally, figures Figure 5.4 and Figure 5.5 do not account for the 8 [m^3] extra volume that Owner 3 and 4 are willing to convert into technical space, which has a different impact for the two yachts. In fact this extra volume corresponds to 27% of the 30 [m^3] available tank volume for Yacht A, and only 9% of the 85 [m^3] available tank volume for Yacht B. Consequently the different solutions accepted by the 4 owners in Table 5.1 have a different impact that could imply differences in the technical feasibility of the various energy configurations between the two yachts.

5.2. Yacht A

The assessment of the technical feasibility of various energy configurations depends on the analyzed yacht. For this reason, this section presents the results obtained by applying the model to Yacht A, with a GT of less than 500. For the solutions deemed technically feasible, the associated emissions, required docking time, and costs will also be reported.

5.2.1. Technical feasibility

The technical feasibility is assessed by analyzing the required volume and associated weights of alternative energy carriers and converters to navigate the design range at the design speed, with the respective variations based on the owner profile as reported in Table 5.1. The maximum power output of the energy converters is not modified, and consequently, the maximum speed is not reduced either. Initially, single fuel configurations are analyzed in which the type of energy converters is the same for both the propulsion and hotel load parts. The volume and weight results obtained for Owners 1 and 2 are shown in Table 5.4. The table also indicates the percentage of volume and weight of these configurations compared to the current configuration with ICE powered by MGO for both propulsion and hotel load. The reference values for Owner 1 and 2 are 33.37 [m^3] and 28.76 [t], which correspond to those of the current configuration since these owner profile do not accept crew cabin conversion into technical space. After discussions with expert designers from Royal Huisman, it was decided to consider a tolerance of 5% on volume and 10% on weight. This decision was made to not exclude solutions that were only slightly above the current volume, as the required volume is calculated in the model with a 10% safety margin, leaving a remaining 5% margin. Regarding weight, since 10% of the current energy carriers and converters weight is less than 1% of the total displacement of the yacht, staying below this limit is still considered acceptable.

Table 5.4: Yacht A volume and weight of single fuel configurations for Owner 1 and 2 with percentage increase over the current MGO configuration

Propulsion	Hotel load	Owner 1				Owner 2			
		$[m^3]$	[%]	[t]	[%]	$[m^3]$	[%]	[t]	[%]
HVO	HVO	34,19	102%	27,13	94%	22,17	66%	17,74	62%
Methanol (ICE)	Methanol (ICE)	77,11	231%	73,09	254%	49,30	148%	46,21	161%
Methanol (LT-PEMFC)	Methanol (LT-PEMFC)	92,96	279%	78,50	273%	65,10	195%	51,58	179%
Methanol (HT-PEMFC)	Methanol (HT-PEMFC)	102,17	306%	89,52	311%	71,70	215%	60,09	209%
Hydrogen (LT-PEMFC)	Hydrogen (LT-PEMFC)	494,32	1482%	176,26	613%	307,46	921%	109,74	382%
Batteries	Batteries	717,27	2150%	1001,70	3483%	454,32	1362%	634,49	2206%

As expected, for Owner 1 and 2, whose energy demand is closest to the current one, the only technically feasible configuration is the one using HVO instead of MGO. Noteworthy is the high volume of the hydrogen configuration, which is nearly 15 times the available volume, and the weight of the battery configuration, which is 34 times higher than that of the current diesel.

On the other hand, for Owners 3 and 4, the available volume and weight are higher than the current ones. They are indeed 41.37 [m^3] and 29.26 [t], values obtained by adding the volume and weight of the converted crew cabin, which are 8 [m^3] and 0.5 [t], to the current available volume and weight values. The volume and weight associated with these configurations is shown in Table 5.5.

Table 5.5: Yacht A volume and weight of single fuel configurations for Owner 3 and 4 with percentage increase over the current MGO configuration

Propulsion	Hotel load	Owner 3				Owner 4			
		$[m^3]$	[%]	[t]	[%]	$[m^3]$	[%]	[t]	[%]
HVO	HVO	15,75	38%	12,72	43%	9,71	23%	7,99	27%
Methanol (ICE)	Methanol (ICE)	34,29	83%	31,72	108%	20,22	49%	18,11	62%
Methanol (LT-PEMFC)	Methanol (LT-PEMFC)	50,07	121%	37,06	127%	35,97	87%	23,43	80%
Methanol (HT-PEMFC)	Methanol (HT-PEMFC)	55,27	134%	44,21	151%	39,85	96%	29,31	100%
Hydrogen (LT-PEMFC)	Hydrogen (LT-PEMFC)	206,68	500%	73,86	252%	112,10	271%	40,19	137%
Batteries	Batteries	311,24	752%	434,66	1486%	174,82	423%	244,14	834%

From the results obtained, it can be seen that for Owner 3, even the configuration with Methanol ICE is technically feasible considering the 10% weight tolerance. However, for the Methanol LT-PEMFC and Methanol HT-PEMFC configurations to become feasible as well, compromises associated with Owner 4 profile must be accepted. The volume and weight of the single-fuel hydrogen and battery configurations remain too high even for Owner 4.

Regarding hybrid configurations that include different types of energy carriers and converters for propulsion and hotel load, theoretically, there would be 36 possible combinations, which are the 6 configurations listed in Table 5.4 and Table 5.5 combined with each other. However, after considering how excessively high the volumes and weights are for the single-fuel hydrogen and battery configurations, and based on the fact that the vast majority of the energy demand is for propulsion, as shown in Figure 5.4, it was decided not to analyze configurations that involve hydrogen or batteries for propulsion. Configurations that combine methanol PEMFC for propulsion and hydrogen for hotel load or different types of PEMFC for propulsion and hotel load were also excluded from the analysis as outside the interest of Royal Huisman, since having onboard different types of fuel cells currently is not an option that could be advantageous compared to the other combinations analysed.

The bar charts of Figure 5.6 and Figure 5.7 represent the configurations with different energy carriers and converters for propulsion and hotel load, along with the results of the required volume and associated weight for Owner 1 and 2. These results are compared to the current values of 33.37 [m^3] and

28.76 [t], which are represented in each bar chart by the vertical line and are the same as those in Table 5.4.

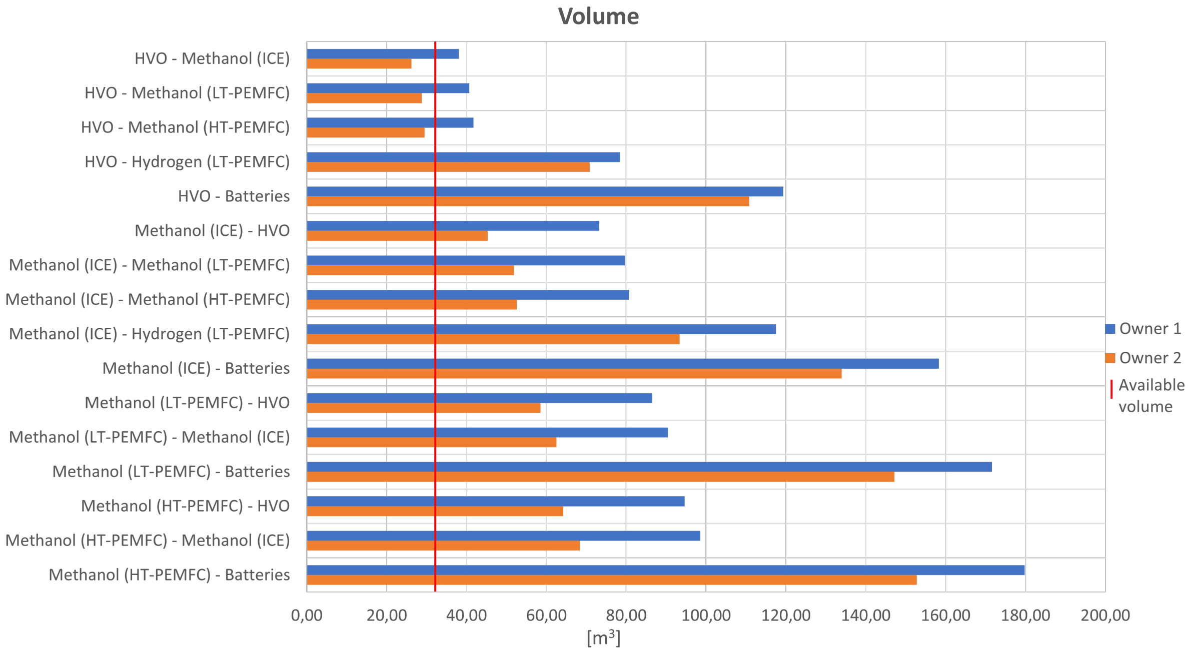

Figure 5.6: Yacht A volume of hybrid configurations for Owner 1 and 2

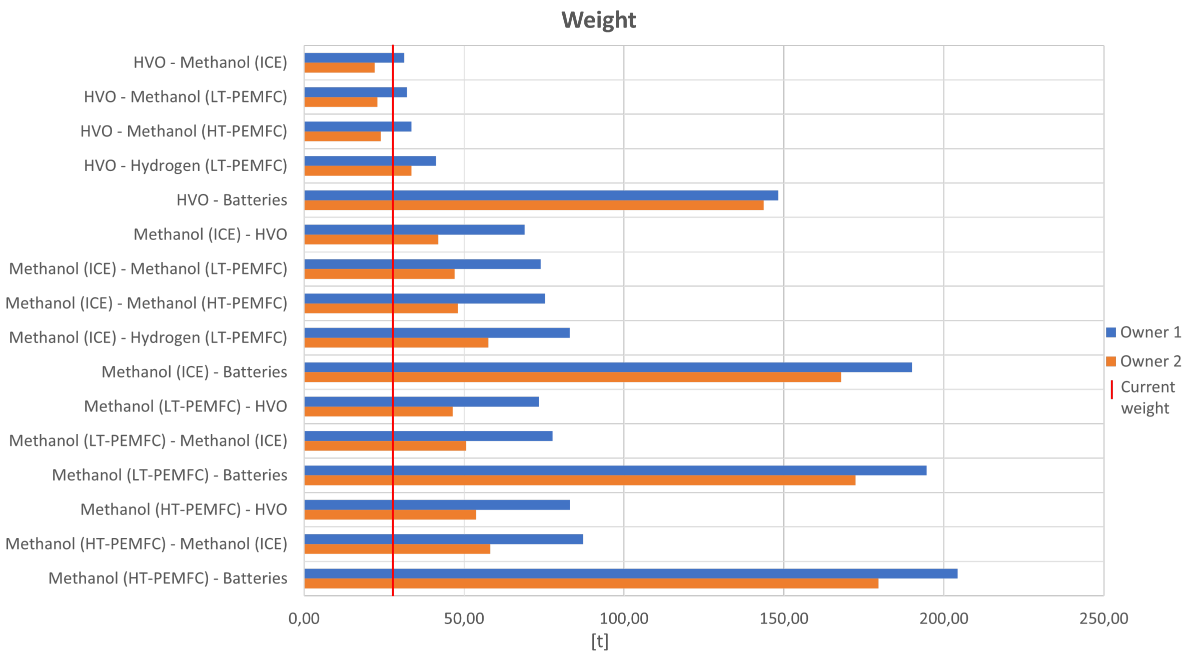

Figure 5.7: Yacht A weight of hybrid configurations for Owner 1 and 2

From these results, it can be observed that for Owner 1, none of the hybrid configurations are technically feasible, while for Owner 2, all three configurations with an HVO ICE for propulsion and methanol for hotel load are feasible, regardless of whether it powers an ICE methanol, LT-PEMFC, or HT-PEMFC.

As for Owner 3 and 4, just like for the non-hybrid configurations, the reference values for volume and weight are 41.37 [m^3] and 29.26 [t] respectively. The results obtained for the different configurations are shown in Figure 5.8 and Figure 5.9.

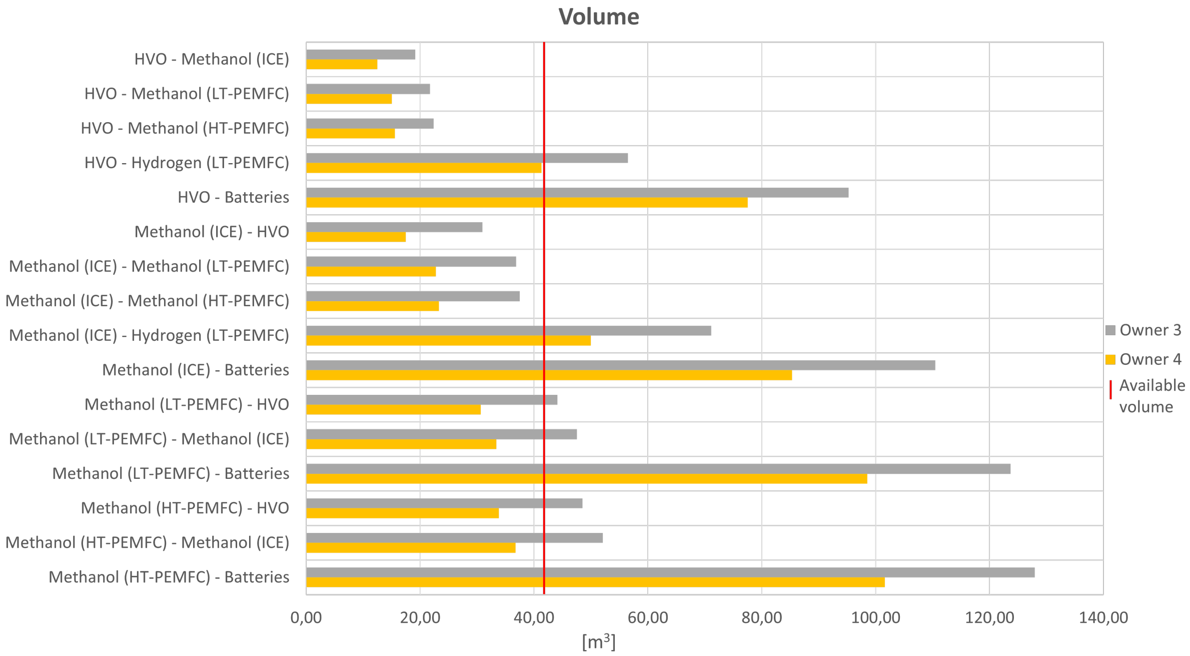

Figure 5.8: Yacht A volume of hybrid configurations for Owner 3 and 4

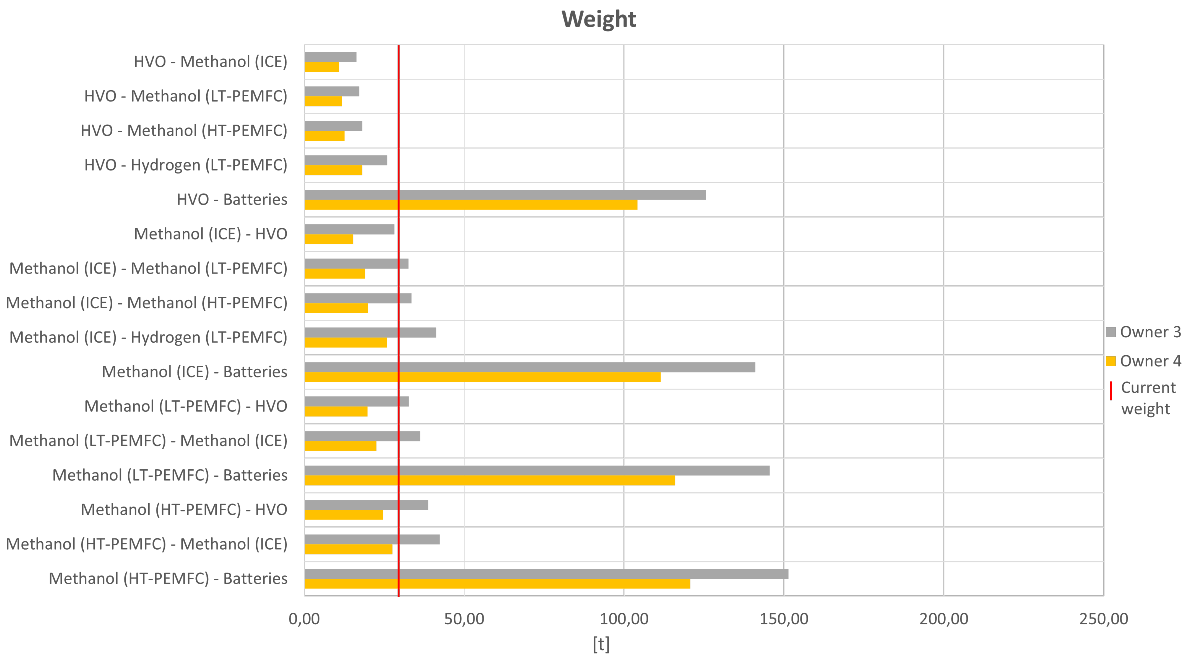

Figure 5.9: Yacht A weight of hybrid configurations for Owner 3 and 4

Analyzing the results obtained, it can be seen that compared to the case of Owner 2, for Owner 3, the solution involving an ICE methanol for propulsion and ICE HVO for hotel load is technically feasible. Configurations with ICE methanol for propulsion and LT-PEMFC or HT-PEMFC methanol are not considered feasible due to their associated weight being too high. The fact that solutions involving methanol are not feasible due to excessive weight while their associated volume would be compatible with the available volume is because of the sandwich arrangement with a 25 mm polymer layer between two steel panels which is considered to avoid the excessively large cofferdams required by regulations [64]. Finally, considering Owner 4 case, the following seven Propulsion - Hotel load hybrid configurations also become feasible:

- HVO - Hydrogen (LT-PEMFC)
- Methanol (ICE) - Methanol (LT-PEMFC)
- Methanol (ICE) - Methanol (HT-PEMFC)
- Methanol (LT-PEMFC) - HVO
- Methanol (LT-PEMFC) - Methanol (ICE)
- Methanol (HT-PEMFC) - HVO
- Methanol (HT-PEMFC) - Methanol (ICE)

In conclusion, Table 5.6 summarizes which configurations are technically feasible for Yacht A, including both single fuel and hybrid ones for all 4 owner cases. The red cells indicate that the configuration for that particular owner is not feasible, the yellow cells that considering the tolerance margin of 5% on volume and 10% on weight it can be considered technically feasible, and the green cells indicate technical feasibility even without tolerance margin.

Table 5.6: Yacht A technical feasibility summary

Propulsion	Hotel load	**Owner 1**	**Owner 2**	**Owner 3**	**Owner 4**
HVO	HVO	Yellow	Green	Green	Green
Methanol (ICE)	Methanol (ICE)	Red	Red	Yellow	Green
Methanol (LT-PEMFC)	Methanol (LT-PEMFC)	Red	Red	Red	Green
Methanol (HT-PEMFC)	Methanol (HT-PEMFC)	Red	Red	Red	Yellow
Hydrogen (LT-PEMFC)	Hydrogen (LT-PEMFC)	Red	Red	Red	Red
Batteries	Batteries	Red	Red	Red	Red
HVO	Methanol (ICE)	Red	Green	Green	Green
HVO	Methanol (LT-PEMFC)	Red	Green	Green	Green
HVO	Methanol (HT-PEMFC)	Red	Green	Green	Green
HVO	Hydrogen (LT-PEMFC)	Red	Red	Red	Yellow
HVO	Batteries	Red	Red	Red	Red
Methanol (ICE)	HVO	Red	Red	Green	Green
Methanol (ICE)	Methanol (LT-PEMFC)	Red	Red	Red	Green
Methanol (ICE)	Methanol (HT-PEMFC)	Red	Red	Red	Green
Methanol (ICE)	Hydrogen (LT-PEMFC)	Red	Red	Red	Red
Methanol (ICE)	Batteries	Red	Red	Red	Red
Methanol (LT-PEMFC)	HVO	Red	Red	Red	Green
Methanol (LT-PEMFC)	Methanol (ICE)	Red	Red	Red	Green
Methanol (LT-PEMFC)	Batteries	Red	Red	Red	Red
Methanol (HT-PEMFC)	HVO	Red	Red	Red	Green
Methanol (HT-PEMFC)	Methanol (ICE)	Red	Red	Red	Green
Methanol (HT-PEMFC)	Batteries	Red	Red	Red	Red

Green: Technically feasible
Yellow: Technically feasible with tolerance margin
Red: Technically not feasible

It is noteworthy that among the four yellow configurations that become feasible due to the 5% tolerance margin on volume and 10% on weight, in the single fuel HVO and hybrid HVO + hydrogen configurations, the limiting factor is volume, while the two single fuel methanol (ICE) and (HT-PEMFC) configurations are limited by weight. This is justified by the SPS barrier solution adopted for the cofferdams. Furthermore, Table 5.6 shows that none of the configurations including batteries is feasible. This does not mean that batteries cannot be on board, but rather that they are not able to guarantee the hotel load nor the propulsion power required to achieve the design range at a certain design speed. Regarding hydrogen, the only feasible configuration among those proposed involves ICE with HVO for propulsion and LT-PEMFC for the hotel load in the case of Owner 4. Despite the fact that the combination of ICE with methanol and LT-PEMFC for Owner 4 has a lower weight than the current configuration with ICE with MGO, the volume is 21% larger, making the result unacceptable.

5.2.2. Emissions

At this point, CO_2 emissions are calculated both on a TTW and overall WTW basis, as well as NO_x and PM emissions for the configurations that have been deemed technically feasible. Unlike the evaluation of technical feasibility, which analyzed the volume and weight of energy carriers and converters associated with the design range at the design speed, emissions are calculated on a yearly basis. To do this, it is assumed that the time spent sailing under sail only, motor only, and motor sailing, at anchor, and moored is the same for the 4 owners according to Figure 2.2, but all other differences between the 4 owner cases remain as presented in Table 5.1. While for the technical feasibility assessment it was not necessary to divide methanol into grey methanol, bio-methanol, and e-methanol, and hydrogen into grey hydrogen and e-hydrogen, since the volumetric and gravimetric energy densities are respectively the same, in the evaluation of WTW CO_2 emissions, this division is necessary. Emissions depend on the energy carriers considered but are also influenced by the efficiency of the converter considered, as it affects energy demand as explained in Chapter 4, Equation 4.6 and Equation 4.7. However, the efficiency difference between methanol ICE and PEMFC has been neglected in this phase to avoid overly complicating the calculation and creating an excessive number of new possible combinations.

Figure 5.10 shows the reductions in tons of CO_2 emitted on a WTW basis for the various configurations compared to the current diesel one, represented by the vertical red line. Bar chart representing CO_2 TTW emissions results and table listing percentage emission reduction of both CO_2 WTW and TTW values are included in Appendix A. Note that where only the term methanol appears in tables or graphs, it means fossil methanol. Furthermore, the reason why not all the 4 Owner cases are reported for some configurations is due to the fact that the missing cases were previously evaluated not technically feasible. The current annual CO_2 WTW emissions of the MGO are 188 [t].

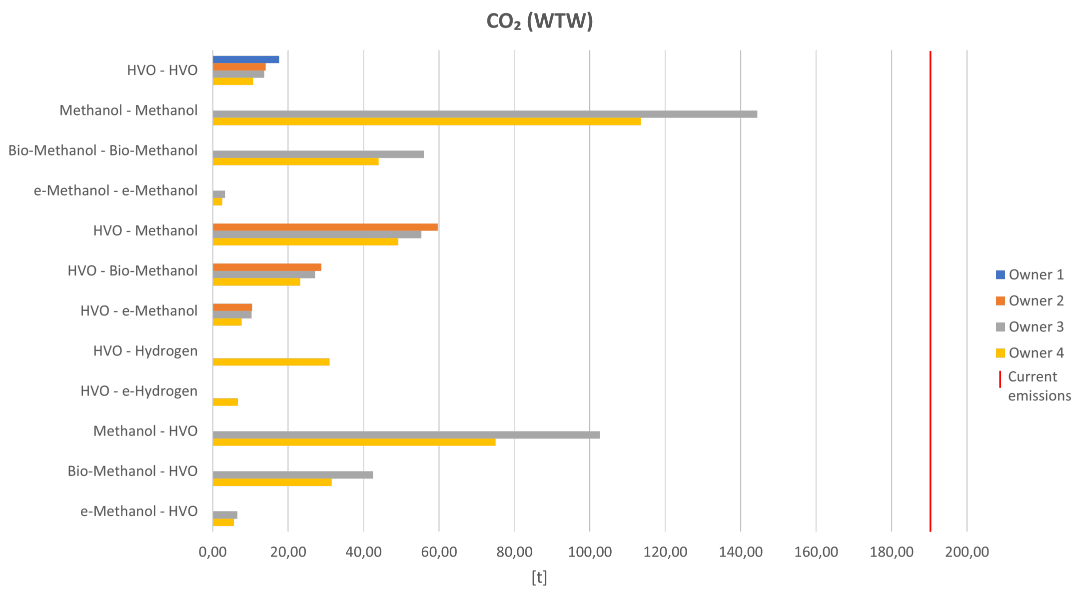

Figure 5.10: Yacht A CO_2 WTW emissions compared to the current ICE configuration at MGO

From the results, it can be observed that the emissions reductions achieved on a WTW level are substantial. HVO WTW CO_2 emission values shows reductions exceeding 90% even in the case of Owner 1. Furthermore, excluding configurations that involve the use of fossil methanol for propulsion, CO_2 emission reductions exceed 65% for all 4 owner cases. It's worth noting that considering only TTW emissions, there are no differences between the various types of methanol and hydrogen.

NO_x and PM emissions, on the other hand, are analyzed only as local emissions, hence at the TTW level. Since TTW emissions are independent of the various types of methanol and hydrogen considered in this analysis, the results involving the terms methanol and hydrogen encompass all variants. NO_x and PM emission values in tons are displayed respectively in the bar charts of Figure 5.11 and Figure 5.12, corresponding respectively to NO_x and PM emissions. Note that the results differ when methanol directly powers an ICE or is reformed into hydrogen onboard and powers a PEMFC. In the latter case, NO_x and PM emissions are considered zero. The current annual emission values for MGO are 2.11 [t] of NO_x and 0.091 [t] of PM, considered as reference. The percentage NO_x and PM emission variation respect to MGO are shown in Appendix A.

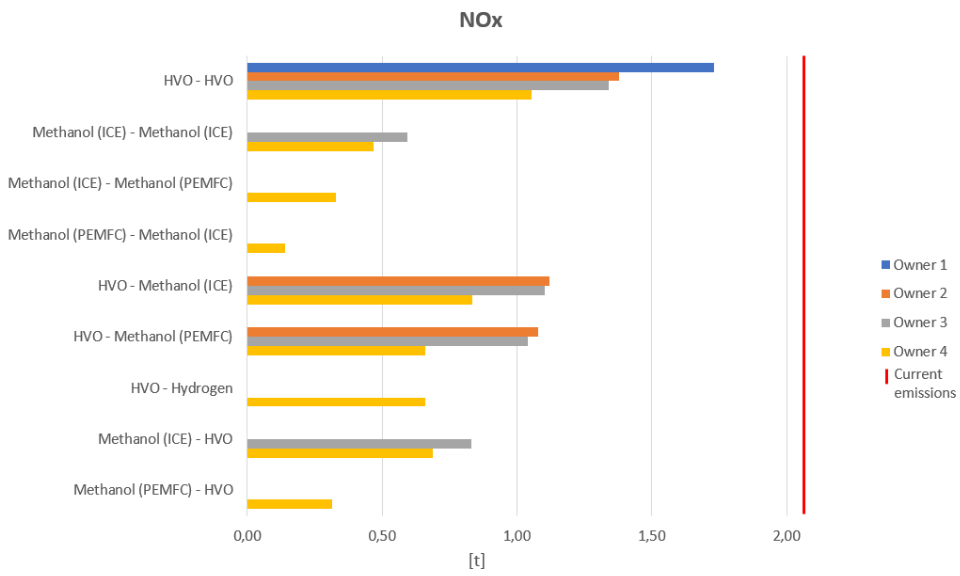

Figure 5.11: Yacht A NO_x emissions compared to the current ICE configuration at MGO

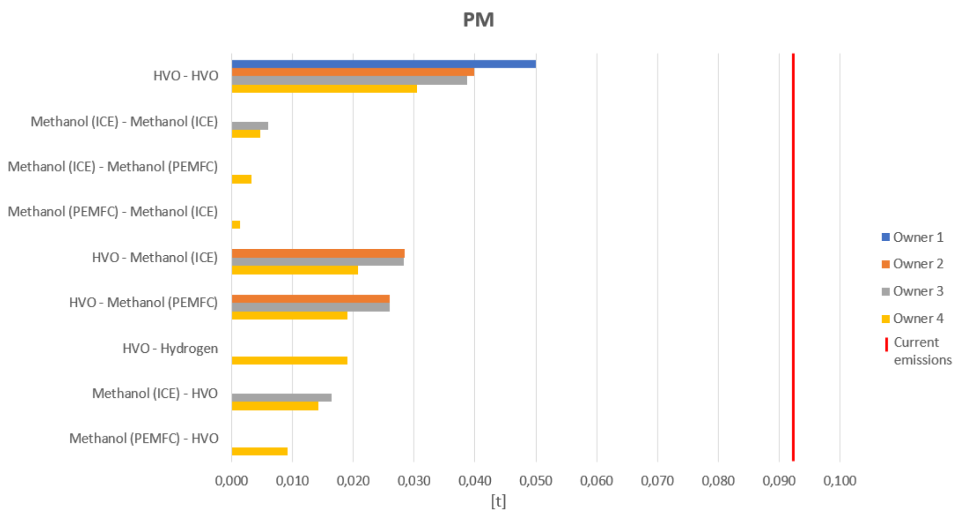

Figure 5.12: Yacht A PM emissions compared to the current ICE configuration at MGO

From the results obtained, it can be observed that on average, the percentage reductions in PM emissions are higher than those for NO_x. Among the configurations presented as technically feasible, the one with the lowest NO_x and PM emissions is the methanol (PEMFC) + methanol (ICE) configuration, with reductions of over 90% compared to MGO. In the case of Owner 1, HVO results in an 18% reduction in NO_x and a significant 45% reduction in PM emissions, with values reaching 50% and 66% respectively in the case of Owner 4.

5.2.3. Refit timeframe

The required docking time to install alternative energy converters on board and make necessary modifications to storage tanks depends on the configurations considered. Following discussions with an expert project manager from Huisfit, who has over 20 years of experience in yacht refits, it is assumed that the time needed to install a fuel cell is equal to that for installing an ICE since the differences would be difficult to predict. Table 5.7 shows the obtained results of the refit timeframe to install sustainable technologies calculated on a monthly basis for the various configurations and across different owner cases.

Table 5.7: Yacht A docking time in months required for different energy configurations depending on owner profiles

Propulsion	Hotel load	**Owner 1** [months]	**Owner 2** [months]	**Owner 3** [months]	**Owner 4** [months]
HVO	HVO	1	3	3	3
Methanol (ICE)	Methanol (ICE)	6	6	6	6
HVO	Methanol (ICE)	4	4	4	4
Methanol (ICE)	HVO	5	5	5	5
HVO	Hydrogen	4	4	4	4

As seen in Table 5.7, the only configuration for which the refit timeframe varies depending on the owner is the HVO single fuel configuration. This variation is linked to the fact that Owner 1 is the only one of the 4 without solar panels on board, the installation of which is estimated to take 3 months. The docking month associated with Owner 1 in this configuration is due to the installation of the DX system for HVAC, an installation that can be done simultaneously with that of the solar panels, thus not affecting the 3 months required for the other owner cases. For the other configurations, the installation or absence of solar panels does not impact the timeframe because all system installations can be done concurrently, and all other combinations require at least 4 months. The configuration that requires the most time to install is the single fuel methanol, which requires 6 months. Hybrid combinations, on the other hand, require between 4 and 5 months depending on whether HVO is for propulsion or hotel load, and therefore whether the associated ICE and tanks have larger or smaller dimensions. In general, installation timelines are manageable, since as described in Chapter 4 the parts that require the most time are those preceding it, namely project feasibility and design and engineering.

5.2.4. Economic feasibility

A final and crucial aspect in evaluating the trade-off regarding the sustainable refit of a sailing yacht is the economic aspect. As reported in Chapter 4 in Table 4.6, alternative energy converters indeed have a high cost, and the OpEx associated with alternative energy carriers is currently more than double the cost of the MGO currently used, as shown in Figure 4.10. Since CapEx is not dependent on fuel cost variations and the possible introduction of a carbon tax, the results related to them will be presented first. Subsequently, the current scenario and the three possible future scenarios presented in Chapter 4 will be analyzed, and for each of them, the respective OpEx and TCO of each energy configuration for each owner case will be examined.

Consistent with the emissions calculation, costs are also calculated on an annual basis and referenced to the operational profile described in Figure 2.2. However, unlike emissions, it is not possible to overlook the difference between ICE and PEMFC due to the significant price difference described in Table 4.6. Nevertheless, it is still possible to reduce the total number of possible combinations by considering both LT-PEMFC with methanol and HT-PEMFC with methanol generically as PEMFC, since by adding the cost of the hydrogen reformer to LT-PEMFC, the cost of the two types of fuel cells is equal. This can be seen in table Table 4.6, and also the lifetime of LT-PEMFC and HT-PEMFC are the same, as reported in Table 4.7.

CapEx

The yearly CapEx can be obtained by considering the refit cost, which is the cost of the various systems that the different configurations install, and taking into account the lifetime of these systems, as described in Chapter 4 in Table 4.7. In order to make a coherent and meaningful comparison with the current configuration in terms of CapEx and especially TCO, it is assumed that the sailing yacht analyzed during a non-sustainable refit still replaces the diesel ICE and changes the current sails with new sails of the same type. This non-sustainable refit would have a total cost of €723.840 and an yearly CapEx cost of €142.260. The cost of replacing the sails in the current case, and therefore also for Owners 1 and 2, is €465.840, with corresponding yearly CapEx of €116.460 given the considered lifetime of 4 years. On the other hand, the cost of delivery sails is lower, at €388.200, with yearly CapEx of €77.640, since the considered lifetime is higher and equal to 5 years.

Figure 5.13 shows a bar chart representing the refit cost of the technically feasible configurations for the 4 owner cases. It should be noted that in this chart no distinction is made according to the type of methanol and hydrogen as they only influence OpEx and TCO and not CapEx. The refit cost and yearly CapEx results are presented as tables in Appendix A.

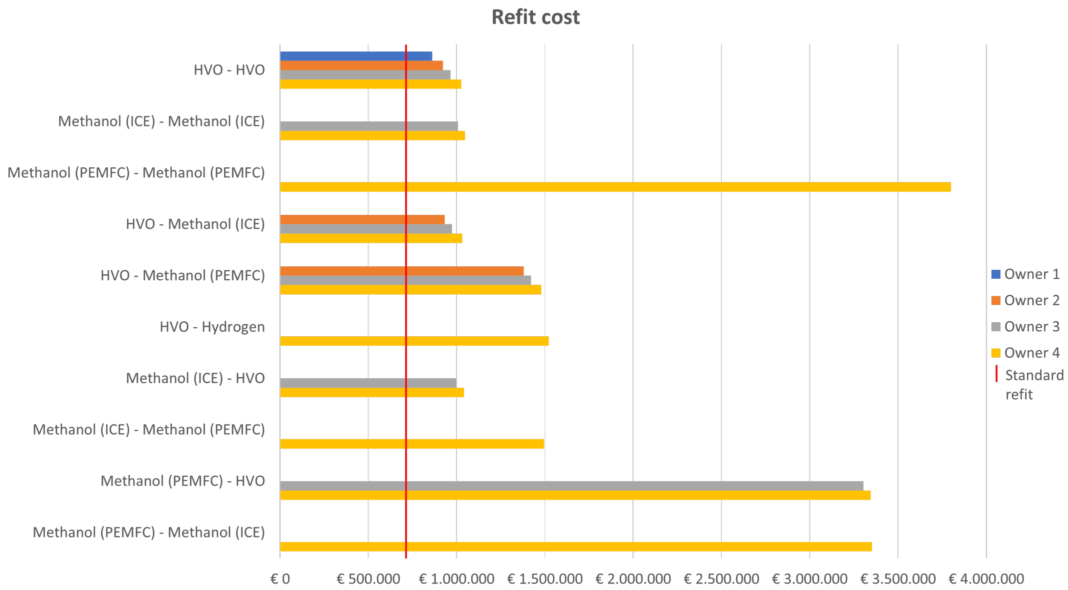

Figure 5.13: Yacht A sustainable refit cost compared to conventional refit

These results show that, as expected, the most expensive configuration in terms of CapEx is the single fuel methanol with PEMFC as energy converters. This solution indeed exceeds €3.7 million for Owner 4, followed by the hybrid methanol PEMFC for propulsion and methanol ICE for hotel load, with a cost of over €3.3 million for Owner 4. The solution closest to the cost of a conventional refit is single fuel HVO in the case of Owner 1, since the cost of the energy converters is the same and the only difference is the cost of the DX system for HVAC.

OpEx & TCO

Several scenarios were considered for OpEx and TCO analysis due to uncertainty about future fuel prices and the introduction of a carbon tax. Initially, the Current scenario is considered, representing OpEx and TCO if the sustainable refit were done today. For the near future of 2030, Scenario 1, Scenario 2, and Scenario 3 are considered. In Scenario 1, the highest expected values of alternative fuels represented in Figure 4.10 are considered, and there is no carbon tax present that would partially rebalance the costs of MGO and alternative fuels. Scenarios 2 and 3 are more optimistic about the future of alternative fuels, considering both the lower cost of fuel as reported in Figure 4.10 and considering respectively 100 [€/t] and 200 [€/t] of carbon tax per tonne of CO_2 emitted.

Current scenario

The Current scenario represents the OpEx and TCO that would be incurred if the sustainable refit were done today, with current fuel prices and no carbon tax. Figure 5.14 shows the OpEx, while Figure 5.15 represents the TCO obtained by adding OpEx with the respective yearly CapEx. The vertical red lines show the cost of MGO and the TCO that would be incurred if a standard refit were performed, replacing diesel ICEs and sails. The TCO percentage variation compared to the case where the yacht continues to use MGO and undergoes a conventional refit is reported in Appendix A. The reference values for OpEx and TCO are €27.424 and €169.683, respectively.

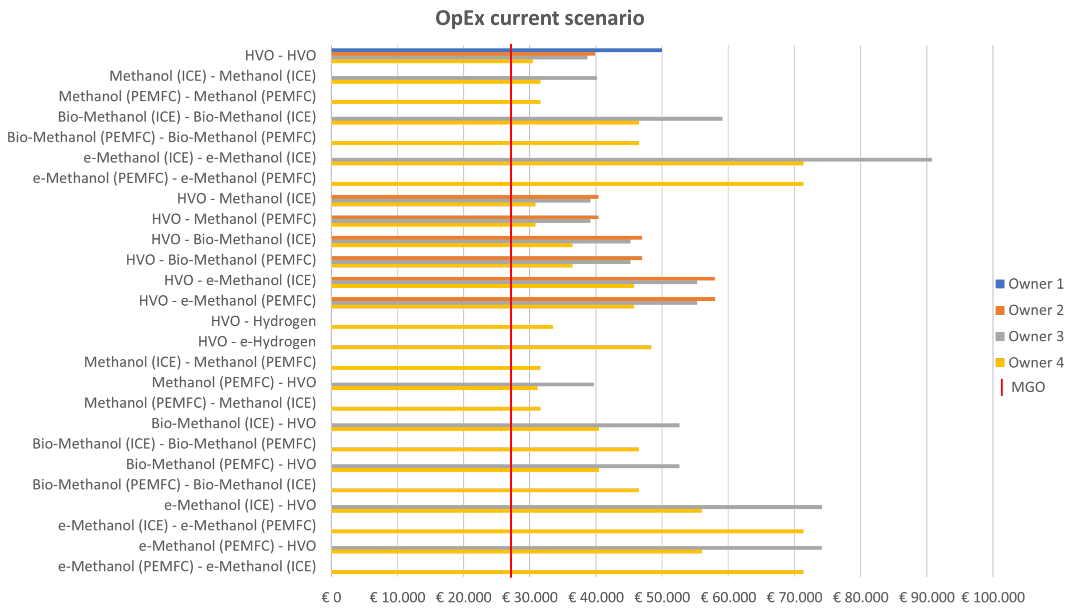

Figure 5.14: Yacht A OpEx of possible configurations compared to MGO for current scenario

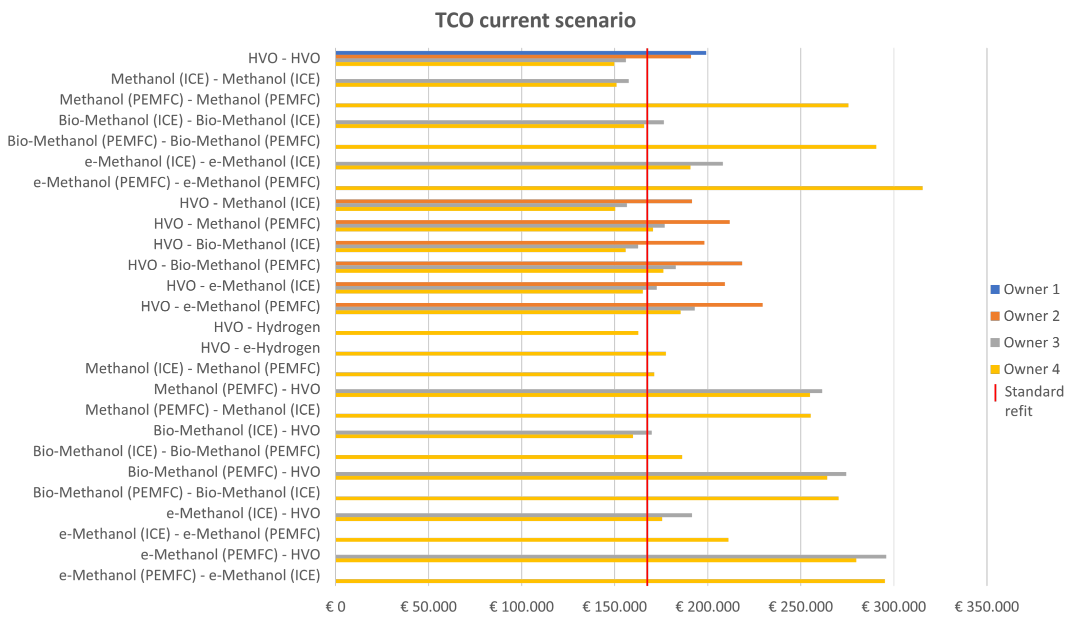

Figure 5.15: Yacht A TCO of possible configurations compared to MGO for current scenario

From these graphs, it can be noticed how the yearly CapEx significantly impacts the TCO, reducing the variation among the different types of methanol and hydrogen compared to OpEx, assuming the same energy converters. The reduction in TCO generally observed when transitioning from Owner 2 to Owner 3 is influenced by both lower OpEx and reduced CapEx. The latter are obtained due to the longer lifetime of the delivery sails compared to the standard sails currently used and considered for Owner 2. Furthermore, even though yearly CapEx increases from Owner 3 to 4, the TCO decreases further because the reduction in OpEx outweighs the increase in CapEx. All other results are as expected and in line with the fuel costs reported in Table 4.8 and the CapEx from Figure 5.13.

Scenario 1

Regarding the future scenarios, Scenario 1 is the most pessimistic for alternative fuels integration, with the highest expected fuel costs and without a carbon tax, that would increase the cost of diesel. MGO has indeed the highest CO_2 emissions among the alternative fuels considered in this thesis, and consequently, the carbon tax would reduce the cost gap between diesel and alternative fuels. Figure 5.16 shows the OpEx results obtained, while Figure 5.17 shows the TCO. The TCO percentage variation compared to the case where the yacht continues to use MGO and undergoes a conventional refit is reported in Appendix A. The reference values for OpEx and TCO are €39.215 and €181.475, respectively.

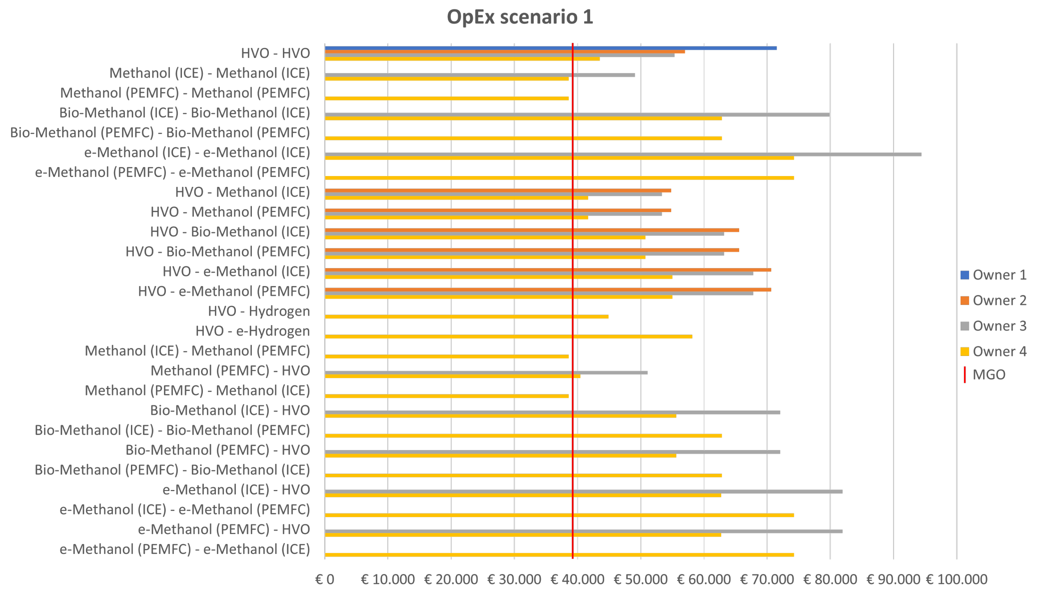

Figure 5.16: Yacht A OpEx of possible configurations compared to MGO for scenario 1

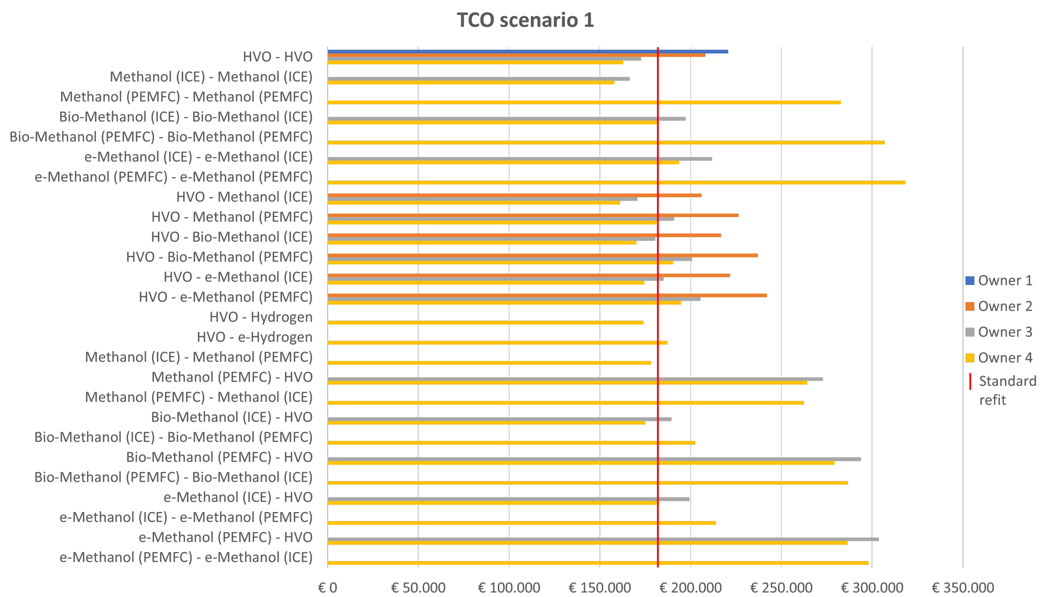

Figure 5.17: Yacht A TCO of possible configurations compared to MGO for scenario 1

The fuel costs vary in accordance with Figure 4.10, and the TCO compared to the Current scenario increases only due to higher OpEx. The percentage reductions in TCO achieved for each energy configuration when transitioning from Owner 2 to Owner 3 and then from Owner 3 to Owner 4 are due to the same reasons described for the Current scenario.

Scenario 2

Scenario 2 considers the lowest fuel costs of the projections for 2030 and also includes a carbon tax of 100 [€/t] for each tonne of CO_2 emitted. Figure 5.18 shows the OpEx results obtained, while Figure 5.19 shows the TCO. The TCO percentage variation compared to the case where the yacht continues to use MGO and undergoes a conventional refit is reported in Appendix A. The reference values for OpEx and TCO are €36.957 and €179.217, respectively.

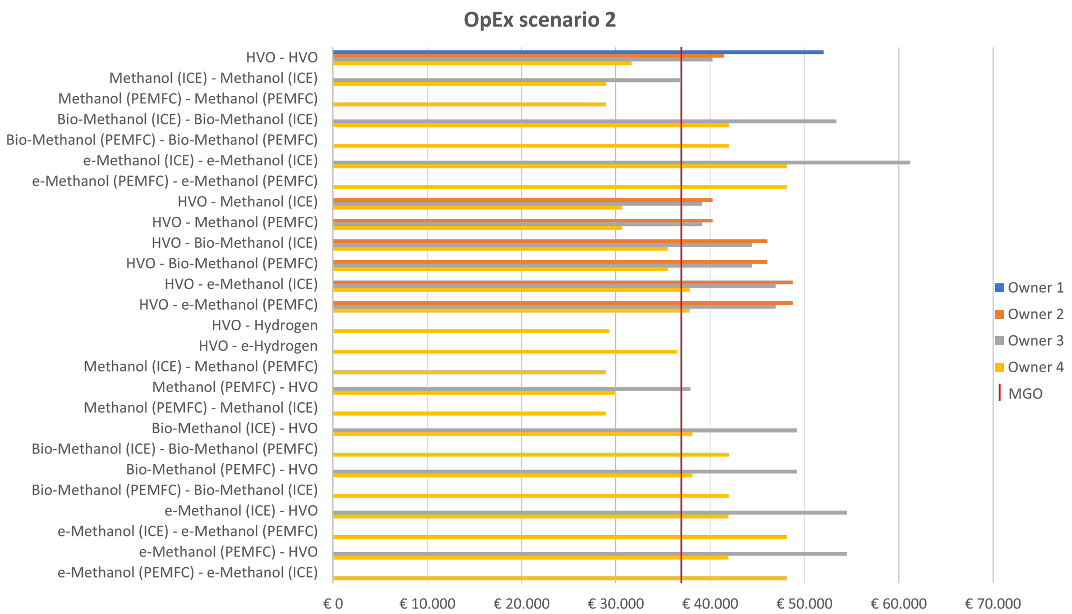

Figure 5.18: Yacht A OpEx of possible configurations compared to MGO for scenario 2

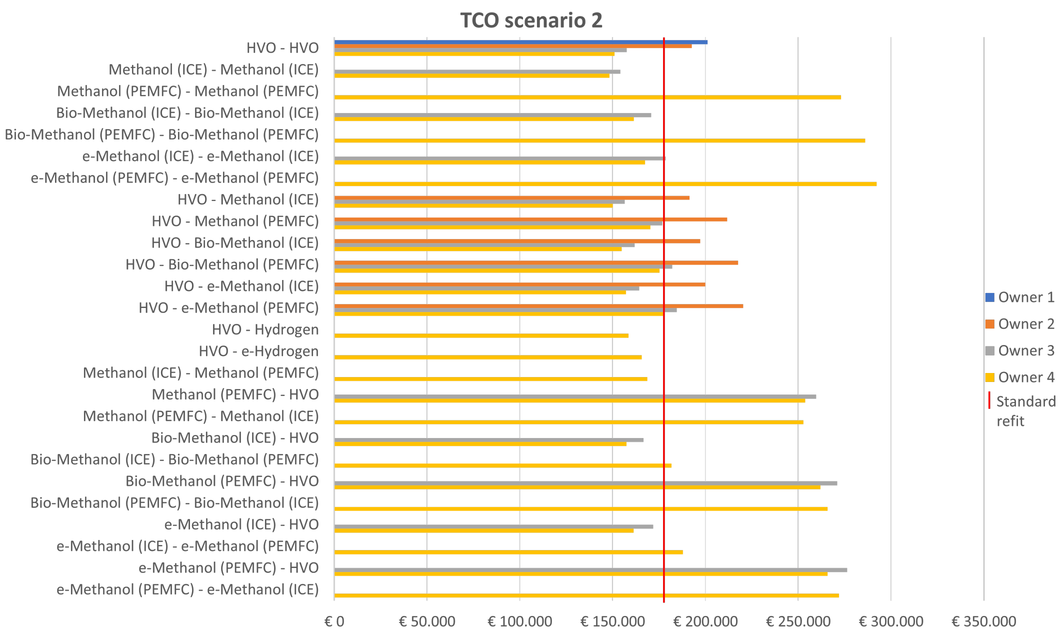

Figure 5.19: Yacht A TCO of possible configurations compared to MGO for scenario 2

In Scenario 2, the OpEx is lower than both the Current scenario and Scenario 1, while due to the introduction of the carbon tax, the gap between MGO and alternative fuels diminishes, resulting in a TCO for several configurations lower than that associated with current MGO. The percentage reductions in TCO achieved for each energy configuration when transitioning from Owner 2 to Owner 3 and then from Owner 3 to Owner 4 are due to the same reasons described for the Current scenario.

Scenario 3

Finally, Scenario 3 is the most optimistic in terms of transitioning from conventional diesel to alternative fuels. It indeed considers the lowest fuel prices from the 2030 projections and additionally doubles the carbon tax compared to Scenario 2, reaching 200 [€/t]. Figure 5.20 shows the OpEx results obtained, while Figure 5.21 shows the TCO. The TCO percentage variation compared to the case where the yacht continues to use MGO and undergoes a conventional refit is reported in Appendix A. The reference values for OpEx and TCO are €52.799 and €195.059, respectively.

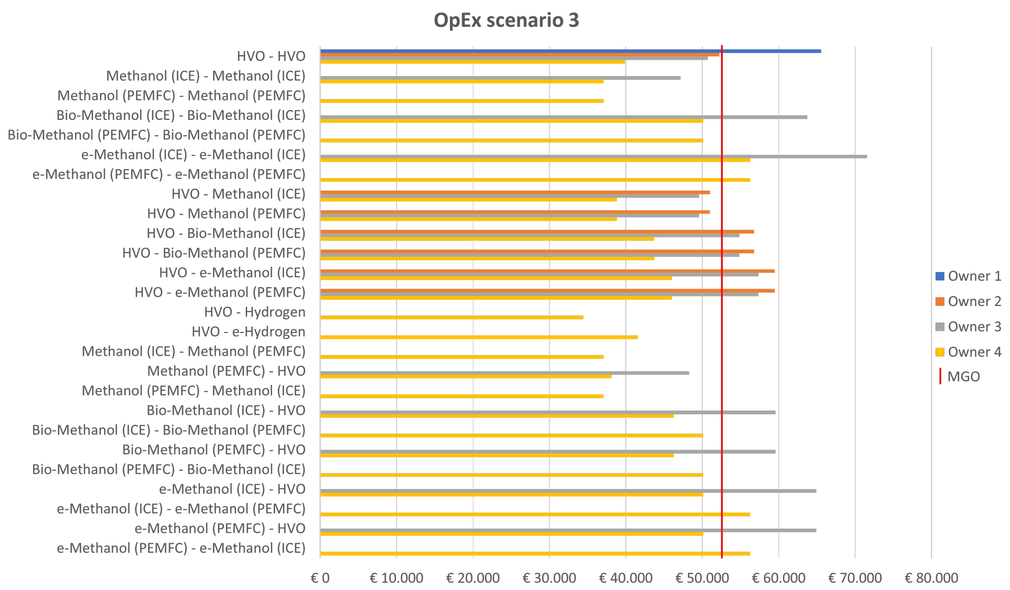

Figure 5.20: Yacht A OpEx of possible configurations compared to MGO for scenario 3

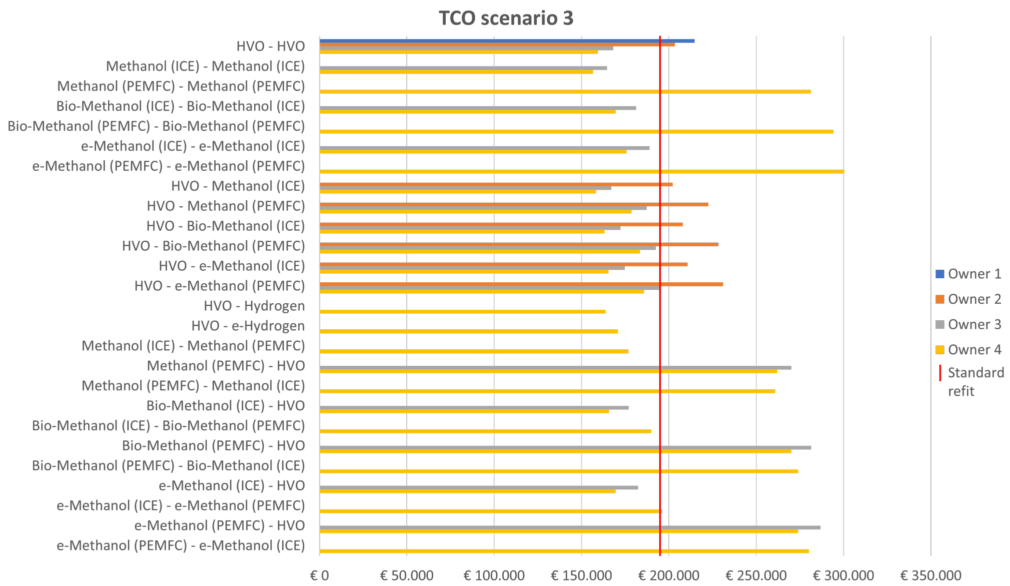

Figure 5.21: Yacht A TCO of possible configurations compared to MGO for scenario 3

Observing the results obtained in this scenario and comparing them with those of Scenario 2, it can be noted how the carbon tax contributes to reducing the cost gap between configurations using MGO as the energy carrier and others using alternative fuels. The only configurations that, despite considering the Owner 4 profile, remain with a TCO higher than that of a standard refit are those using PEMFC for propulsion, regardless of the converter for the hotel load, and bio-methanol ICE + bio-methanol PEMFC and e-methanol ICE + e-methanol PEMFC. The percentage reductions in TCO achieved for each energy configuration when transitioning from Owner 2 to Owner 3 and then from Owner 3 to Owner 4 are due to the same reasons described for the Current scenario.

5.3. Yacht B

In this section, the results obtained from the assessment model applied to Yacht B are reported. Yacht B is a Royal Huisman sailing yacht with a GT exceeding 1000 GT. As for Yacht A, the technical feasibility of various configurations will be initially assessed, and for those feasible, the associated emissions, required docking time, and costs will also be reported. The purpose of analyzing a second sailing yacht of different sizes is to verify how the impact of integrating sustainable technologies varies depending on the yacht's size, especially in terms of technical feasibility.

5.3.1. Technical feasibility

The assessment of technical feasibility is carried out in the same way as for Yacht A. Initially, single fuel configurations are analyzed in which the type of energy converters is the same for both the propulsion and hotel load parts. The volume and weight results obtained for Owners 1 and 2 are shown in Table 5.8. The table also indicates the percentage of volume and weight of these configurations compared to the current configuration with ICE powered by MGO for both propulsion and hotel load. The reference values for Owner 1 and 2 are 93.55 [m^3] and 80.65 [t], which correspond to those of the current configuration since these owner profiles do not accept crew cabin conversion into technical space. As already explained for Yacht A, a tolerance of 5% on volume and 10% on weight is applied.

Table 5.8: Yacht B volume and weight of single fuel configurations for Owner 1 and 2 with percentage increase over the current MGO configuration

Propulsion	Hotel load	Owner 1				Owner 2			
		[m^3]	[%]	[t]	[%]	[m^3]	[%]	[t]	[%]
HVO	HVO	95,25	102%	75,61	94%	62,93	67%	50,34	62%
Methanol (ICE)	Methanol (ICE)	214,16	229%	202,88	252%	139,62	149%	130,85	162%
Methanol (LT-PEMFC)	Methanol (LT-PEMFC)	259,31	277%	218,30	271%	184,64	197%	146,15	181%
Methanol (HT-PEMFC)	Methanol (HT-PEMFC)	285,01	305%	249,20	309%	203,37	217%	170,31	211%
Hydrogen (LT-PEMFC)	Hydrogen (LT-PEMFC)	1371,15	1466%	488,94	606%	870,38	930%	310,66	385%
Batteries	Batteries	2001,46	2139%	2795,15	3466%	1294,73	1384%	1808,16	2242%

As for Yacht A, the only technically feasible configuration for Owner 1 and 2 is the one replacing MGO with HVO. Noteworthy is the high volume of the hydrogen configuration, which is nearly 15 times the available volume, and the weight of the battery configuration, which is 34 times higher than that of the current diesel.

The available volume and weight for Owners 3 and 4 are higher than the current ones. They are indeed 101.55 [m^3] and 81.15 [t], values obtained by adding the volume and weight of the converted crew cabin, which are 8 [m^3] and 0.5 [t], to the current available volume and weight values. The volume and weight associated with these configurations are shown in Table 5.9.

Table 5.9: Yacht B volume and weight of single fuel configurations for Owner 3 and 4 with percentage increase over the current MGO configuration

Propulsion	Hotel load	Owner 3				Owner 4			
		$[m^3]$	[%]	[t]	[%]	$[m^3]$	[%]	[t]	[%]
HVO	HVO	45,52	45%	36,73	45%	28,84	28%	23,69	29%
Methanol (ICE)	Methanol (ICE)	98,93	97%	91,54	113%	60,17	59%	54,09	67%
Methanol (LT-PEMFC)	Methanol (LT-PEMFC)	143,88	142%	106,77	132%	105,05	103%	69,26	85%
Methanol (HT-PEMFC)	Methanol (HT-PEMFC)	158,81	156%	127,26	157%	116,35	115%	86,24	106%
Hydrogen (LT-PEMFC)	Hydrogen (LT-PEMFC)	597,06	588%	213,36	263%	336,68	332%	120,66	149%
Batteries	Batteries	904,25	890%	1262,84	1556%	524,72	517%	732,80	903%

From the results obtained, it can be seen that contrary to Yacht A, the configuration with Methanol ICE for Owner 3 and the one with methanol HT-PEMFC for Owner 4 are not technically feasible. As for Yacht A, the volume and weight of the single-fuel hydrogen and battery configurations remain too high for each of the four configurations.

Regarding hybrid configurations, it was decided not to analyze configurations that involve hydrogen or batteries for propulsion, with the same rationale applied to Yacht A. As for Yacht A, configurations that combine methanol PEMFC for propulsion and hydrogen for hotel load or different types of PEMFC for propulsion and hotel load were also excluded. The bar charts of Figure 5.22 and Figure 5.23 represent the configurations with different energy carriers and converters for propulsion and hotel load, along with the results of the required volume and associated weight for Owner 1 and 2. These results are compared to the current values of 93.55 [m^3] and 80.65 [t], which are represented in each bar chart by the vertical line and are the same as those in Table 5.8.

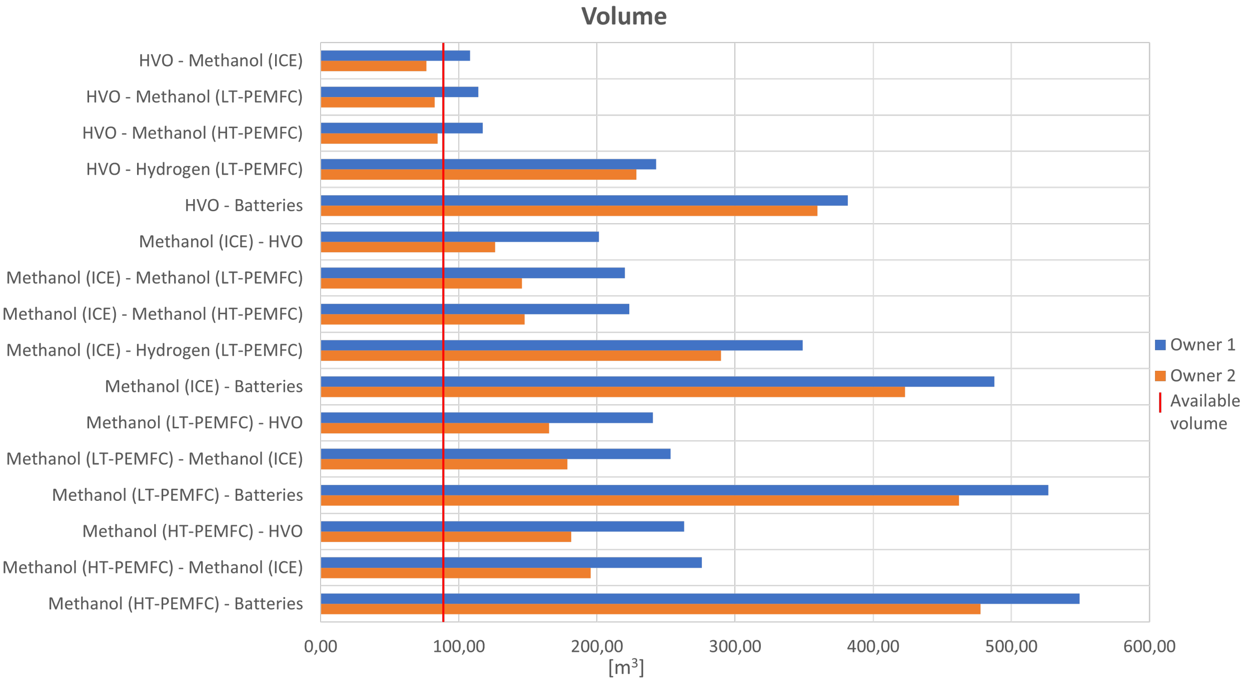

Figure 5.22: Yacht B volume of hybrid configurations for Owner 1 and 2

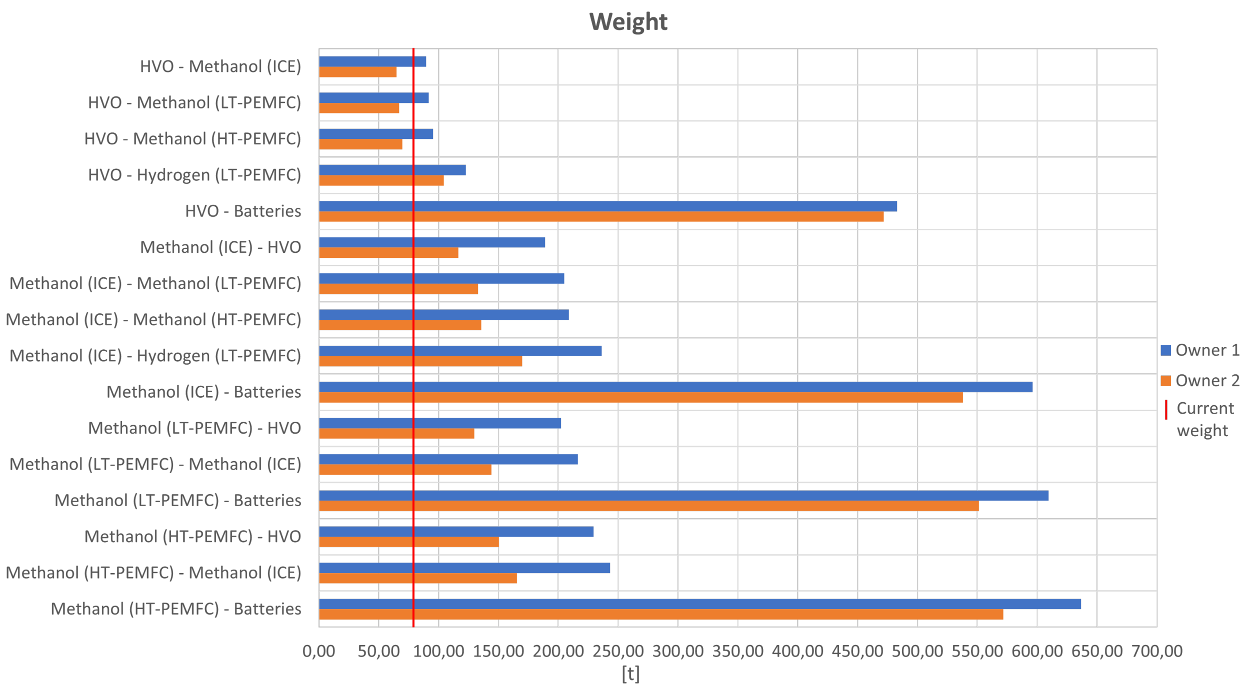

Figure 5.23: Yacht B weight of hybrid configurations for Owner 1 and 2

As for Yacht A, results show that for Owner 1, none of the hybrid configurations are technically feasible, while for Owner 2, all three configurations with an HVO ICE for propulsion and methanol for hotel load are feasible, regardless of whether it powers an ICE methanol, LT-PEMFC, or HT-PEMFC.

For Owner 3 and 4, just like for the non-hybrid configurations, the reference values for volume and weight are 101.55 [m^3] and 81.15 [t] respectively. The results obtained for the different configurations are shown in Figure 5.24 and Figure 5.25.

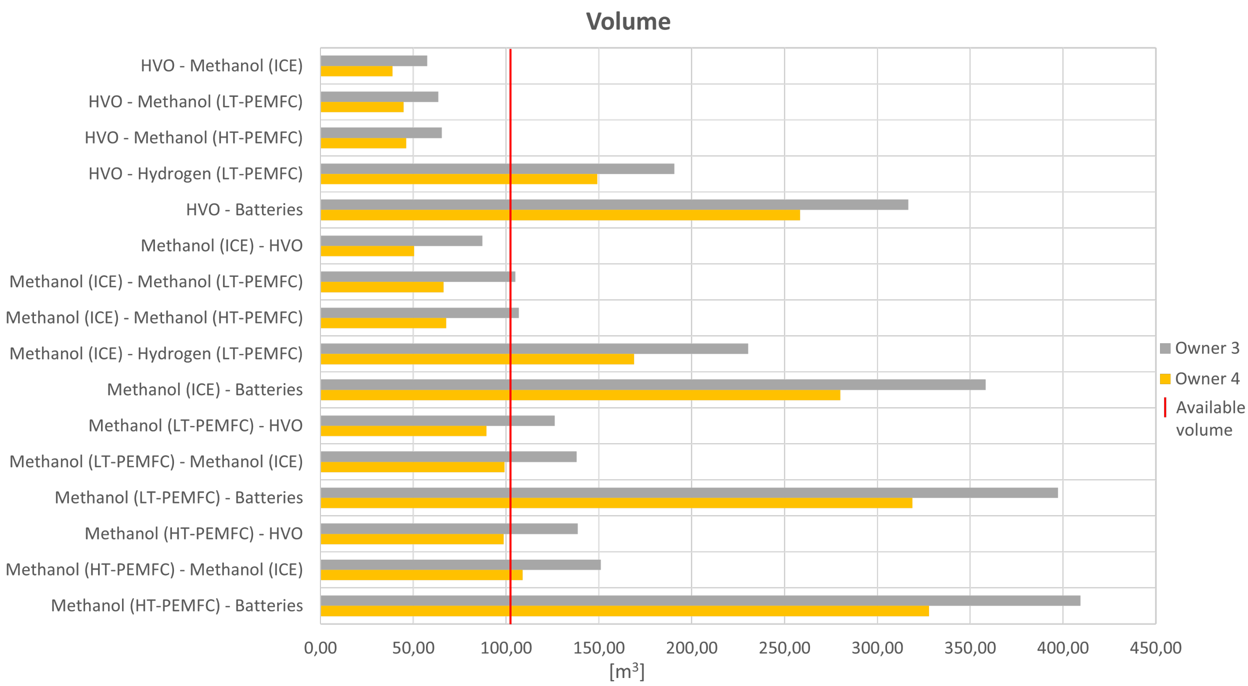

Figure 5.24: Yacht B volume of hybrid configurations for Owner 3 and 4

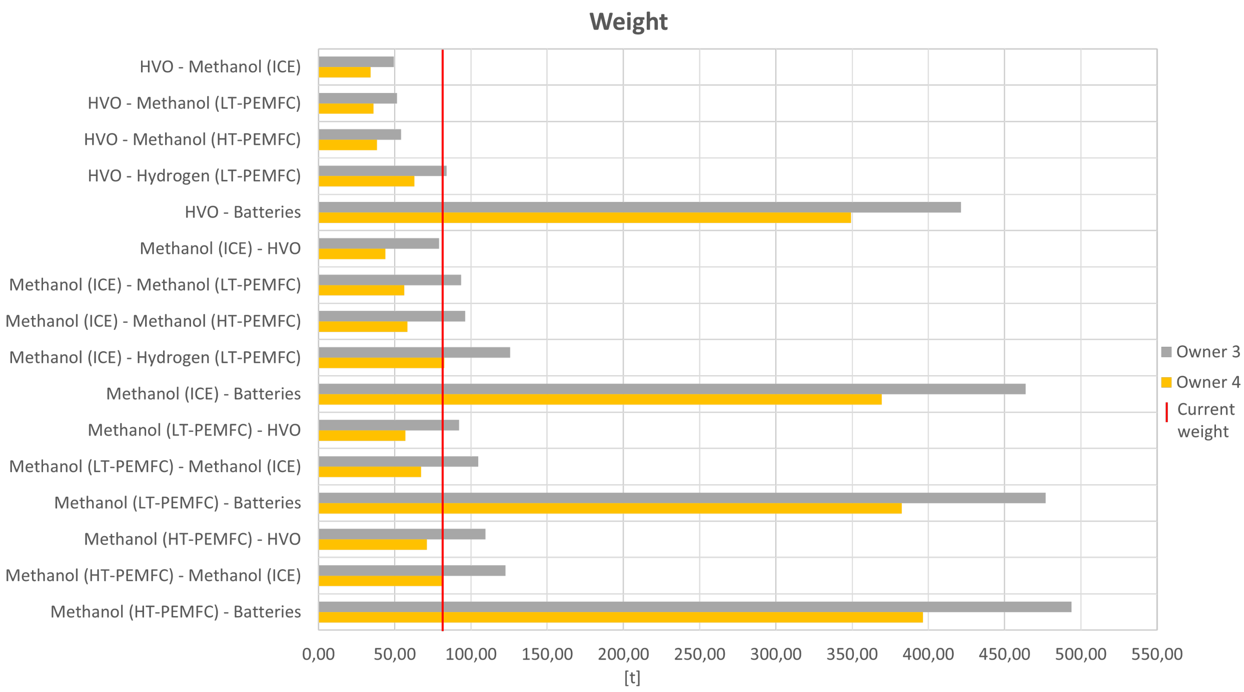

Figure 5.25: Yacht B weight of hybrid configurations for Owner 3 and 4

Analyzing the results obtained, it can be seen that compared to the case of Owner 2, for Owner 3, the solution involving an ICE methanol for propulsion and ICE HVO for hotel load is technically feasible. Configurations with ICE methanol for propulsion and LT-PEMFC or HT-PEMFC methanol are not considered feasible due to their associated weight being too high. The biggest differences between Yacht A and Yacht B for hybrid configurations can be observed in the case of Owner 4. The HVO configuration for propulsion and Hydrogen LT-PEMFC for the hotel load is not feasible due to the excessive volume required, and the same is true for the combination of methanol HT-PEMFC + Methanol ICE. Consequently, the following five combinations become feasible when considering the Owner 4 case instead of Owner 3.

- Methanol (ICE) - Methanol (LT-PEMFC)
- Methanol (ICE) - Methanol (HT-PEMFC)
- Methanol (LT-PEMFC) - HVO
- Methanol (LT-PEMFC) - Methanol (ICE)
- Methanol (HT-PEMFC) - HVO

In conclusion, Table 5.10 summarizes which configurations are technically feasible for Yacht B, including both single fuel and hybrid ones for all 4 owner cases. The red cells indicate that the configuration for that particular owner is not feasible, the yellow cells that considering the tolerance margin of 5% on volume and 10% on weight it can be considered technically feasible, and the green cells indicate technical feasibility even without tolerance margin. Finally the dark red cells are configurations that were technically feasible for Yacht A but not for Yacht B.

Table 5.10: Yacht B technical feasibility summary

Propulsion	Hotel load	Owner 1	Owner 2	Owner 3	Owner 4
HVO	HVO	Yellow	Green	Green	Green
Methanol (ICE)	Methanol (ICE)	Red	Red	Dark red	Green
Methanol (LT-PEMFC)	Methanol (LT-PEMFC)	Red	Red	Red	Yellow
Methanol (HT-PEMFC)	Methanol (HT-PEMFC)	Red	Red	Red	Dark red
Hydrogen (LT-PEMFC)	Hydrogen (LT-PEMFC)	Red	Red	Red	Red
Batteries	Batteries	Red	Red	Red	Red
HVO	Methanol (ICE)	Red	Green	Green	Green
HVO	Methanol (LT-PEMFC)	Red	Green	Green	Green
HVO	Methanol (HT-PEMFC)	Red	Green	Green	Green
HVO	Hydrogen (LT-PEMFC)	Red	Red	Red	Dark red
HVO	Batteries	Red	Red	Red	Red
Methanol (ICE)	HVO	Red	Red	Green	Green
Methanol (ICE)	Methanol (LT-PEMFC)	Red	Red	Red	Green
Methanol (ICE)	Methanol (HT-PEMFC)	Red	Red	Red	Green
Methanol (ICE)	Hydrogen (LT-PEMFC)	Red	Red	Red	Red
Methanol (ICE)	Batteries	Red	Red	Red	Red
Methanol (LT-PEMFC)	HVO	Red	Red	Red	Green
Methanol (LT-PEMFC)	Methanol (ICE)	Red	Red	Red	Green
Methanol (LT-PEMFC)	Batteries	Red	Red	Red	Red
Methanol (HT-PEMFC)	HVO	Red	Red	Red	Green
Methanol (HT-PEMFC)	Methanol (ICE)	Red	Red	Red	Dark red
Methanol (HT-PEMFC)	Batteries	Red	Red	Red	Red

Green: Technically feasible
Yellow: Technically feasible with tolerance margin
Red: Technically not feasible
Dark red: Technically not feasible for Yacht B, but technically feasible for Yacht A

The single fuel methanol configurations with (ICE), the one with (HT-PEMFC), the hybrid HVO + hydrogen and also the methanol (HT-PEMFC) + methanol (ICE) one represented in dark red are not technically feasible for Yacht B in contrast to Yacht A. The single fuel methanol (LT-PEMFC) configuration is, however, also feasible for Yacht B due to the tolerance margin, evidenced by the yellow colour of the cell. It is interesting to note that all cells that change colour compared to Table 5.6 referred to Yacht A are for Owner 3 and 4. This can be justified by the proportionally different energy demand reduction between the two yachts explained in subsection 5.1.1.

As for Yacht A, Table 5.10 shows that none of the configurations including batteries is feasible. This does not mean that batteries cannot be on board, but rather that they are not able to guarantee the hotel load nor the propulsion power required to achieve the design range at a certain design speed. Regarding hydrogen, there are no feasible configurations. Just like with batteries, this does not mean that hydrogen cannot be used as an energy carrier for Yacht B, but rather that it would not be possible to meet the energy requirements not only for propulsion but also for the hotel load within the design range. Despite the fact that the combination of ICE with HVO and hydrogen LT-PEMFC for Owner 4 has an acceptable weight, the volume is 47% larger than the available one, making the result unacceptable.

5.3.2. Emissions

Just like for Yacht A, CO_2 yearly emissions are calculated both on a TTW and overall WTW basis, as well as NO_x and PM emissions for the configurations that have been deemed technically feasible. Figure 5.26 shows the reductions in tons of CO_2 emitted on a WTW basis for the various configurations compared to the current diesel one, represented by the vertical red line. Bar chart representing CO_2 TTW emissions results and table listing percentage emission reduction of both CO_2 WTW and TTW values are included in Appendix A. Note that where only the term methanol appears in tables or graphs, it means fossil methanol. Furthermore, the reason why not all the 4 Owner cases are reported for some configurations is due to the fact that the missing cases were previously evaluated not technically feasible. The current annual CO_2 TTW and WTW emissions of the MGO are respectively 357 [t] and 424 [t].

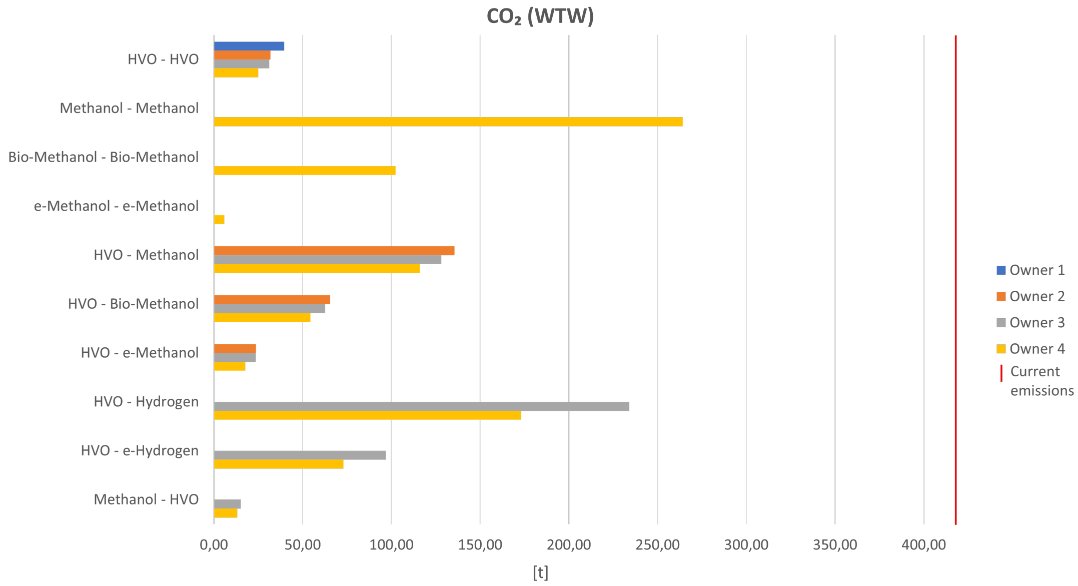

Figure 5.26: Yacht B CO_2 WTW emissions compared to the current ICE configuration at MGO

As for Yacht A, results show that CO_2 WTW emission reductions achieved are significant. Single fuel HVO WTW CO_2 emission values allow a reduction exceeding 90% even in the case of Owner 1. It's worth noting that considering only TTW emissions, there are no differences between the various types of methanol and hydrogen. Regarding CO_2 WTW emissions, excluding configurations that involve the use of fossil methanol for propulsion, reductions exceed 65% for all 4 owner cases.

NO_x and PM TTW percentage emission reductions achieved by the potential configurations compared to the current MGO configuration are presented respectively in the bar charts of Figure 5.27 and Figure 5.28. The current annual emission values for MGO are 4.75 [t] of NO_x and 0.204 [t] of PM, considered as reference. The percentage NO_x and PM emission variation respect to MGO are shown in Appendix A.

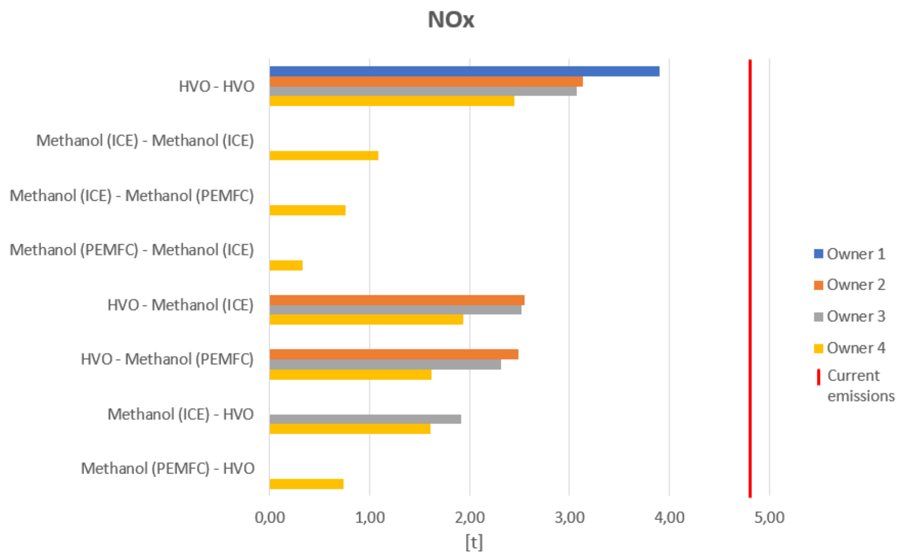

Figure 5.27: Yacht B NO_x emissions compared to the current ICE configuration at MGO

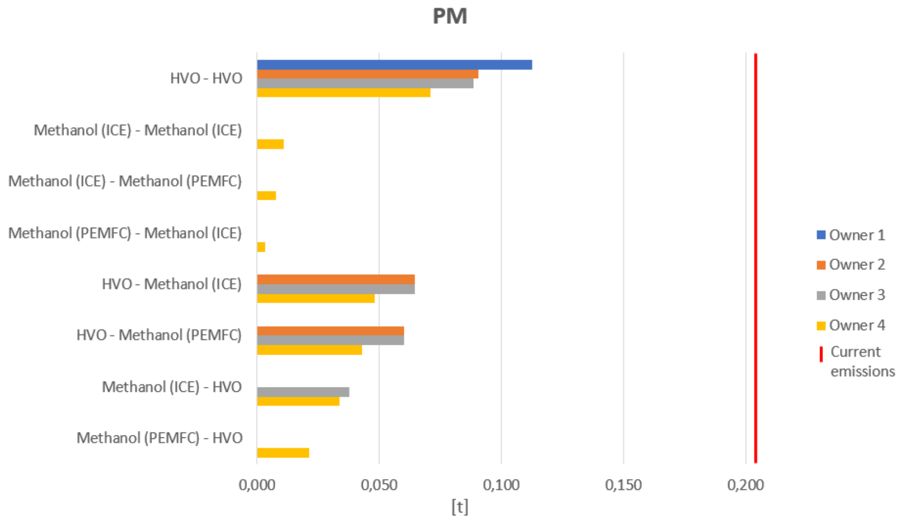

Figure 5.28: Yacht B PM emissions compared to the current ICE configuration at MGO

From the results obtained, it can be observed that on average, the percentage reductions in PM emissions are higher than those for NO_x. Among the configurations presented as technically feasible, the one with the lowest NOx and PM emissions is the methanol (PEMFC) + methanol (ICE) configuration, with reductions of over 90% compared to MGO. In the case of Owner 1, HVO results in an 18% reduction in NO_x and a significant 45% reduction in PM emissions, with values reaching 48% and 65% respectively in the case of Owner 4.

In general, it can be concluded that in terms of emissions, Yacht A and Yacht B are aligned proportionally. In fact, by observing the tables reporting the percentage reduction of different emissions, each energy configuration for the same owner case considered deviates by a maximum of 2% when transitioning from Yacht A to Yacht B.

5.3.3. Refit timeframe

The docking timeframe for Yacht B remains unchanged compared to Yacht A, with the exception that the HVO - Hydrogen configuration is absent in this case as it is not considered technically feasible. There are no variations for installation time between the two yachts as for the purpose of this thesis, after discussions with an expert project manager from Huisfit who has over 20 years of experience in yacht refits, differences in installing larger energy converters or bigger storage tanks have been neglected among yachts of diverse sizes. Table 5.11 shows the obtained results of the refit timeframe calculated on a monthly basis for the various configurations and across different owner cases.

Table 5.11: Yacht B docking time in months required for different energy configurations depending on owner profiles

Propulsion	Hotel load	**Owner 1** [months]	**Owner 2** [months]	**Owner 3** [months]	**Owner 4** [months]
HVO	HVO	1	3	3	3
Methanol (ICE)	Methanol (ICE)	6	6	6	6
HVO	Methanol (ICE)	4	4	4	4
Methanol (ICE)	HVO	5	5	5	5

The explanation for these values is also the same as in the case of Yacht A and is therefore not repeated in this section.

5.3.4. Economic feasibility

As for Yacht A the economic aspect is also considered to evaluate the trade-off of a sustainable refit. In order to do so, CapEx, OpEx, and TCO associated with various possible configurations are analysed. Since CapEx is not dependent on fuel cost variations and the possible introduction of a carbon tax, the results related to them will be presented first. Subsequently, the current scenario and the three possible future scenarios presented in Chapter 4 will be analyzed, and for each of them, the respective OpEx and TCO of each energy configuration for each owner case will be examined.

CapEx

The yearly CapEx can be obtained by considering the refit cost, which is the cost of the various systems that the different configurations install, and taking into account the lifetime of these systems, as described in Chapter 4 in Table 4.7. As for Yacht A, in order to make a coherent and meaningful comparison with the current configuration in terms of CapEx and especially TCO, it is assumed that the sailing yacht analyzed during a non-sustainable refit still replaces the diesel ICE and changes the current sails with new sails of the same type. This non-sustainable refit would have a total cost of €1.663.800 and an yearly CapEx cost of €305.700. The cost of replacing the sails in the current case, and therefore also for Owners 1 and 2, is €928.800, with corresponding yearly CapEx of €232.200 given the considered lifetime of 4 years. On the other hand, the cost of delivery sails is lower, at €774.000, with yearly CapEx of €154.800, since the considered lifetime is higher and equal to 5 years.

Figure 5.29 shows a bar chart representing the refit cost of the technically feasible configurations for the 4 owner cases. It should be noted that in this chart no distinction is made according to the type of methanol and hydrogen as they only influence OpEx and TCO and not CapEx. The refit cost and yearly CapEx results are presented as tables in Appendix A.

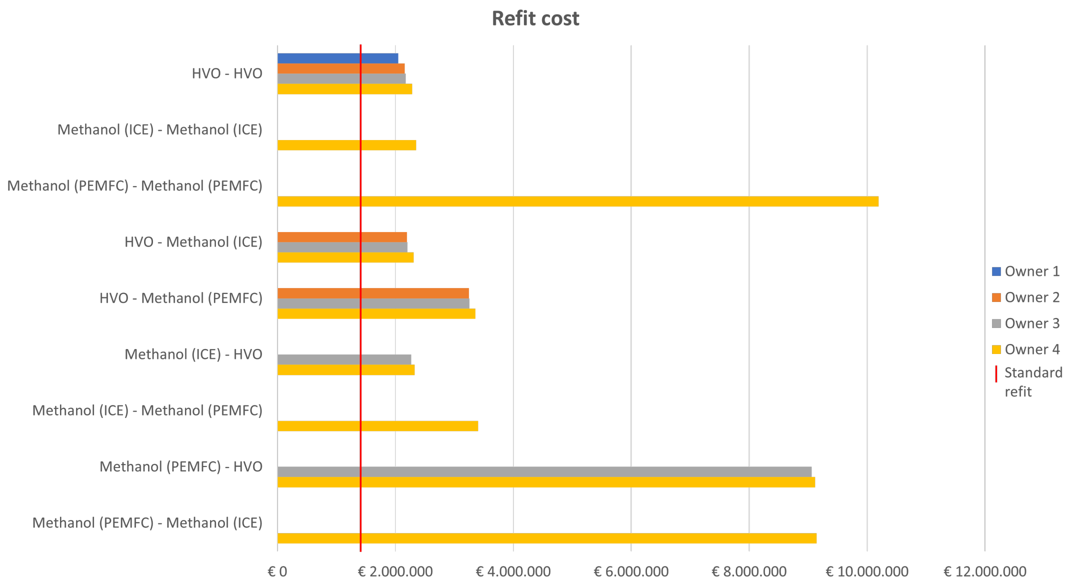

Figure 5.29: Yacht B sustainable refit cost compared to conventional refit

These results show that, as expected, the most expensive configuration in terms of CapEx is the single fuel methanol with PEMFC as energy converters. This solution indeed exceeds €10 million for Owner 4, followed by the hybrid methanol PEMFC for propulsion and methanol ICE for hotel load, with a cost of over €9 million for Owner 4. As for Yacht A, the solution closest to the cost of a conventional refit is single fuel HVO in the case of Owner 1, since the cost of the energy converters is the same and the only difference is the cost of the DX system for HVAC.

OpEx & TCO

This section presents OpEx and TCO results obtained for the Current scenario and each of the three scenarios projected for 2030 that have already been presented and described for Yacht A.

Current scenario

The Current scenario represents the OpEx and TCO that would be incurred if the sustainable refit were done today, with current fuel prices and no carbon tax. Figure 5.30 represents the OpEx, while Figure 5.31 represents the TCO obtained by adding OpEx with the respective CapEx listed in Table A.11 and Table A.6. The vertical red lines represent the cost of MGO and the TCO that would be incurred if a standard refit were performed, replacing diesel ICEs and sails. The TCO percentage variation compared to the case where the yacht continues to use MGO and undergoes a conventional refit is reported in Appendix A. The reference values for OpEx and TCO are €61.745 and €367.445, respectively.

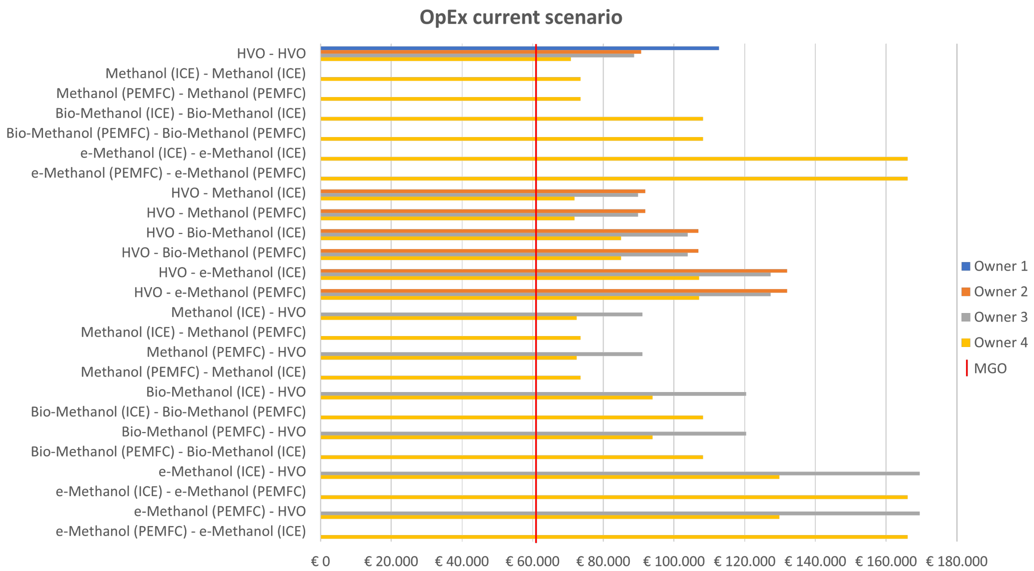

Figure 5.30: Yacht B OpEx of possible configurations compared to MGO for current scenario

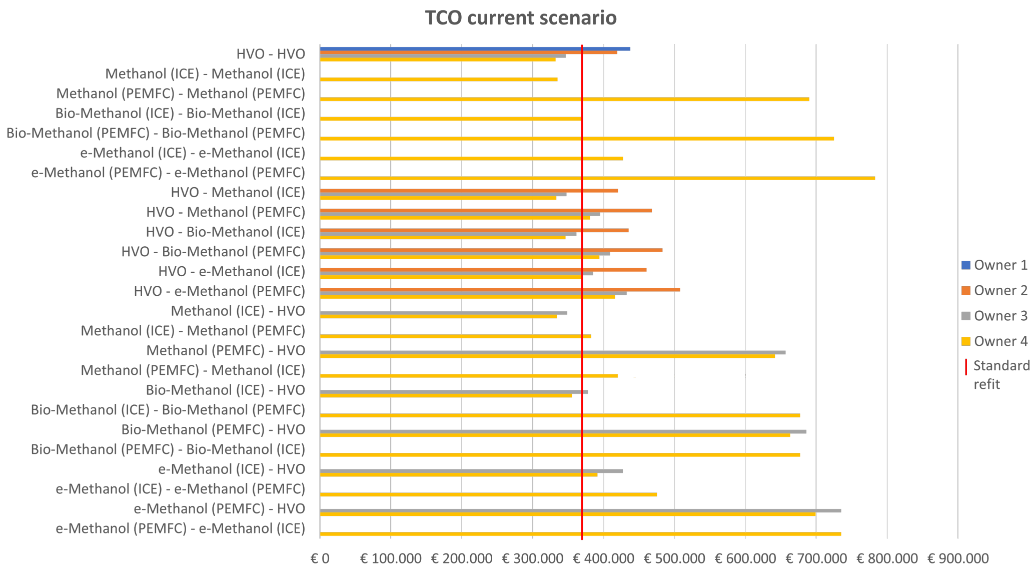

Figure 5.31: Yacht B TCO of possible configurations compared to MGO for current scenario

From these graphs, it can be noticed how the yearly CapEx significantly impacts the TCO, reducing the variation among the different types of methanol and hydrogen compared to OpEx, assuming the same energy converters. The reduction in TCO generally observed when transitioning from Owner 2 to Owner 3 is influenced by both lower OpEx and reduced CapEx. The latter are obtained due to the longer lifetime of the delivery sails compared to the standard sails currently used and considered for Owner 2. Furthermore, even though yearly CapEx increases from Owner 3 to 4, the TCO decreases further because the reduction in OpEx outweighs the increase in CapEx. All other results are as expected and in line with the fuel costs reported in Table 4.8 and the CapEx from Table A.11 and Table A.12.

Scenario 1
Regarding the future scenarios, Scenario 1 is the most pessimistic for alternative fuels integration, with the highest expected fuel costs and without a carbon tax, that would increase the cost of diesel. MGO has indeed the highest CO_2 emissions among the alternative fuels considered in this thesis, and consequently, the carbon tax would reduce the cost gap between diesel and alternative fuels. Figure 5.32 shows the OpEx results obtained, while Figure 5.33 shows the TCO. The TCO percentage variation compared to the case where the yacht continues to use MGO and undergoes a conventional refit is reported in Appendix A. The reference values for OpEx and TCO are €88.296 and €393.996, respectively.

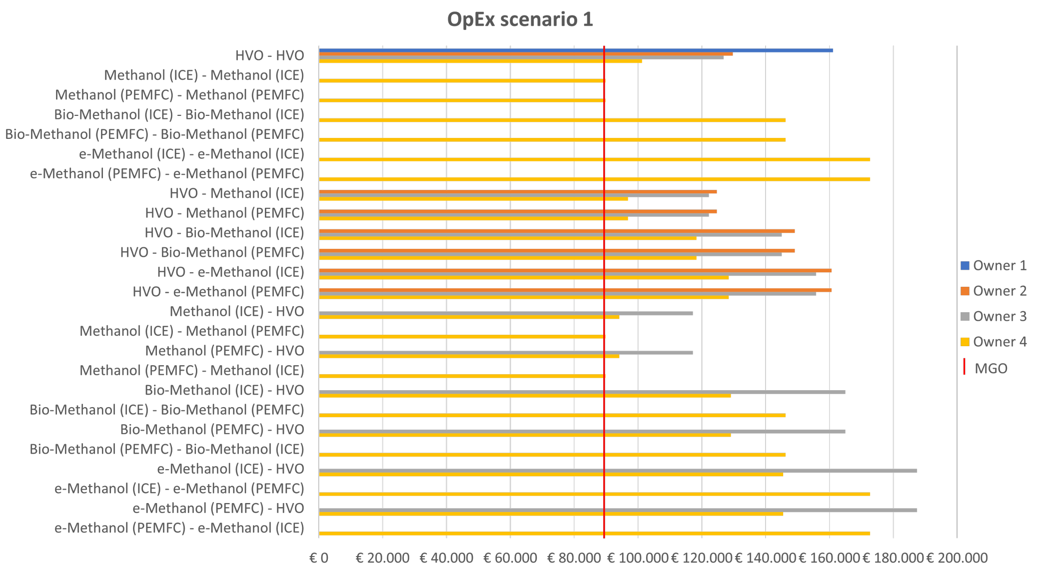

Figure 5.32: Yacht B OpEx of possible configurations compared to MGO for scenario 1

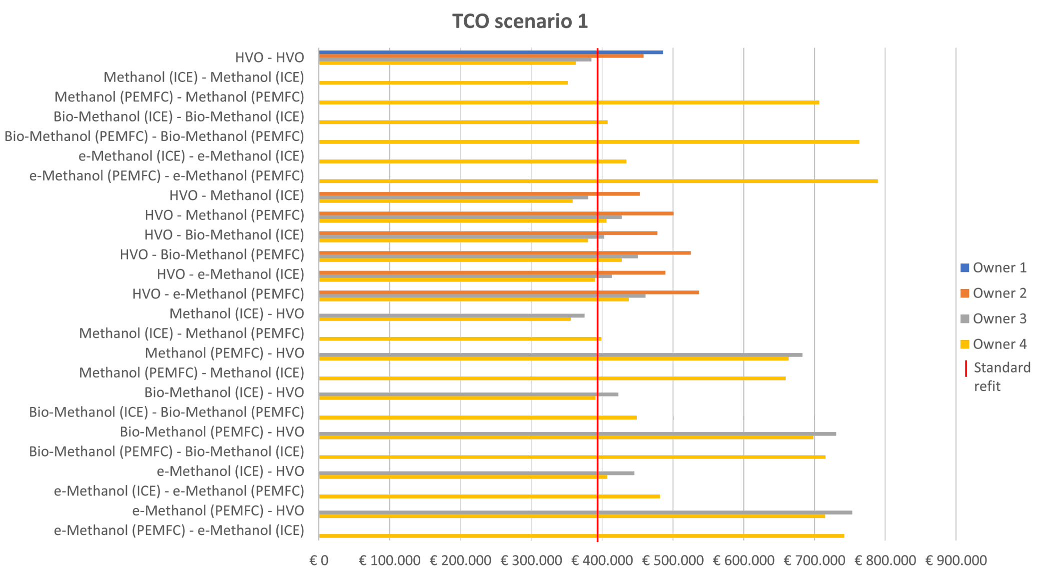

Figure 5.33: Yacht B TCO of possible configurations compared to MGO for scenario 1

The fuel costs vary in accordance with Figure 4.10, and the TCO compared to the Current scenario increases only due to higher OpEx. The percentage reductions in TCO achieved for each energy configuration when transitioning from Owner 2 to Owner 3 and then from Owner 3 to Owner 4 are due to the same reasons described for the Current scenario.

Scenario 2

Scenario 2 considers the lowest fuel costs of the projections for 2030 and also includes a carbon tax of 100 [€/t] for each tonne of CO_2 emitted. Figure 5.34 shows the OpEx results obtained, while Figure 5.35 shows the TCO. The TCO percentage variation compared to the case where the yacht continues to use MGO and undergoes a conventional refit is reported in Appendix A. The reference values for OpEx and TCO are €83.214 and €388.914, respectively.

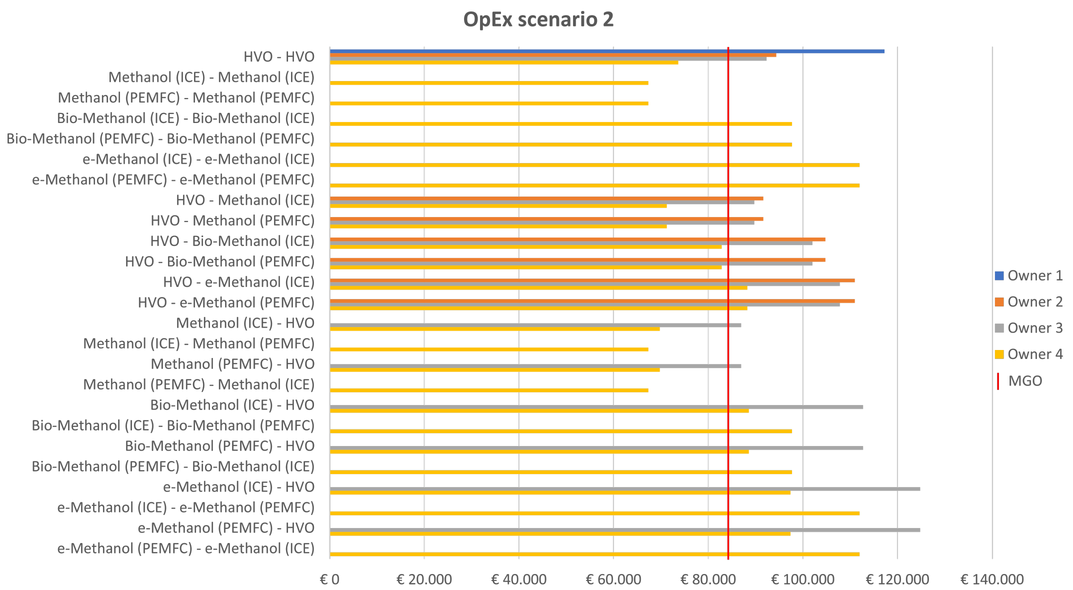

Figure 5.34: Yacht B OpEx of possible configurations compared to MGO for scenario 2

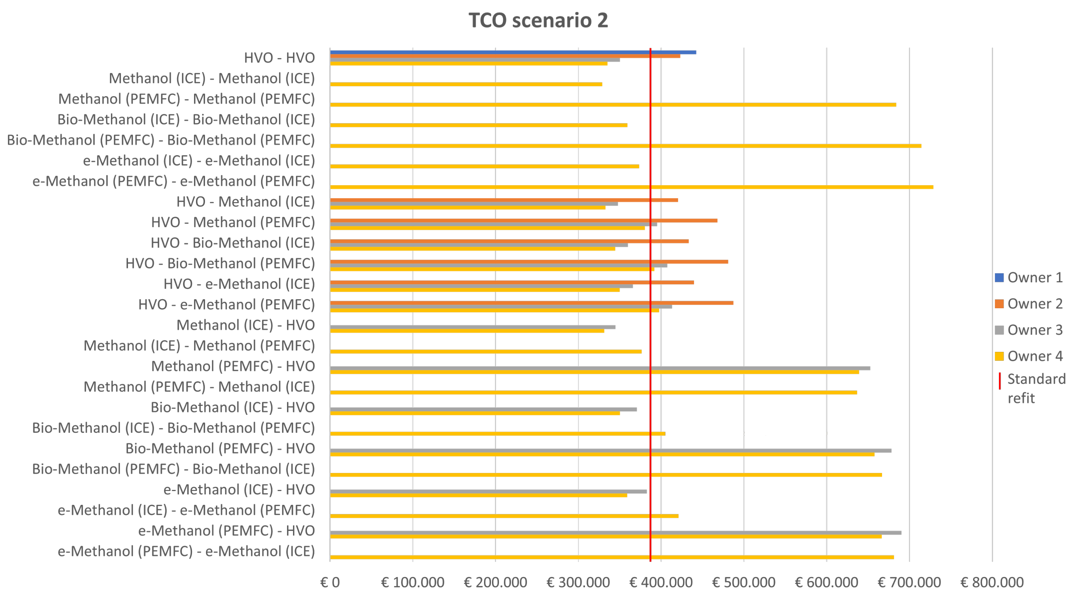

Figure 5.35: Yacht B TCO of possible configurations compared to MGO for scenario 2

In Scenario 2, the OpEx is lower than both the Current scenario and Scenario 1, while due to the introduction of the carbon tax, the gap between MGO and alternative fuels diminishes, resulting in a TCO for several configurations lower than that associated with current MGO. The percentage reductions in TCO achieved for each energy configuration when transitioning from Owner 2 to Owner 3 and then from Owner 3 to Owner 4 are due to the same reasons described for the Current scenario.

Scenario 3

Finally, Scenario 3 is the most optimistic in terms of transitioning from conventional diesel to alternative fuels. It indeed considers the lowest fuel prices from the 2030 projections and additionally doubles the carbon tax compared to Scenario 2, reaching 200 [€/t]. Figure 5.36 shows the OpEx results obtained, while Figure 5.37 shows the TCO. The TCO percentage variation compared to the case where the yacht continues to use MGO and undergoes a conventional refit is reported in Appendix A. The reference values for OpEx and TCO are €118.883 and €424.583, respectively.

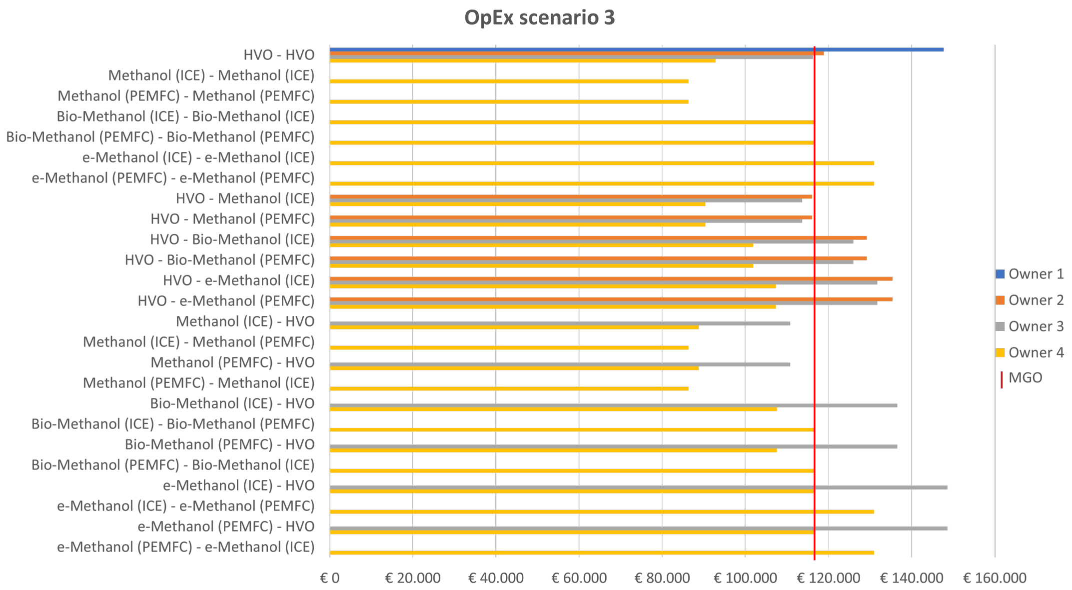

Figure 5.36: Yacht B OpEx of possible configurations compared to MGO for scenario 3

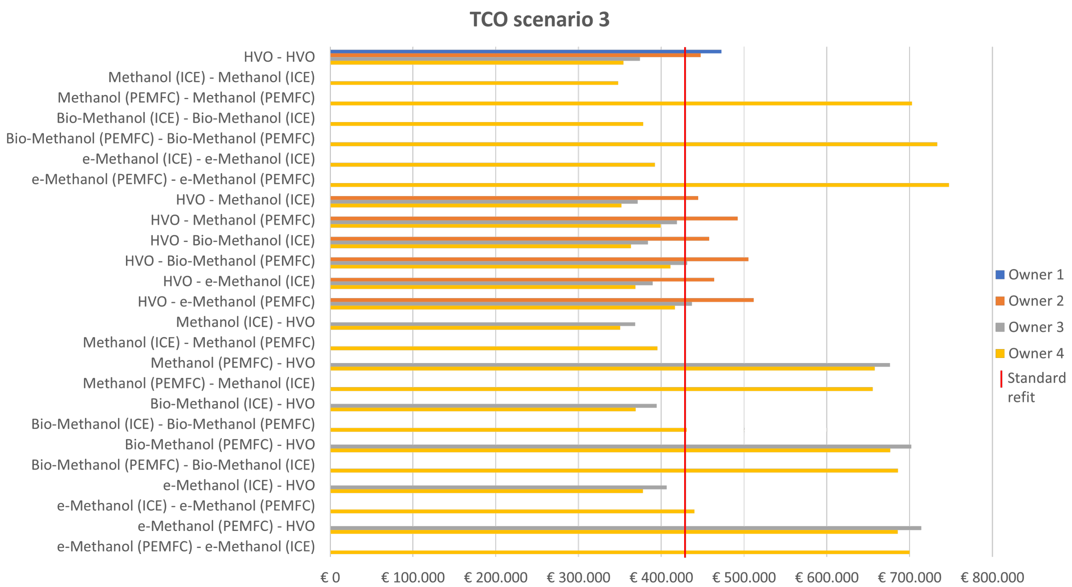

Figure 5.37: Yacht B TCO of possible configurations compared to MGO for scenario 3

Observing the results obtained in this scenario and comparing them with those of Scenario 2, it can be noted how the carbon tax contributes to reducing the cost gap between configurations using MGO as the energy carrier and others using alternative fuels. The only configurations that, despite considering the Owner 4 profile, remain with a TCO higher than that of a standard refit are those using PEMFC for propulsion, regardless of the converter for the hotel load, and e-methanol ICE + e-methanol PEMFC. The percentage reductions in TCO achieved for each energy configuration when transitioning from Owner 2 to Owner 3 and then from Owner 3 to Owner 4 are due to the same reasons described for the Current scenario.

5.4. Conclusion on results

In conclusion of this section, a concise and effective response to the following subquestion is provided:

"How do the volumes and weights of alternative energy carriers and converters vary in sailing yachts compared to the current energy configuration considering possible energy demand reduction? How do emissions and costs change?"

Chapter 5 presents the results obtained by applying the assessment model described in chapter 4 to two Royal Huisman sailing yachts of different sizes. Yacht A has a GT below 500, while Yacht B exceeds 1000 GT. The purpose of analyzing two different yachts is to demonstrate the model's applicability to multiple yachts and analyze any impact differences, particularly in terms of technical feasibility. For each yacht, four hypothetical owner profiles have been identified, ranging from Owner 1, who is less inclined to make changes to reduce onboard energy demand, to Owner 4, who is more inclined to make operational changes and install solar panels and hydrogenerators to significantly reduce energy demand. This choice was made because all the alternative fuels considered have lower values of both volumetric and gravimetric energy density compared to the diesel currently used [41]. Therefore, to make a sustainable refit technically feasible, it is necessary to implement modifications aimed at reducing onboard energy demand or converting non-technical spaces into storage tanks or an engine room since hull extension has not been considered a viable option for a sailing superyacht.

Given the assumption that for a configuration to be technically feasible, it must be able to provide the required energy for propulsion and hotel load in the case of the design range and design speed (with appropriate modifications based on owner cases), some solutions are not feasible even in the case of compromises that Owner 4 is willing to accept. These include batteries for both yachts considered and hydrogen for Yacht B. This does not mean that batteries or hydrogen cannot be present on board an existing Royal Huisman sailing yacht, but rather that they are not able to meet the energy requirement of the longest crossing considered.

In general, results have shown that for a sustainable refit of a sailing yacht, integrating alternative energy carriers and converters on board is not feasible unless the energy required is reduced or the internal volume dedicated to the storage of energy carriers and converters is increased. For both Yacht A and Yacht B, the only feasible option obtained in the case of Owner 1 is a single-fuel solution with HVO for both propulsion and hotel load. This solution allows for a reduction of approximately 15% in CO_2 TTW emissions and about 90% in CO_2 WTW emissions, 18% in NO_x emissions, and 45% in PM emissions compared to the current configuration with MGO. These are significant results, especially for CO_2 WTW and PM emissions. Furthermore, the additional docking time would be just a month. Regarding costs, the increase in TCO, compared to the case of a standard refit that replaces the current engines with new diesel ICE engines and install new identical sails, ranges from 11% to 26%, depending on the future scenario considered.

Worth noting is the fact that configurations involving ICE with HVO for propulsion and methanol PEMFC or methanol ICE for the hotel load are technically feasible for Owner 2. The reduction in energy demand associated with this profile does not entail substantial changes in terms of operational profile and internal layout, unlike Owners 3 and 4. Assuming that the yacht will motor sail for 50% of the ocean crossing reflects how such yachts typically navigate during long sailings. Additionally, reducing speed by just one knot and the range by 5% are minor adjustments. The solar panels occupy only 10% of the main deck area, and there is no change in the type of sails, nor is a crew cabin converted into technical space. These HVO + methanol energy configurations, in terms of TTW emissions, would reduce CO_2 emissions by approximately 32%, NO_x by 47%, and PM by 69% compared to the current MGO configuration of the yachts. Regarding WTW emissions, CO_2 emissions depend on the type of methanol considered: 68% for grey methanol, 85% for bio-methanol, and 94% for e-methanol. The time required for installing the solutions envisioned for this configuration is 4 months. However, TCO depends on both the type of methanol and the choice of PEMFC or ICE. The percentage increase compared to the current configuration with MGO as the energy carrier, where a standard refit includes the replacement of energy converters and sails, ranges from approximately 11% for ICE with fossil methanol in Scenario 2 to 39% for e-methanol PEMFC in Scenario 1.

On the other hand, thanks to compromises in terms of energy demand reduction and internal layout changes applied to Owner 4 case, there are many technically feasible energy configurations. Generally, the only configurations among these associated with a TCO increase of over 50% compared to the current configuration, with a maximum value reaching about double in the case of the single-fuel e-methanol PEMFC configuration in Scenario 1 for Yacht B, are those using PEMFC for propulsion. Indeed, this energy converter has a much higher cost than ICE, as reported in Table 4.6 of Chapter 4. The refit costs for such configurations are over €3 million for Yacht A and over €9 million for Yacht B. The related docking time is over 5 months, while emissions are not significantly different from the HVO + methanol configurations described earlier. Considering Owner 4 case for both these configurations, the reductions in CO_2 TTW emissions vary by only 1%, while for CO_2 WTW, by 2% and are even higher for configurations with PEMFC methanol rather than HVO for propulsion, regardless of the energy carrier and converter used for the hotel load. The gap in reductions in NO_x and PM emissions compared to MGO remain below 18%. The differences in terms of compromises required to make configurations using methanol for propulsion compared to HVO + methanol are therefore significant, and the TCO, especially when the considered energy converter is PEMFC, is considerably higher, despite a less substantial reduction in emissions.

5.4.1. Yacht A and Yacht B impact differences

Finally, regarding the differences between the results obtained for Yacht A and Yacht B in terms of technical feasibility, it is worth noting that the energy configuration of ICE with HVO for propulsion and PEMFC with hydrogen for the hotel load is feasible only for Yacht A and not for Yacht B. Being the only hydrogen configuration feasible for Yacht A, it follows that no hydrogen configuration for Yacht B meets the energy requirement of the longest crossing considered. Despite Yacht B having a GT of more than double that of Yacht A, there is no extra space available to accommodate the additional volume required by alternative energy carriers and converters, as it is also a sailing yacht with limited interior spaces. However, the feasibility difference between Yacht A and Yacht B is due to the fact that the crew cabin that Owners 3 and 4 are willing to convert into technical space for energy carriers and converters is always 8 [m^3] for both yachts. Therefore, this volume is proportionally different for a yacht under 500 GT and one that exceeds 1000 GT. Furthermore, this difference can be justified by the varying impact that a 1 or 2 knots speed reduction has on different yachts with different power-to-speed curves. Additionally, the hydrogenerator installed on both yachts is the same with the same power output, meaning it will have a proportionally greater effect on energy demand reduction for Yacht A than for Yacht B.

The percentage reductions in CO_2 TTW, CO_2 WTW, NO_x, and PM emissions are aligned and do not differ by more than 2%. The required docking time for a selected configuration is the same for the two yachts. Indeed, there are no variations for installation time between the two yachts as differences in installing larger energy converters or bigger storage tanks are neglected among diverse yachts. Finally, the TCO for both yachts follows the same trend, albeit with some differences when compared to the current diesel configuration present on each yacht. These percentage differences remain below 3% for Owner 1 and 2 scenarios, while they reach up to 18% for Owner 3 and 4 scenarios. This difference is due to Yacht A and Yacht B variations in percentage reductions with respect to the current energy demand configuration.

6
Verification and Validation

The assessment model built in this thesis needs to be verified and validated to ensure that it is implemented correctly, accurately represents the intended calculations, and to prove that its outputs are realistic and align with real-world data and outcomes. In modeling literature, verification refers to internal consistency, whereas validation refers to justification of knowledge claims [177]. This chapter attempts to answer the following subquestion:

”How can the assessment model developed to analyze the impact of sustainable solutions on sailing yachts be validated and verified?”

Initially, focus will be placed on model verification, followed by its validation to increase the credibility of the results.

6.1. Model verification

Chapter 4 explained all the calculations and procedures followed to observe the trade-offs made by the different combinations of energy carriers and energy converters that can be installed when refitting a sailing yacht to increase energy efficiency and minimize emissions, ensuring future sustainability. Due to the high number of equations linking many parameters and the reasoning behind certain values, it is important to verify the model to ensure that it is implemented correctly. This is achieved by inputting various parameters known to lead to specific outcomes, and tested cases and their related results are presented in Table 6.1. Initially, the model is tested using the current state scenario, which involves MGO-powered ICE. A comparison is made to determine if the obtained values align with the expected outcomes. All expected outcomes, as outlined in Table 6.1, aligned with the obtained results, demonstrating that the model operated as expected and thus has been successfully verified.

Table 6.1: Model verification comparing the results obtained with expectations [41, 33]

Trial condition	Obtained result	Expectation
Yacht A MGO storage volume	30 m^3	Confirmed
Yacht B MGO storage volume	85 m^3	Confirmed
Single fuel methanol configuration storage volume compared to current MGO configuration for both Yacht A and Yacht B Owner 1 case	2.3 times higher	Confirmed
Single fuel hydrogen configuration storage volume including tanks compared to current MGO configuration for both Yacht A and Yacht B Owner 1 case	14 times higher	Confirmed
HVO ICE + hydrogen LT-PEMFC technical feasibility	Feasible for Yacht A but not for Yacht B	Confirmed
Capacity of the batteries to meet the energy demand of the hotel load for the design range	Not feasible regardless of the configuration selected for propulsion	Confirmed
CO2 WTW emission reduction for single fuel HVO configuration	>90% for each Owner case	Confirmed
Total refit cost single fuel methanol ICE for Yacht B Owner 4 case	€2.35 million	Confirmed
Price of bio-methanol increased by 30% in the high fuel cost scenario of 2030 without carbon tax	OpEx increase by 30% for single fuel bio-methanol configuration for a selected owner case	Confirmed

6.2. Model validation

Validation of engineering research is typically rooted in the scientific inquiry tradition, which primarily relies on logical induction and/or deduction [177]. However, there are various processes that can be implemented to validate a research design method. Logical empiricist validation is a strictly formal, algorithmic, reductionist, and 'confrontational' process, where new knowledge is either true or false. Validation then becomes a matter of formal accuracy rather than practical use. This approach is suitable for closed problems that have clear right or wrong answers, such as mathematical expressions or algorithms. On the other hand, relativist validation is a semi-formal and communicative process, viewing validation as a gradual process of building confidence in the usefulness of new knowledge relative to a specific purpose. This approach is suitable for open problems, where new knowledge is connected with heuristics and non-precise representations [177].

This thesis uses the 'Validation Square', a relativist validation method which is represented in Figure 6.1. This approach provides a framework for validating internal consistency as well as external relevance for specific instances, to establish confidence in its general usefulness concerning a particular purpose. As can be seen from the grey box in Figure 6.1, the Validation Square can be divided into Structural validity and Performance validity, and each of these can be further divided into empirical and theoretical validity. The validation method is defined by the following six steps:

1. Accepting the individual constructs constituting the method;
2. Accepting the internal consistency of the way the constructs are put together in the method;
3. Accepting the appropriateness of the example problems that will be used to verify the performance of the method;
4. Accepting that the outcome of the method is useful with respect to the initial purpose for some chosen example problem(s);
5. Accepting that the achieved usefulness is linked to applying the method;
6. Accepting that the usefulness of the method is beyond the case studies.

As can be seen from the grey box in Figure 6.1, the first three belong to structural validation, while the last three belong to performance validation.

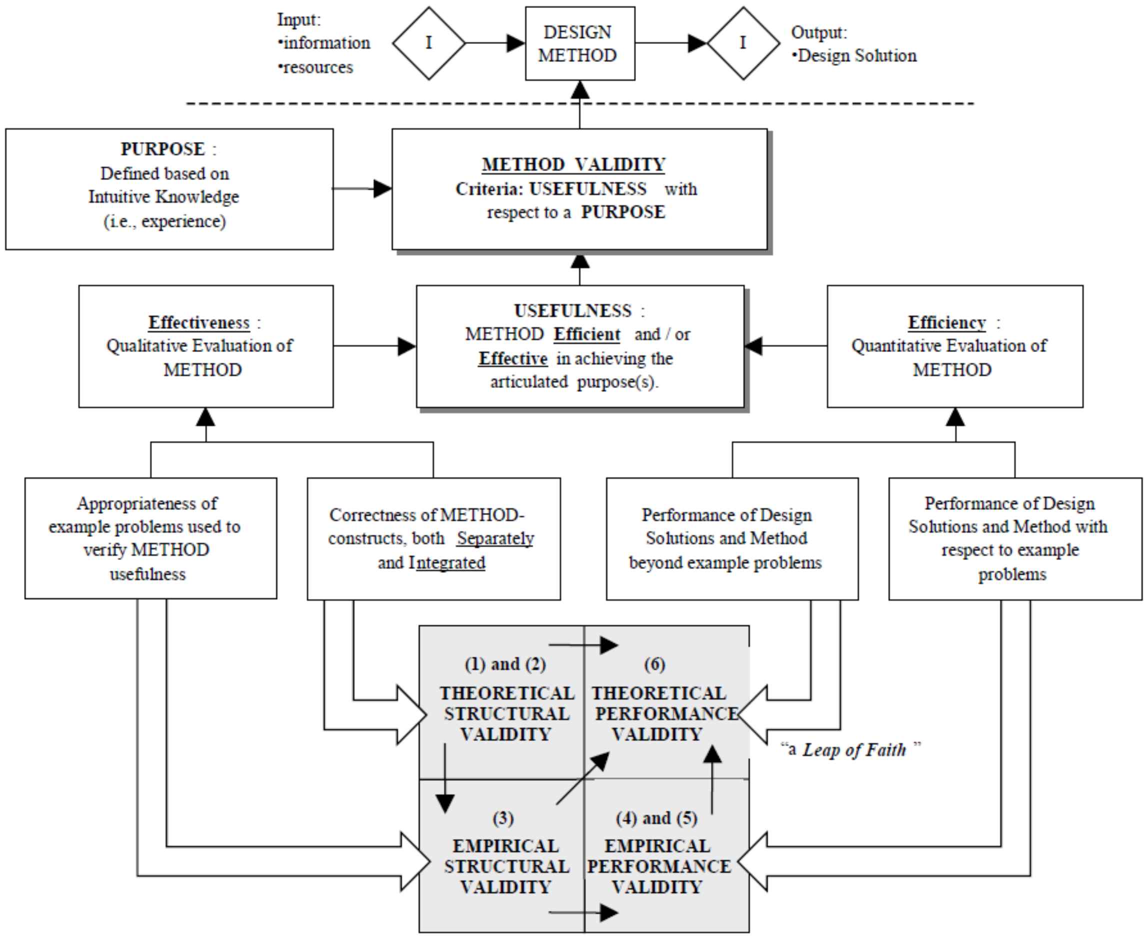

Figure 6.1: Design method validation by using the Validation Square [177]

6.2.1. Structural validation

This section analyses the three steps that being effective embodies, as can be seen in Figure 6.1. Initially, attention will be focused on accepting the individual constructs constituting the method, then on accepting the internal consistency of the way the constructs are put together in the method, and finally on accepting the appropriateness of the example problems that will be used to verify the performance of the method.

Individual constructs validity

The first step concerns accepting the individual constructs constituting the method. In Chapter 4, the structure of the assessment model was presented, and the calculations performed were explained. In order to demonstrate the appropriateness of the steps taken, they are explained here and briefly reiterated.

- **Required volume & weight energy carrier:** The starting point to obtain the volume and weight associated with the energy carriers is the required energy [83]. It is derived by considering the average power needed for both propulsion and hotel load, obtained from current and internal company data. The associated time depends on the design range and speed, both of which are known characteristics for each yacht. As for the efficiencies of the energy converters, values were chosen based on data provided by manufacturers [128, 129, 124, 155]. By simply dividing the energy by the volumetric or gravimetric energy density of the energy carrier in question, the volume or weight is obtained, respectively. The energy density values were obtained from MARIN [41], ensuring the validity of the results. Although well-founded studies are used, some uncertainty cannot be avoided. Regarding the hydrogen storage tanks, real values provided by manufacturers are used [178], while for the cofferdams required by methanol, a solution featuring a sandwich arrangement with a 25 mm polymer layer between two steel panels has been adopted [70]. This solution has only received approval in principle and has not yet been installed on any yacht. However, the solution appears promising and would address many of the issues related to installing cofferdams according to IGF code around the relatively small tanks of Royal Huisman sailing yachts [64].

- **Required volume & weight energy converter:** The dimensions, weight, and power characteristics of the energy converters considered in this thesis are provided by manufacturers [128, 129, 124, 155], allowing for the determination of the [m³/kW] and [t/kW] associated with each converter. At this point, their volume and weight were determined by multiplying the converter's relative volume and weight by the total installed power, which is not altered compared to the configuration with a diesel ICE since the maximum speed is not a parameter modified by the model. Consequently, this contributes to ensuring the validity of the results.

- **Energy demand reduction:** The model presents opportunities to reduce energy demand both in operation and design. Regarding the operational aspect, variations in the time when the yacht sails solely using wind power or is motor sailing are derived from actual and real data provided by yacht captains and crews. Proposed reductions in design speed and range are based on typical routes and stops made by yachts, ensuring the validity of the cases considered. As for design opportunities, the reduction in energy demand achieved by transitioning from a chilled water HVAC system to a DX system is defined according to manufacturer data [141]. The same applies to solar panels and hydrogenerators [163, 135]. The possibility of converting a crew cabin into technical space that can accommodate the extra volume required by alternative energy carriers and converters is obtained with the help of technical drawings.

- **Emissions:** The emissions calculated by the model are CO_2 TTW, CO_2 WTW, and local emissions of NO_x and PM, all evaluated on a yearly basis. Since the energy required has already been calculated, to determine the tons of CO_2, NO_x, and PM emitted by the yacht, we considered the emission values in [g/MJ] associated with the energy carriers linked to their respective energy converters, which are ICE for MGO, HVO, and methanol, while for hydrogen, they are PEMFC. These values were obtained from MARIN [41], DNV report [160], and scientific articles [159, 161].

- **Refit timeframe:** For a fuel retrofit project, the following four stages can be identified: Feasibility, Design & Engineering, Conversion, and Adoption. For the purpose of this thesis, the phase most appropriate to focus on is the conversion phase, during which the yacht must be in dry dock to undergo the selected modifications. It is not possible to accurately consider the time required to install the systems for each of the technically feasible energy configurations due to the innovative project. However, the results obtained are based on a report from Lloyd's Register [33], especially for systems related to alternative energy carriers, while information for hydrogenerators, solar panels, and HVAC was obtained from experienced Project Managers. This approach ensures that the months of dry docking required to install the individual systems in the various configurations are considered reliable.

- **CapEx:** The CapEx analyzed is limited to the cost of energy converters, storage systems, and energy demand reduction solutions. To obtain the specific costs of each system, considering the known power and energy required values, the relative costs [€/kW] and [€/kWh] were taken into account. These values are provided by suppliers and are then summed based on the systems included in the various configurations depending on the owner cases considered [41, 163, 135, 164, 141]. It should be specified that the cost of HT-PEMFC already includes the cost of the methanol-hydrogen reformer. To then add Opex to CapEx to obtain the TCO, they must be provided on an annual basis. To do this, the lifetime of the systems considered is also taken into account, again using data provided by the suppliers [156, 165, 128, 136, 135, 141].

- **OpEx:** The OpEx considered in the model only refer to the cost of fuel and any potential carbon tax based on the future scenario considered. The relative cost in [€/MWh] of current and projected fuels for 2030 was obtained from reliable sources [166, 167, 168, 169, 170, 171]. Multiplying these values by the required energy based on the selected owner case yields the associated OpEx. Finally, the introduction or absence of the carbon tax and its potential amount is determined based on the Lloyd's report, scientific articles, and expert opinions [171, 33, 172, 173].

- **TCO:** To complete the analysis of costs related to a sustainable refit, the model allows for the TCO calculation. The yearly TCO is obtained by summing OpEx and CapEx for each configuration, scenario, and owner case. It should also include the value of yacht depreciation, but a detailed calculation of it would therefore require a thorough technical analysis that is beyond the scope of this thesis. Consequently, the values of yearly TCO are considered reliable and indicative of how this index would vary following a sustainable refit.

Constructs internal consistency
The second step involves accepting the internal consistency of how the constructs are assembled in the method. To gain confidence in the construct assembly, Figure 4.1 illustrates a flowchart focused on information flow. This demonstration shows that each step has sufficient input available, that the expected output is likely based on the input, and that this output adequately feeds into the next step. The model considers three primary variable inputs: ship dimensions, operational profile, and the selection of energy carriers. By using the first two inputs, the model calculates energy production from hydrogenerators and solar panels, explores energy demand reduction techniques, and determines the necessary stored energy. To achieve this, the model factors in ship resistance, power requirements, and the efficiency of transmission, reformers, and converters to calculate the required stored energy. The third input involves selecting energy carriers to compute the necessary volume and weight.

If the new operational requirements and vessel dimensions are technically feasible, emissions resulting from the solution are also assessed, along with an estimate of the installation time for necessary yacht modifications while in dock. Attention then turns to the economic feasibility of the analyzed power configuration. CapEx and OpEx are derived as outputs from the literature review and are used as inputs to calculate the TCO. Consequently, it can be asserted that the assessment model is theoretically structurally valid.

Example problems appropriateness
The third and final step of structural validity involves accepting the appropriateness of the example problem that will be used to verify the performance of the method. The documentation is carried out in the following three stages:

- Document that the example problem is similar to the problem for which the method constructs are generally accepted;
- Document that the example problem represents the actual problem for which the method is intended;
- Document that the data associated with the example problem can support a conclusion.

The example problem considered again involves a sailing yacht where the energy carrier is MGO and the energy converter is an ICE, thus representing a single fuel diesel energy configuration. In order to assess the volume required by the yacht and the associated weight of the energy carrier and converter, as well as yearly emissions, CapEx, OpEx, and TCO, the required calculation steps are analogous. Consequently, it can be stated that the example problem is similar to the problem for which the method constructs are generally accepted. Furthermore, the example problem is also aimed at analyzing the volume, weight of energy carriers and converters, emissions, and associated costs. For this reason, it can be considered that the example problem represents the actual problem for which the method is intended. Finally, the data associated with the example problem regarding the energy density of diesel and the characteristics of the sailing yacht can thus support a conclusion.

6.2.2. Performance validation
This section analyzes the three steps that being efficient embodies. Initially, the focus will be on accepting that the outcome of the method is useful with respect to the initial purpose for some chosen

example problem. Next, attention will be given to accepting that the achieved usefulness is linked to applying the method. Finally, consideration will be given to accepting that the usefulness of the method extends beyond the case studies.

Method outcome usefulness for some examples

The first step in performance validity involves accepting that the outcome of the method is useful for the initial purpose, using a chosen example problem. Starting from the design range and design speed requirements that every yacht has, it is crucial to dimension the fuel storage tanks and the space required, along with the weight associated with the energy converters in the engine room. To comply with emissions regulations, it is also important to calculate the yacht's emissions. Specifically, if the yacht uses MGO as fuel, SO_x emissions can be neglected as they are very low, [179], and therefore attention is focused on NO_x, PM, and CO_2. The method allows for the calculation of all these emissions on a yearly basis. Additionally, CapEx and OpEx are important data. They provide the owner and their team with information on the initial investment required for the refit project and the operating costs they will incur. These two factors, when summed, constitute the TCO, which is also an output of the model. Consequently, it can be asserted that the method builds confidence in its usefulness for a specific purpose.

Usefulness linked to applying method

The second step in performance validity involves accepting that the usefulness of the outcome is linked to applying the method. To build confidence in the usefulness of the resulting solutions for a specific example problem, the contributions to usefulness from each individual construct can be evaluated. This is achieved by comparing solutions with and without the construct, allowing for a quantitative evaluation. By comparing the required storage tank volume obtained using the method with the actual available volume on the yacht, a difference of less than 2% is achieved. It is important to note that this value obtained from the model is higher than the actual value, indicating that the method slightly overestimates the fuel storage volume. Therefore, this difference can be considered an approximation on the side of safety. The tank volume in the method was calculated with an additional 10% margin, as is done during the design phase of a new yacht. Similarly, the weights associated with the energy configuration match the actual values. The calculation of CO_2 TTW, CO_2 WTW, NO_x, and PM emissions also aligns with the current emissions of the yacht. Furthermore, regarding costs, especially CapEx and OpEx, they reflect the current situation accurately. Consequently, it can be concluded that the usefulness of the resulting solutions for the example problem is indeed linked to applying the method.

Usefulness beyond the case studies

The last step for performance validity, which is also the final of the six total steps in the Validation Square method, involves accepting that the method's usefulness extends beyond the specific case studies. This step represents theoretical performance validity, achieved as long as inferences can be made regarding the general usefulness of any research results. In this thesis, the method is applied to two specific case studies, both Royal Huisman sailing yachts, one with GT < 500 and one with GT > 1000.

However, by varying the inputs while keeping the constructs constant, useful results can be obtained not only for other sailing yacht case studies but also for other types of vessels. By adjusting the operational profile and removing systems like hydrogenerators, which are unique to sailing yachts, the general usefulness of any research results can be asserted. In conclusion, it can be affirmed that the sixth and final step of the Validation Square regarding theoretical performance validity is accepted.

6.3. Verification and validation conclusion

In conclusion of this section, a concise and effective response to the following subquestion is provided:

"How can the assessment model developed to analyze the impact of sustainable solutions on sailing yachts be validated and verified?"

The assessment model built in this thesis has been verified and validated to ensure that it is implemented correctly, accurately represents the intended calculations, and to prove that its outputs are realistic and align with real-world data and outcomes. The verification procedure included testing the model with various parameters that are known for producing specific results. All expected outcomes, as outlined in Table 6.1, aligned with the obtained results, demonstrating that the model operated as expected and thus has been successfully verified.

Regarding the validation of the model, this thesis uses the Validation Square, a relativist validation method depicted in Figure 6.1. This approach offers a framework for validating both internal consistency and external relevance for specific instances, establishing confidence in its general usefulness for a particular purpose. In this section, all six steps required by the Validation Square method have been explored. The first step is part of theoretical structural validity and involves accepting the individual constructs constituting the method. Consequently, all individual steps in the model have been reviewed to demonstrate their appropriateness and general acceptance for specific applications. The second step is also part of the quadrant of theoretical structural validity and concerns accepting the internal consistency of how the constructs are integrated into the method. This was achieved by demonstrating that each step has sufficient input available, that the expected output is likely based on the input, and that this output adequately feeds into the next step, thus gaining confidence in the construct assembly.

The third step is part of empirical structural validity and involves accepting the appropriateness of the example problem used to verify the method's performance. The documentation occurs in three stages. The first stage documents that the example problem is similar to problems for which the method constructs are generally accepted. The second stage documents that the example problem represents the actual problem intended for the method. Finally, the third stage documents that the data associated with the example problem can support a conclusion. Using an example problem of a sailing yacht with a single fuel ICE and HVO energy configuration was demonstrated to be appropriate for testing the method. Moving on to the performance validation part, the fourth step specifically falls under empirical performance validity and involves accepting that the outcome of the method is useful for the initial purpose, using a chosen example problem. It was demonstrated how the model outputs of volumes, weights, emissions, and costs are useful for the example problem.

The fifth step is also part of empirical performance validity and involves accepting that the usefulness of the outcome is linked to applying the method. To do so, the contributions to usefulness from each individual construct were evaluated by comparing solutions with and without the construct, allowing for a quantitative evaluation. All outputs of the various steps of the model align with real values of the yacht under examination, demonstrating that the achieved usefulness is due to applying the method. The last step for performance validity, also the final of the six total steps in the Validation Square method, involves accepting that the method's usefulness extends beyond specific case studies. This was explained by demonstrating that by varying the inputs while keeping the constructs constant, useful results can be obtained not only for other sailing yacht case studies but also for other types of vessels.

7 Conclusion

To reduce the environmental impact of the maritime sector, the IMO has introduced regulations on emission limits and established ambitious targets. However, superyachts constitute a niche to which most of these regulations currently do not apply. Nevertheless, the yachting sector must adhere to the ambitions outlined by the IMO both to establish itself as a responsible industry, and since more and more limits are being applied to them as well. An increasing number of new yachts feature sustainable technologies aimed at increasing energy efficiency and reducing emissions. However, to achieve IMO's goals, acting on new building is not sufficient and sustainable refit projects must also be carried out on already existing yachts. This is not only valid for motor yachts but also for sailing yachts, a niche within the yachting sector that, however, predominantly uses propulsion engines for most of their sailing time. They have limited interior available space, and since alternative energy carriers such as methanol, hydrogen, and batteries have a lower energy density than the commonly used MGO, there are complications regarding the technical feasibility of their integration on board. Another problem related to alternative energy carriers and converters is their high price compared to conventional energy solutions.

Despite the existence of various studies exploring alternative energy carriers and converters, there is a notable absence of information on how these options can be combined and integrated on-board and their respective impacts on internal volumes, weights, emissions, refit timeframe, and costs of existing yachts. This knowledge is crucial for yacht owners and their teams to assess the feasibility of integrating sustainable technologies and make informed decisions regarding the substantial changes such a refit would bring to their vessels. To address this identified research gap, the following research question is addressed in this thesis:

"What trade-offs are made by the different combinations of energy carriers and energy converters that can be installed when refitting a sailing yacht by reducing energy demand and minimising emissions in order to ensure future sustainability?"

To answer this question comprehensively, six subquestions have been formulated and addressed in this thesis. They are listed below along with a succinct answer for each of them.

1) *"What are the peculiarities of a sailing yacht in terms of interior space, operational profile, and energy demand?"*

Sailing yachts have unique characteristics, with their primary advantage being the ability to use sails for propulsion. However, the instances where sailing superyachts sail exclusively under sails are in the minority. Increasing the time spent sailing under sail or motor sailing, especially during long crossings, which represent the most challenging scenarios in terms of energy demand, would lower energy requirements. This reduction in energy demand would also lessen the impact of integrating alternative energy carriers and converters on board, as they require more space compared to the current diesel ICE configuration. The interior spaces of sailing yachts are constrained and meticulously optimized, further complicating the integration of sustainable technologies.

The operational modes of a typical Royal Huisman sailing yacht encompass motoring, motor sailing, pure sailing, anchor, and moored. Analysis of AIS data and crew input shows that yachts spend about 75% of their time moored, and the time spent sailing under only engine is similar to that of sailing only with sails, but more often yachts do motor sailing. Despite needing a 4000 nm range for an Atlantic crossing, most yachts stop at the Azores or Canary Islands, allowing for reduced fuel tank capacity without impacting operations substantially. On a yearly base, energy demand is higher for hotel loads than propulsion, with HVAC systems being the highest consumers. It is noteworthy that sailing yachts can generate electricity via hydrogenerators while sailing under sail, contributing to the hotel load energy demand.

2) *"Which are the most promising alternative energy carriers? What alternative energy converters hold the most potential?"*

There are several promising alternative fuels that allow for the reduction of emissions from Royal Huisman sailing yachts, but it is difficult to identify one as more promising because of their trade-offs between associated emissions, energy density and TRL. This thesis is focused on HVO, methanol, hydrogen and batteries. As shown in Table 3.1, except for HVO, both methanol and hydrogen, as well as batteries, have a volumetric energy density that is much lower than the traditional diesel currently used in yachts. The sustainable pathway that would have the least impact on design and operational profile without the need for additional storage volume consequently is by using HVO. Batteries are too heavy and have too low energy density to replace diesel, but they are still crucial for peak shaving. Furthermore, they can ensure silent periods by allowing diesel generators to be turned off, for example, while anchoring. They can also be combined with other alternative energy converters powered by methanol or hydrogen, or hydrogenerators for the storage of generated electricity. As for methanol and hydrogen, they are the most promising for emission reduction and are indeed at the centre of attention from the maritime industry. However, the TRL is still not high, and they face challenges related to availability, high costs, safety, and, as mentioned earlier, low volumetric energy density.

Regarding alternative energy converters, replacing the current ICE engines using MGO with a single type of energy converter powered by alternative fuel is very complex unless the energy demand of the yacht is significantly reduced. The solution that would have less impact on technical feasibility would be to maintain ICE engines but powered by HVO. However, it can be concluded that currently the most promising alternative energy converter is LT-PEMFC with methanol stored onboard and reformed to hydrogen before feeding the fuel cell. This type of fuel cell has undergone significant and rapid development in recent decades, reaching a high TRL. Fuel cells do not have noise and vibrations compared to ICE, and boast a quick start-up time and exhibit a high efficiency. However, they require hydrogen, which can be stored directly in special tanks or instead reformed from stored methanol. Although methanol storage is more easily achievable than hydrogen storage, it still presents more complications than traditional diesel, or even HVO, and therefore LT-PEMFCs feasibility depends on the combination of energy requirement, energy converters and energy carriers. Thanks to HVO, ICEs will likely continue to be used for several years. Hydro generation is a crucial aspect for sailing yachts, allowing the production of energy that can be used for the hotel load while sailing. If done with a separate turbine, it is also easily achievable for refit projects, as the propulsion system does not require changes. Solar panels can also contribute to meeting the energy demand of yachts, especially since they are often navigating in areas with strong sunlight exposure. However, power output and efficiency are limited, and aesthetically impact the design of the yacht.

In conclusion, replacing the current energy configuration composed of ICE with MGO with LT-PEMFCs and no other energy converters without reducing the energy demand is an option that would have a significant impact on the design and operational profile of the yacht, and consequently, it would be feasible only if the client is particularly motivated in having a sustainable yacht. For this reason, also possible combinations of ICE with HVO, LT-PEMFCs, batteries, and also hydrogenerator, solar panels are investigated proving satisfactory, as the thesis results showed.

3) *"Which are the opportunities to reduce the energy demand in design and operation?"*

One of the main issues related to the use of alternative fuels is the lower volumetric energy density, resulting in a larger volume required for on-board fuel storage. Reducing energy demand is the first step toward emissions reduction and can simplify the integration of alternative energy carriers and converters by decreasing the amount of fuel required on board to meet the yacht's energy demand. There are primarily two ways to reduce energy demand: opportunities in design and opportunities in operational use. Regarding opportunities in the design, Royal Huisman has established design standards to guarantee a consistently high level of quality and comfort across all yachts. Indeed, ensuring a yacht's design minimizes energy demand is important, but this should not come at the expense of compromising Royal Huisman's established standards for comfort and net interior volume. Among all the possibilities regarding energy demand reduction acting on design, the most relevant for this thesis are the transition from a chilled water HVAC system to a DX system, and the use of delivery sails instead of conventional sails.

A substantial contribution to energy demand reduction can also be obtained by acting on the operational profile of sailing yachts. First of all, the energy that the engines need to provide can be reduced by sailing under sail more often. Moreover, other effective methods include reducing the design speed by one or two knots, and reducing the range, while still ensuring, for example, the crossing of the Atlantic, and consequently without making substantial changes to the operational profile. Finally, weather routing and voyage planning are not only crucial to avoid rough seas, which cause increased resistance to motion, but for sailing yachts, it can also mean favorable winds, eliminating the need for propulsion engines and even allowing the use of hydrogenerators for the hotel load.

4) *"What is the structure of the assessment model used to evaluate the technical and economic feasibility of integrating sustainable solutions on already-built sailing yachts to reduce emissions?"*

The assessment model built in this thesis is designed to be easily applicable to various sailing yachts, serving as a support tool for making informed decisions when assessing retrofit possibilities. The process of the developed model is automated, integrating all information from the literature review and the corresponding equations developed to obtain the desired outputs. Initially, the technical feasibility of each selected energy configuration is assessed by calculating the volume and weight associated with it and comparing these with the current energy configuration values of the yacht in question. In order to do so, the most critical scenario is considered first, considering the requirements to travel a certain range at a certain speed using only the engine without deploying any sails. Subsequently, the impact of implementing energy reduction methods, modifying the operational profile based on the yacht's actual usage in recent years, and reorganizing internal space on the technical feasibility of the selected energy configuration is verified.

For configurations deemed technically feasible, the associated emissions are calculated on an annual basis. Additionally, an estimate of the time the yacht will need to remain in the dock for the installation of necessary modifications is provided. Since a significant factor preventing many owners from using alternative fuels is their high price compared to diesel, an economic feasibility analysis is also conducted. Consequently, the CapEx related to energy converters, storage systems, and energy demand reduction solutions is calculated based on the yacht and its configuration. Regarding OpEx, the focus is on fuel costs, and apart from the current scenario, three different future scenarios are analyzed to account for the uncertainty regarding the cost of energy carriers in 2030 and the potential extension of the carbon tax to yachts and its amount. To provide a more comprehensive understanding of the economic impact of a sustainable refit for a yacht, the yearly TCO is also calculated. As it is derived from the sum of CapEx and OpEx, it considers not only the upfront investment costs but also the expenses related to the system's lifetime and yacht operation.

5) *"How do the volumes and weights of alternative energy carriers and converters vary in sailing yachts compared to the current energy configuration considering possible energy demand reduction? How do emissions and costs change?"*

This thesis presents the results obtained by applying the assessment model to two Royal Huisman sailing yachts of different sizes. Yacht A has a GT below 500, while Yacht B exceeds 1000 GT. The purpose of analyzing two different yachts is to demonstrate the model's applicability to multiple yachts and analyze any impact differences, particularly in terms of technical feasibility. For each yacht, four hypothetical owner profiles have been identified, ranging from Owner 1, who is less inclined to make changes to reduce onboard energy demand, to Owner 4, who is more inclined to make operational changes and install solar panels and hydrogenerators to significantly reduce energy demand. This choice was made because to make a sustainable refit of a sailing yacht technically feasible, it is necessary implement modifications aimed at reducing onboard energy demand or converting non-technical spaces into storage tanks or an engine room.

In general, results have shown that for a sustainable refit of a sailing yacht, integrating alternative energy carriers and converters on board is not feasible unless the energy required is reduced or the internal volume dedicated to the storage of energy carriers and converters is increased. For both Yacht A and Yacht B, the only feasible option obtained in the case of Owner 1 is a single-fuel solution with HVO for both propulsion and hotel load. This solution allows for a reduction of approximately 15% in CO_2 TTW emissions and about 90% in CO_2 WTW emissions, 18% in NO_x emissions, and 45% in PM emissions compared to the current configuration with MGO. These are significant results, especially for CO_2 WTW and PM emissions. Furthermore, the docking time would be just a month. Regarding costs, the increase in TCO, compared to the case of a standard refit that replaces the current engines with new diesel ICE engines and install new identical sails, ranges from 11% to 26%, depending on the future scenario considered.

Worth noting is the fact that configurations involving ICE with HVO for propulsion and methanol PEMFC or methanol ICE for the hotel load are technically feasible for Owner 2. The reduction in energy demand associated with this profile does not entail substantial changes in terms of operational profile and internal layout, unlike Owners 3 and 4. Assuming that the yacht will motor sail for 50% of the ocean crossing reflects how such yachts typically navigate during long sailings. Additionally, reducing speed by just one knot and the range by 5% are minor adjustments. The solar panels occupy only 10% of the main deck area, and there is no change in the type of sails, nor is a crew cabin converted into technical space. These HVO + methanol energy configurations, in terms of TTW emissions, would reduce CO_2 emissions by approximately 32%, NO_x by 47%, and PM by 69% compared to the current MGO configuration of the yachts. Regarding WTW emissions, CO_2 emissions depend on the type of methanol considered: 68% for grey methanol, 85% for bio-methanol, and 94% for e-methanol. The time required for installing the solutions envisioned for this configuration is 4 months. However, TCO depends on both the type of methanol and the choice of PEMFC or ICE. The percentage increase compared to the current configuration with MGO as the energy carrier, where a standard refit includes the replacement of energy converters and sails, ranges from approximately 11% for ICE with fossil methanol in Scenario 2 to 39% for e-methanol PEMFC in Scenario 1.

On the other hand, thanks to compromises in terms of energy demand reduction and internal layout changes applied to Owner 4 case, there are many technically feasible energy configurations. Generally, the only configurations among these associated with a TCO increase of over 50% compared to the current configuration, with a maximum value reaching about double in the case of the single-fuel e-methanol PEMFC configuration in Scenario 1 for Yacht B, are those using PEMFC for propulsion. Indeed, this energy converter has a much higher cost than ICE, as reported in Table 4.6 of Chapter 4. The refit costs for such configurations are over €3 million for Yacht A and over €9 million for Yacht B. The related docking time is over 5 months, while emissions are not significantly different from the HVO + methanol configurations described earlier. Considering Owner 4 case for both these configurations, the reductions in CO_2 TTW emissions vary by only 1%, while for CO_2 WTW, by 2% and are even higher for configurations with PEMFC methanol rather than HVO for propulsion, regardless of the energy carrier and converter used for the hotel load. The differences in reductions in NO_x and PM emissions compared to MGO remain below 18%. The differences in terms of compromises required to make configurations using methanol for propulsion compared to HVO + methanol are therefore significant, and the TCO, especially when the considered energy converter is PEMFC, is considerably higher, despite a less substantial reduction in emissions.

Finally, regarding the differences between the results obtained for Yacht A and Yacht B in terms of technical feasibility, it is worth noting that the energy configuration of ICE with HVO for propulsion and PEMFC with hydrogen for the hotel load is feasible only for Yacht A and not for Yacht B. Being the only hydrogen configuration feasible for Yacht A, it follows that no hydrogen configuration for Yacht B meets the energy requirement of the longest crossing considered. Despite Yacht B having a GT of more than double that of Yacht A, there is no extra space available to accommodate the additional volume required by alternative energy carriers and converters, as it is also a sailing yacht with limited interior spaces. However, the feasibility difference between Yacht A and Yacht B is due to the fact that the crew cabin that Owners 3 and 4 are willing to convert into technical space for energy carriers and converters is always 8 [m^3] for both yachts. Therefore, this volume is proportionally different for a yacht under 500 GT and one that exceeds 1000 GT. Furthermore, this difference can be justified by the varying impact that a 1 or 2 knots speed reduction has on different yachts with different power-to-speed curves. Additionally, the hydrogenerator installed on both yachts is the same with the same power output, meaning it will have a proportionally greater effect on energy demand reduction for Yacht A than for Yacht B.

The percentage reductions in CO_2 TTW, CO_2 WTW, NO_x, and PM emissions are aligned and do not differ by more than 2%. The required docking time for a selected configuration is the same for the two yachts. Indeed, there are no variations for installation time between the two yachts as differences in installing larger energy converters or bigger storage tanks are neglected among diverse yachts. Finally, the TCO for both yachts follows the same trend, albeit with some differences when compared to the current diesel configuration present on each yacht. These percentage differences remain below 3% for Owner 1 and 2 scenarios, while they reach up to 18% for Owner 3 and 4 scenarios. This difference is due to Yacht A and Yacht B variations in percentage reductions with respect to the current energy demand configuration.

6) *”How can the assessment model developed to analyze the impact of sustainable solutions on sailing yachts be validated and verified?”*

The assessment model built in this thesis has been verified and validated to ensure that it is implemented correctly, accurately represents the intended calculations, and to prove that its outputs are realistic and align with real-world data and outcomes. The verification procedure included testing the model with various parameters that are known for producing specific results. All expected outcomes, aligned with the obtained results, demonstrating that the model operated as expected and thus has been successfully verified. Regarding the validation of the model, this thesis used the relativist validation method of the Validation Square [177]. This approach is defined by the six steps and offers a framework for validating both internal consistency and external relevance for specific instances, establishing confidence in its general usefulness for a particular purpose.

The first step is part of theoretical structural validity and involves accepting the individual constructs constituting the method. The second step is also part of the quadrant of theoretical structural validity and concerns accepting the internal consistency of how the constructs are integrated into the method. The third step is part of empirical structural validity and involves accepting the appropriateness of the example problem used to verify the method’s performance. Moving on to the performance validation part, the fourth step specifically falls under empirical performance validity and involves accepting that the outcome of the method is useful for the initial purpose, using a chosen example problem. The fifth step is also part of empirical performance validity and involves accepting that the usefulness of the outcome is linked to applying the method. The last step for performance validity, also the final of the six total steps in the Validation Square method, involves accepting that the method’s usefulness extends beyond specific case studies. All the six steps have been accepted for the thesis method, consequently proving its validity.

8 Discussion

Finally, this concluding discussion chapter is presented for three purposes. First, to clarify the contribution this thesis makes to the state of the art, ensuring that the research gap has been filled. Second, to present the limitations due to the assumptions inherent in constructing a parametric model for a thesis. The last section of this chapter is dedicated to the possibilities for expanding the model, and thus, possible future work will be presented.

8.1. Filled research gap

The literature review has shown that there are numerous scientific articles, conference papers, reports, and master's theses that explore alternative energy carriers and converters. However, each of these studies has its own limitations. There is a notable absence of information on how these options can be combined and integrated on board a sailing yacht, and what their respective impact is on internal volumes, weights, emissions, refit timeframe, and costs of existing yachts. This knowledge is crucial for yacht owners and their teams to assess the feasibility of integrating sustainable technologies and to make informed decisions regarding the substantial changes such a refit would bring to their vessels. As a result, this thesis aimed to fill the research gap concerning the trade-offs associated with different combinations of energy carriers and converters during the refitting of sailing yachts to reduce energy demand and minimize emissions for future sustainability.

To achieve a satisfactory result, an assessment model was constructed that can be easily applicable to various sailing yachts, serving as a support tool for making informed decisions when assessing retrofit possibilities. Firstly, it allowed obtaining results regarding technical feasibility, specifically the volume and weight required by the alternative energy configurations analyzed compared to the current configuration of the yachts. These results depend on the specific yacht considered, and especially on the owner's willingness to reduce the current energy demand of their yacht. For configurations evaluated as technically feasible, values for CO_2, NO_x, and PM emissions on a yearly basis were provided, as well as the docking time required to install the necessary modifications. Finally, an important part of evaluating the trade-off of these solutions is the cost assessment, both for refit and operational costs. For this reason, the model also provides results on the TCO, composed of the sum of CapEx and OpEx. Therefore, it can be concluded that the research gap has been filled.

8.2. Model limits

Due to the vastness of the research question and the time and resource limitations associated with a master thesis, the assessment model presents several assumptions and simplifications. These were necessary to evaluate both technical feasibility and economic feasibility when refitting a sailing yacht by reducing energy demand and minimising emissions in order to ensure future sustainability. Complicating the model is that it does not refer to a specific case study of a sailing yacht but can be applied to various yachts. Additionally, it does not focus on a specific energy carrier or converter but analyzes several and considers their possible combinations. An accurate calculation of emissions and the refit timeframe are themselves lengthy and demanding studies. Finally, a detailed estimate of the refit costs associated with the installation of all considered systems and a calculation of OpEx require a lot of time and expertise, so simplifications were also necessary in this area. The final conclusion of this thesis heavily relies on these design choices and, despite providing to the owners and their teams informed decisions regarding the substantial changes such a refit would bring to their vessels, may not provide a complete representation of the overall picture. Some assumptions have already emerged in Chapter 4, where the model was presented, but they will be presented more clearly in this section. Despite the numerous assumptions made, the list below will primarily focus on the points that have had a significant impact on the conclusion of this thesis.

- Hybrid energy configurations have only one type of energy converter that provides all the power required for propulsion and one type of converter for hotel load (in addition to solar panels and hydrogenerators, which are supplementary). Consequently, the possibility of having batteries to ensure only a limited silent period, perhaps while at anchor, or using hydrogen as fuel for a limited number of nautical miles in certain geographical areas is not considered.

- The four owner profiles are representative but hypothetical. Consequently, by changing their willingness to reduce energy demand, certain energy configurations considered technically feasible in the thesis might turn out to be unfeasible, and vice versa.

- The speed reduction caused by the increased resistance due to the presence of the hydrogenerator is neglected.

- The size of the crew cabin that Owner 3 and Owner 4 are willing to convert into technical space is the same for all Royal Huisman sailing yachts. Furthermore, even the larger sailing yachts convert only one crew cabin and no more.

- Regarding the volume and weight of the energy converters, they are based on [m^3/kW] and [t/kW], and therefore there is no specific selection of the number of energy converters depending on power requirements.

- Regarding the technical feasibility of energy configurations including methanol, fuel piping and the fuel preparation room, which includes fuel pumps, fuel valve trains, heat exchangers, and filters, are neglected.

- Regarding methanol cofferdams, a solution that has received only an approval in principle from Lloyd's Register is considered. This solution involves a 25mm thick Technology Sandwich Plate System barrier surrounded by two thin layers of steel. However, the application of this solution to aluminum hulls requires further studies, given the possible galvanic corrosion between the steel external plates and the aluminum hull.

- Volume and weight of energy carriers and converters are calculated separately, but to evaluate technical feasibility, they are summed and compared to the available volume and weight of the energy carriers and converters currently used.

- Emissions and fuel costs, unlike technical feasibility, are calculated using an average operational profile of Royal Huisman sailing yachts, so the division into sailing modes—under sail only, under engine only, and motor sailing—is the same for all four owner cases.

- The difference in efficiency between ICE and PEMFC is neglected for the calculation of CO_2 yearly emissions and fuel costs, while it is taken into account for the technical feasibility assessment.

- All the energy required by the yacht's hotel load while moored is considered to be provided by shore power.

- The differences in the time required for the installation of an ICE and a PEMFC are neglected, and the difference in time to install a larger or smaller energy converter among diverse yachts is not considered.

- Regarding CapEx, the cost of control and safety systems, bunkering, and piping systems are neglected, affecting the accuracy of the calculated TCO.

- The energy converters and storage systems cost are based on [m^3/kW] or [m^3/kWh] and [t/kW] or [t/kWh], and therefore there is no specific selection of the number of energy converters depending on power requirements.

- Regarding OpEx, the maintenance cost and crew cost changes are neglected, affecting the accuracy of the calculated TCO.

- The TCO is considered as the sum of only CapEx and OpEx, without taking into account yacht depreciation, which may undergo changes following a sustainable refit.

8.3. Future work

Although the thesis is able to answer the main research question, the model built has limitations and assumptions related to the time available and the resources of a master thesis. Consequently, in the future, it will be possible to expand and further develop the model by reducing the number of assumptions to ensure greater accuracy of the results obtained and introducing updates to the TRL of sustainable solutions and regulations. Through careful analysis of specific cases and tests, it will be possible to provide more detailed information on the docking time required to install certain energy converters on board, also taking into account variations due to their size. With more specific case-by-case studies, the space and cost required for the methanol fuel piping and fuel preparation room could be integrated, as well as the maintenance costs of the energy converters and all associated systems.

Additionally, it is important to continuously update the model to include emerging energy technologies and more efficient converters, like SOFC, which were excluded after the literature review due to their currently low TRL but might soon prove to be better than PEMFC. Furthermore, it is crucial to consider future regulatory landscapes and their potential impact on energy choices, including emission regulations and incentives for renewable energy adoption. It will also be possible to make improvements to the model's user interface to make it more accessible and user-friendly for yacht owners and designers. The possibility of establishing a continuous feedback loop where users can report their experiences and provide data should also be considered, helping to iteratively improve the model.

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A

Appendix A

Table A.1: Yacht A volume and weight of hybrid configurations for Owner 1 and 2 with percentage increase over the current MGO configuration

Propulsion	Hotel load	Owner 1				Owner 2			
		$[m^3]$	[%]	[t]	[%]	$[m^3]$	[%]	[t]	[%]
HVO	Methanol (ICE)	38,10	114%	31,32	109%	26,23	79%	22,01	77%
HVO	Methanol (LT-PEMFC)	40,68	122%	32,19	112%	28,79	86%	22,88	80%
HVO	Methanol (HT-PEMFC)	41,72	125%	33,55	117%	29,51	88%	23,92	83%
HVO	Hydrogen (LT-PEMFC)	78,48	235%	41,25	143%	70,83	212%	33,53	117%
HVO	Batteries	119,30	358%	148,28	516%	110,80	332%	143,61	499%
Methanol (ICE)	HVO	73,20	219%	68,90	240%	45,29	136%	41,98	146%
Methanol (ICE)	Methanol (LT-PEMFC)	79,68	239%	73,96	257%	51,86	155%	47,08	164%
Methanol (ICE)	Methanol (HT-PEMFC)	80,73	242%	75,32	262%	52,58	158%	48,12	167%
Methanol (ICE)	Hydrogen (LT-PEMFC)	117,49	352%	83,02	289%	93,37	280%	57,58	200%
Methanol (ICE)	Batteries	158,31	474%	190,04	661%	133,94	401%	167,89	584%
Methanol (LT-PEMFC)	HVO	86,48	259%	73,44	255%	58,52	175%	46,48	162%
Methanol (LT-PEMFC)	Methanol (ICE)	90,39	271%	77,63	270%	62,53	187%	50,71	176%
Methanol (LT-PEMFC)	Batteries	171,59	514%	194,59	677%	147,17	441%	172,38	599%
Methanol (HT-PEMFC)	HVO	94,63	284%	83,10	289%	64,22	192%	53,75	187%
Methanol (HT-PEMFC)	Methanol (ICE)	98,55	295%	87,29	304%	68,42	205%	58,18	202%
Methanol (HT-PEMFC)	Batteries	179,74	539%	204,25	710%	152,74	458%	179,55	624%

Table A.2: Yacht A volume and weight of hybrid configurations for Owner 3 and 4 with percentage increase over the current MGO configuration

Propulsion	Hotel load	Owner 3				Owner 4			
		$[m^3]$	[%]	[t]	[%]	$[m^3]$	[%]	[t]	[%]
HVO	Methanol (ICE)	19,17	46%	16,28	56%	12,49	30%	10,83	37%
HVO	Methanol (LT-PEMFC)	21,73	53%	17,14	59%	15,05	36%	11,70	40%
HVO	Methanol (HT-PEMFC)	22,38	54%	18,11	62%	15,60	38%	12,57	43%
HVO	Hydrogen (LT-PEMFC)	56,48	137%	25,91	89%	42,56	103%	18,12	62%
HVO	Batteries	95,25	230%	125,53	429%	77,53	187%	104,15	356%
Methanol (ICE)	HVO	30,92	75%	28,20	96%	17,47	42%	15,31	52%
Methanol (ICE)	Methanol (LT-PEMFC)	36,86	89%	32,58	111%	22,78	55%	18,98	65%
Methanol (ICE)	Methanol (HT-PEMFC)	37,50	91%	33,55	115%	23,32	56%	19,85	68%
Methanol (ICE)	Hydrogen (LT-PEMFC)	71,13	172%	41,22	141%	49,97	121%	25,83	88%
Methanol (ICE)	Batteries	110,44	267%	141,03	482%	85,32	206%	111,49	381%
Methanol (LT-PEMFC)	HVO	44,13	107%	32,67	112%	30,66	74%	19,77	68%
Methanol (LT-PEMFC)	Methanol (ICE)	47,51	115%	36,19	124%	33,41	81%	22,57	77%
Methanol (LT-PEMFC)	Batteries	123,65	299%	145,50	497%	98,51	238%	115,94	396%
Methanol (HT-PEMFC)	HVO	48,52	117%	38,68	132%	33,85	82%	24,61	84%
Methanol (HT-PEMFC)	Methanol (ICE)	52,06	126%	42,38	145%	36,74	89%	27,58	94%
Methanol (HT-PEMFC)	Batteries	127,93	309%	151,42	518%	101,58	246%	120,69	412%

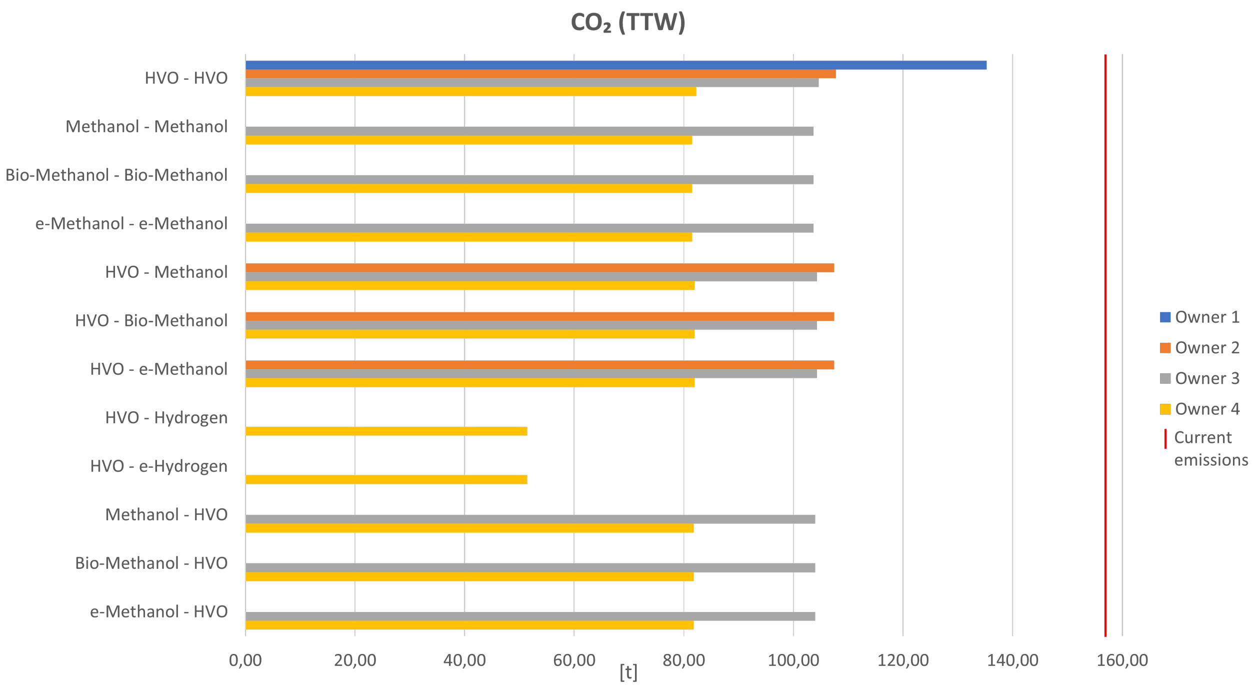

Figure A.1: Yacht A CO_2 TTW emissions compared to the current ICE configuration at MGO

Table A.3: Yacht A CO_2 TTW and WTW emission percentage reduction compared to the current ICE configuration at MGO

Propulsion	Hotel load	CO_2 TTW				CO_2 WTW			
		Owner 1	**Owner 2**	**Owner 3**	**Owner 4**	**Owner 1**	**Owner 2**	**Owner 3**	**Owner 4**
HVO	HVO	15%	32%	34%	48%	91%	93%	93%	94%
Methanol	Methanol	-	-	35%	49%	-	-	23%	40%
Bio-Methanol	Bio-Methanol	-	-	35%	49%	-	-	70%	77%
e-Methanol	e-Methanol	-	-	35%	49%	-	-	98%	99%
HVO	Methanol	-	32%	34%	48%	-	68%	71%	74%
HVO	Bio-Methanol	-	32%	34%	48%	-	85%	86%	88%
HVO	e-Methanol	-	32%	34%	48%	-	94%	95%	96%
HVO	Hydrogen	-	-	-	68%	-	-	-	84%
HVO	e-Hydrogen	-	-	-	68%	-	-	-	96%
Methanol	HVO	-	-	34%	48%	-	-	46%	60%
Bio-Methanol	HVO	-	-	34%	48%	-	-	77%	83%
e-Methanol	HVO	-	-	34%	48%	-	-	97%	97%

Table A.4: Yacht A NO_x and PM emission percentage reduction compared to the current ICE configuration at MGO

Propulsion	Hotel load	NO_x				PM			
		Owner 1	**Owner 2**	**Owner 3**	**Owner 4**	**Owner 1**	**Owner 2**	**Owner 3**	**Owner 4**
HVO	HVO	18%	35%	37%	50%	45%	56%	57%	66%
Methanol (ICE)	Methanol (ICE)	-	-	72%	78%	-	-	93%	95%
Methanol (ICE)	Methanol (PEMFC)	-	-	-	84%	-	-	-	96%
Methanol (PEMFC)	Methanol (ICE)	-	-	-	93%	-	-	-	98%
HVO	Methanol (ICE)	-	47%	48%	60%	-	69%	69%	77%
HVO	Methanol (PEMFC)	-	48%	49%	69%	-	70%	70%	79%
HVO	Hydrogen	-	-	-	69%	-	-	-	79%
Methanol (ICE)	HVO	-	-	61%	67%	-	-	82%	84%
Methanol (PEMFC)	HVO	-	-	-	85%	-	-	-	90%

Table A.5: Yacht A total refit cost e yearly CapEx for Owner 1 and 2

Propulsion	Hotel load	Owner 1		Owner 2	
		Refit cost [€]	CapEx [€]	Refit cost [€]	CapEx [€]
HVO	HVO	861.840	149.160	922.322	151.176
HVO	Methanol (ICE)	-	-	932.018	151.176
HVO	Methanol (PEMFC)	-	-	1.380.018	171.476
HVO	Bio-Methanol (ICE)	-	-	932.018	151.176
HVO	Bio-Methanol (PEMFC)	-	-	1.380.018	171.476
HVO	e-Methanol (ICE)	-	-	932.018	151.176
HVO	e-Methanol (PEMFC)	-	-	1.380.018	171.476

Table A.6: Yacht A total refit cost e yearly CapEx for Owner 3 and 4

Propulsion	Hotel load	Owner 3		Owner 4	
		Refit cost [€]	CapEx [€]	Refit cost [€]	CapEx [€]
HVO	HVO	965.164	117.372	1.025.646	119.388
Methanol (ICE)	Methanol (ICE)	1.007.468	117.372	1.047.597	119.388
Methanol (PEMFC)	Methanol (PEMFC)	-	-	3.799.597	244.088
Bio-Methanol (ICE)	Bio-Methanol (ICE)	1.007.468	117.372	1.047.597	119.388
Bio-Methanol (PEMFC)	Bio-Methanol (PEMFC)	-	-	3.799.597	244.088
e-Methanol (ICE)	e-Methanol (ICE)	1.007.468	117.372	1.047.597	119.388
e-Methanol (PEMFC)	e-Methanol (PEMFC)	-	-	3.799.597	244.088
HVO	Methanol (ICE)	973.176	117.372	1.031.922	119.388
HVO	Methanol (PEMFC)	1.421.176	137.672	1.479.922	139.688
HVO	Bio-Methanol (ICE)	973.176	117.372	1.031.922	119.388
HVO	Bio-Methanol (PEMFC)	1.421.176	137.672	1.479.922	139.688
HVO	e-Methanol (ICE)	973.176	117.372	1.031.922	119.388
HVO	e-Methanol (PEMFC)	1.421.176	137.672	1.479.922	139.688
HVO	Hydrogen	-	-	1.521.759	129.188
HVO	e-Hydrogen	-	-	1.521.759	129.188
Methanol (ICE)	HVO	999.456	117.372	1.041.320	119.388
Methanol (ICE)	Methanol (PEMFC)	-	-	1.495.597	139.688
Methanol (PEMFC)	HVO	3.303.456	221.772	3.345.320	223.788
Methanol (PEMFC)	Methanol (ICE)	-	-	3.351.597	223.788
Bio-Methanol (ICE)	HVO	999.456	117.372	1.041.320	119.388
Bio-Methanol (ICE)	Bio-Methanol (PEMFC)	-	-	1.495.597	139.688
Bio-Methanol (PEMFC)	HVO	3.303.456	221.772	3.345.320	223.788
Bio-Methanol (PEMFC)	Bio-Methanol (ICE)	-	-	3.351.597	223.788
e-Methanol (ICE)	HVO	999.456	117.372	1.041.320	119.388
e-Methanol (ICE)	e-Methanol (PEMFC)	-	-	1.495.597	139.688
e-Methanol (PEMFC)	HVO	3.303.456	221.772	3.345.320	223.788
e-Methanol (PEMFC)	e-Methanol (ICE)	-	-	3.351.597	223.788

Table A.7: Yacht B volume and weight of hybrid configurations for Owner 1 and 2 with percentage increase over the current MGO configuration

Propulsion	Hotel load	Owner 1				Owner 2			
		$[m^3]$	[%]	[t]	[%]	$[m^3]$	[%]	[t]	[%]
HVO	Methanol (ICE)	108,07	116%	89,57	111%	76,49	82%	64,88	80%
HVO	Methanol (LT-PEMFC)	114,11	122%	91,63	114%	82,51	88%	66,92	83%
HVO	Methanol (HT-PEMFC)	117,22	125%	95,45	118%	84,52	90%	69,68	86%
HVO	Hydrogen (LT-PEMFC)	242,80	260%	122,84	152%	228,46	244%	104,28	129%
HVO	Batteries	381,51	408%	482,81	599%	359,65	384%	471,70	585%
Methanol (ICE)	HVO	201,34	215%	188,91	234%	126,20	135%	116,47	144%
Methanol (ICE)	Methanol (LT-PEMFC)	220,20	235%	204,94	254%	145,64	156%	132,89	165%
Methanol (ICE)	Methanol (HT-PEMFC)	223,31	239%	208,76	259%	147,65	158%	135,65	168%
Methanol (ICE)	Hydrogen (LT-PEMFC)	348,88	373%	236,15	293%	289,76	310%	169,76	210%
Methanol (ICE)	Batteries	487,60	521%	596,12	739%	423,03	452%	537,92	667%
Methanol (LT-PEMFC)	HVO	240,45	257%	202,28	251%	165,19	177%	129,72	161%
Methanol (LT-PEMFC)	Methanol (ICE)	253,27	271%	216,25	268%	178,62	191%	144,11	179%
Methanol (LT-PEMFC)	Batteries	526,71	563%	609,48	756%	462,01	494%	551,16	683%
Methanol (HT-PEMFC)	HVO	263,04	281%	229,35	284%	181,28	194%	150,43	187%
Methanol (HT-PEMFC)	Methanol (ICE)	275,86	295%	243,32	302%	195,33	209%	165,52	205%
Methanol (HT-PEMFC)	Batteries	549,30	587%	636,56	789%	477,66	511%	571,52	709%

Table A.8: Yacht B volume and weight of hybrid configurations for Owner 3 and 4 with percentage increase over the current MGO configuration

Propulsion	Hotel load	Owner 3				Owner 4			
		$[m^3]$	[%]	[t]	[%]	$[m^3]$	[%]	[t]	[%]
HVO	Methanol (ICE)	57,44	57%	49,43	61%	38,71	38%	34,07	42%
HVO	Methanol (LT-PEMFC)	63,46	62%	51,47	63%	44,72	44%	36,10	44%
HVO	Methanol (HT-PEMFC)	65,29	64%	54,06	67%	46,21	46%	38,36	47%
HVO	Hydrogen (LT-PEMFC)	190,54	188%	83,96	103%	149,10	147%	62,89	78%
HVO	Batteries	316,56	312%	421,38	519%	258,35	254%	349,19	430%
Methanol (ICE)	HVO	87,15	86%	78,98	97%	50,44	50%	43,85	54%
Methanol (ICE)	Methanol (LT-PEMFC)	104,95	103%	93,58	115%	66,18	65%	56,12	69%
Methanol (ICE)	Methanol (HT-PEMFC)	106,78	105%	96,16	118%	67,67	67%	58,37	72%
Methanol (ICE)	Hydrogen (LT-PEMFC)	230,37	227%	125,61	155%	168,95	166%	82,47	102%
Methanol (ICE)	Batteries	358,28	353%	463,71	571%	280,04	276%	369,43	455%
Methanol (LT-PEMFC)	HVO	126,07	124%	92,17	114%	89,30	88%	56,98	70%
Methanol (LT-PEMFC)	Methanol (ICE)	137,87	136%	104,74	129%	99,04	98%	67,23	83%
Methanol (LT-PEMFC)	Batteries	397,20	391%	476,89	588%	318,89	314%	382,55	471%
Methanol (HT-PEMFC)	HVO	138,59	136%	109,44	135%	98,55	97%	71,10	88%
Methanol (HT-PEMFC)	Methanol (ICE)	150,96	149%	122,64	151%	108,85	107%	81,95	101%
Methanol (HT-PEMFC)	Batteries	409,31	403%	493,84	609%	327,75	323%	396,36	488%

Table A.9: Yacht B CO_2 TTW and WTW emission percentage reduction compared to the current ICE configuration at MGO

Propulsion	Hotel load	CO_2 TTW				CO_2 WTW			
		Owner 1	Owner 2	Owner 3	Owner 4	Owner 1	Owner 2	Owner 3	Owner 4
HVO	HVO	15%	31%	33%	46%	91%	92%	93%	94%
Methanol	Methanol	-	-	-	47%	-	-	-	38%
Bio-Methanol	Bio-Methanol	-	-	-	47%	-	-	-	76%
e-Methanol	e-Methanol	-	-	-	47%	-	-	-	99%
HVO	Methanol	-	31%	33%	47%	-	68%	70%	73%
HVO	Bio-Methanol	-	31%	33%	47%	-	85%	85%	87%
HVO	e-Methanol	-	31%	33%	47%	-	94%	94%	96%
Methanol	HVO	-	-	33%	47%	-	-	45%	59%
Bio-Methanol	HVO	-	-	33%	47%	-	-	77%	83%
e-Methanol	HVO	-	-	33%	47%	-	-	96%	97%

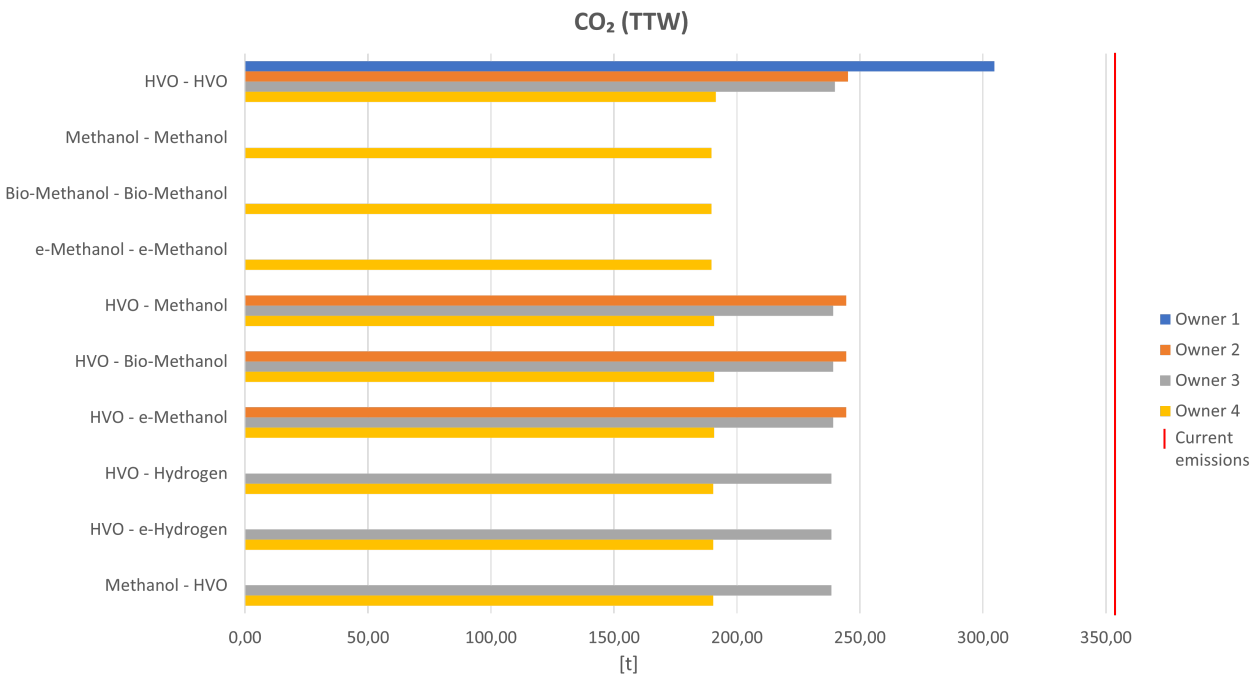

Figure A.2: Yacht B CO_2 TTW emissions compared to the current ICE configuration at MGO

Table A.10: Yacht B NO_x and PM emission percentage reduction compared to the current ICE configuration at MGO

Propulsion	Hotel load	NO_x				PM			
		Owner 1	**Owner 2**	**Owner 3**	**Owner 4**	**Owner 1**	**Owner 2**	**Owner 3**	**Owner 4**
HVO	HVO	18%	34%	35%	48%	45%	56%	57%	65%
Methanol (ICE)	Methanol (ICE)	-	-	-	77%	-	-	-	95%
Methanol (ICE)	Methanol (PEMFC)	-	-	-	83%	-	-	-	96%
Methanol (PEMFC)	Methanol (ICE)	-	-	-	92%	-	-	-	98%
HVO	Methanol (ICE)	-	46%	47%	59%	-	68%	68%	77%
HVO	Methanol (PEMFC)	-	48%	49%	67%	-	69%	69%	78%
Methanol (ICE)	HVO	-	-	60%	66%	-	-	81%	84%
Methanol (PEMFC)	HVO	-	-	-	84%	-	-	-	90%

Table A.11: Yacht B total refit cost e yearly CapEx for Owner 1 and 2

Propulsion	Hotel load	**Owner 1**		**Owner 2**	
		Refit cost [€]	CapEx [€]	Refit cost [€]	CapEx [€]
HVO	HVO	2.049.900	325.005	2.158.979	328.641
HVO	Methanol (ICE)	-	-	2.195.069	328.641
HVO	Methanol (PEMFC)	-	-	3.244.669	376.201
HVO	Bio-Methanol (ICE)	-	-	2.195.069	328.641
HVO	Bio-Methanol (PEMFC)	-	-	3.244.669	376.201
HVO	e-Methanol (ICE)	-	-	2.195.069	328.641
HVO	e-Methanol (PEMFC)	-	-	3.244.669	376.201

Table A.12: Yacht B total refit cost e yearly CapEx for Owner 3 and 4

Propulsion	Hotel load	Owner 3		Owner 4	
		Refit cost [€]	CapEx [€]	Refit cost [€]	CapEx [€]
HVO	HVO	2.173.258	257.877	2.282.337	261.513
Methanol (ICE)	Methanol (ICE)	-	-	2.351.170	261.513
Methanol (PEMFC)	Methanol (PEMFC)	-	-	10.191.170	616.763
Bio-Methanol (ICE)	Bio-Methanol (ICE)	-	-	2.351.170	261.513
Bio-Methanol (PEMFC)	Bio-Methanol (PEMFC)	-	-	10.191.170	616.763
e-Methanol (ICE)	e-Methanol (ICE)	-	-	2.351.170	261.513
e-Methanol (PEMFC)	e-Methanol (PEMFC)	-	-	10.191.170	616.763
HVO	Methanol (ICE)	2.204.565	257.877	2.307.209	261.513
HVO	Methanol (PEMFC)	3.254.165	305.437	3.356.809	309.073
HVO	Bio-Methanol (ICE)	2.204.565	257.877	2.307.209	261.513
HVO	Bio-Methanol (PEMFC)	3.254.165	305.437	3.356.809	309.073
HVO	e-Methanol (ICE)	2.204.565	257.877	2.307.209	261.513
HVO	e-Methanol (PEMFC)	3.254.165	305.437	3.356.809	309.073
Methanol (ICE)	HVO	2.268.737	257.877	2.326.299	261.513
Methanol (ICE)	Methanol (PEMFC)	-	-	3.400.770	309.073
Methanol (PEMFC)	HVO	9.059.137	565.567	9.116.699	569.203
Methanol (PEMFC)	Methanol (ICE)	-	-	9.141.570	569.203
Bio-Methanol (ICE)	HVO	2.268.737	257.877	2.326.299	261.513
Bio-Methanol (ICE)	Bio-Methanol (PEMFC)	-	-	9.141.570	569.203
Bio-Methanol (PEMFC)	HVO	9.059.137	565.567	9.116.699	569.203
Bio-Methanol (PEMFC)	Bio-Methanol (ICE)	-	-	3.400.770	309.073
e-Methanol (ICE)	HVO	2.268.737	257.877	2.326.299	261.513
e-Methanol (ICE)	e-Methanol (PEMFC)	-	-	3.400.770	309.073
e-Methanol (PEMFC)	HVO	9.059.137	565.567	9.116.699	569.203
e-Methanol (PEMFC)	e-Methanol (ICE)	-	-	9.141.570	569.203

Table A.13: Yacht A TCO % variation compared to standard refit in the current scenario

Current scenario					
Propulsion	Hotel load	Owner 1	Owner 2	Owner 3	Owner 4
		TCO [%]	TCO [%]	TCO [%]	TCO [%]
HVO	HVO	122%	117%	96%	92%
Methanol (ICE)	Methanol (ICE)	-	-	97%	93%
Methanol (PEMFC)	Methanol (PEMFC)	-	-	-	169%
Bio-Methanol (ICE)	Bio-Methanol (ICE)	-	-	108%	102%
Bio-Methanol (PEMFC)	Bio-Methanol (PEMFC)	-	-	-	178%
e-Methanol (ICE)	e-Methanol (ICE)	-	-	128%	117%
e-Methanol (PEMFC)	e-Methanol (PEMFC)	-	-	-	194%
HVO	Methanol (ICE)	-	118%	96%	92%
HVO	Methanol (PEMFC)	-	130%	109%	105%
HVO	Bio-Methanol (ICE)	-	122%	100%	96%
HVO	Bio-Methanol (PEMFC)	-	134%	112%	108%
HVO	e-Methanol (ICE)	-	129%	106%	101%
HVO	e-Methanol (PEMFC)	-	141%	119%	114%
HVO	Hydrogen	-	-	-	100%
HVO	e-Hydrogen	-	-	-	109%
Methanol (ICE)	HVO	-	-	96%	92%
Methanol (ICE)	Methanol (PEMFC)	-	-	-	105%
Methanol (PEMFC)	HVO	-	-	161%	157%
Methanol (PEMFC)	Methanol (ICE)	-	-	-	157%
Bio-Methanol (ICE)	HVO	-	-	104%	98%
Bio-Methanol (ICE)	Bio-Methanol (PEMFC)	-	-	-	114%
Bio-Methanol (PEMFC)	HVO	-	-	169%	162%
Bio-Methanol (PEMFC)	Bio-Methanol (ICE)	-	-	-	166%
e-Methanol (ICE)	HVO	-	-	118%	108%
e-Methanol (ICE)	e-Methanol (PEMFC)	-	-	-	130%
e-Methanol (PEMFC)	HVO	-	-	182%	172%
e-Methanol (PEMFC)	e-Methanol (ICE)	-	-	-	181%

Table A.14: Yacht A TCO % variation compared to standard refit in scenario 1

Scenario 1					
Propulsion	Hotel load	**Owner 1**	**Owner 2**	**Owner 3**	**Owner 4**
		TCO [%]	TCO [%]	TCO [%]	TCO [%]
HVO	HVO	126%	119%	99%	93%
Methanol (ICE)	Methanol (ICE)	-	-	95%	91%
Methanol (PEMFC)	Methanol (PEMFC)	-	-	-	162%
Bio-Methanol (ICE)	Bio-Methanol (ICE)	-	-	113%	104%
Bio-Methanol (PEMFC)	Bio-Methanol (PEMFC)	-	-	-	176%
e-Methanol (ICE)	e-Methanol (ICE)	-	-	121%	111%
e-Methanol (PEMFC)	e-Methanol (PEMFC)	-	-	-	182%
HVO	Methanol (ICE)	-	118%	98%	92%
HVO	Methanol (PEMFC)	-	130%	109%	104%
HVO	Bio-Methanol (ICE)	-	124%	103%	97%
HVO	Bio-Methanol (PEMFC)	-	136%	115%	109%
HVO	e-Methanol (ICE)	-	127%	106%	100%
HVO	e-Methanol (PEMFC)	-	139%	118%	112%
HVO	Hydrogen	-	-	-	100%
HVO	e-Hydrogen	-	-	-	107%
Methanol (ICE)	HVO	-	-	96%	92%
Methanol (ICE)	Methanol (PEMFC)	-	-	-	102%
Methanol (PEMFC)	HVO	-	-	156%	151%
Methanol (PEMFC)	Methanol (ICE)	-	-	-	150%
Bio-Methanol (ICE)	HVO	-	-	109%	100%
Bio-Methanol (ICE)	Bio-Methanol (PEMFC)	-	-	-	116%
Bio-Methanol (PEMFC)	HVO	-	-	168%	160%
Bio-Methanol (PEMFC)	Bio-Methanol (ICE)	-	-	-	164%
e-Methanol (ICE)	HVO	-	-	114%	104%
e-Methanol (ICE)	e-Methanol (PEMFC)	-	-	-	123%
e-Methanol (PEMFC)	HVO	-	-	174%	164%
e-Methanol (PEMFC)	e-Methanol (ICE)	-	-	-	171%

Table A.15: Yacht A TCO % variation compared to standard refit in scenario 2

Scenario 2					
Propulsion	Hotel load	**Owner 1**	**Owner 2**	**Owner 3**	**Owner 4**
		TCO [%]	TCO [%]	TCO [%]	TCO [%]
HVO	HVO	117%	112%	91%	88%
Methanol (ICE)	Methanol (ICE)	-	-	89%	86%
Methanol (PEMFC)	Methanol (PEMFC)	-	-	-	158%
Bio-Methanol (ICE)	Bio-Methanol (ICE)	-	-	99%	94%
Bio-Methanol (PEMFC)	Bio-Methanol (PEMFC)	-	-	-	166%
e-Methanol (ICE)	e-Methanol (ICE)	-	-	104%	97%
e-Methanol (PEMFC)	e-Methanol (PEMFC)	-	-	-	170%
HVO	Methanol (ICE)	-	111%	91%	87%
HVO	Methanol (PEMFC)	-	123%	103%	99%
HVO	Bio-Methanol (ICE)	-	114%	94%	90%
HVO	Bio-Methanol (PEMFC)	-	126%	106%	102%
HVO	e-Methanol (ICE)	-	116%	95%	91%
HVO	e-Methanol (PEMFC)	-	128%	107%	103%
HVO	Hydrogen	-	-	-	92%
HVO	e-Hydrogen	-	-	-	96%
Methanol (ICE)	HVO	-	-	90%	87%
Methanol (ICE)	Methanol (PEMFC)	-	-	-	98%
Methanol (PEMFC)	HVO	-	-	151%	147%
Methanol (PEMFC)	Methanol (ICE)	-	-	-	147%
Bio-Methanol (ICE)	HVO	-	-	97%	91%
Bio-Methanol (ICE)	Bio-Methanol (PEMFC)	-	-	-	105%
Bio-Methanol (PEMFC)	HVO	-	-	157%	152%
Bio-Methanol (PEMFC)	Bio-Methanol (ICE)	-	-	-	154%
e-Methanol (ICE)	HVO	-	-	100%	94%
e-Methanol (ICE)	e-Methanol (PEMFC)	-	-	-	109%
e-Methanol (PEMFC)	HVO	-	-	160%	154%
e-Methanol (PEMFC)	e-Methanol (ICE)	-	-	-	158%

Table A.16: Yacht A TCO % variation compared to standard refit in scenario 3

Scenario 3					
Propulsion	Hotel load	**Owner 1**	**Owner 2**	**Owner 3**	**Owner 4**
		TCO [%]	TCO [%]	TCO [%]	TCO [%]
HVO	HVO	114%	108%	89%	85%
Methanol (ICE)	Methanol (ICE)	-	-	87%	83%
Methanol (PEMFC)	Methanol (PEMFC)	-	-	-	149%
Bio-Methanol (ICE)	Bio-Methanol (ICE)	-	-	96%	90%
Bio-Methanol (PEMFC)	Bio-Methanol (PEMFC)	-	-		156%
e-Methanol (ICE)	e-Methanol (ICE)	-	-	100%	93%
e-Methanol (PEMFC)	e-Methanol (PEMFC)	-	-	-	160%
HVO	Methanol (ICE)	-	107%	89%	84%
HVO	Methanol (PEMFC)	-	118%	100%	95%
HVO	Bio-Methanol (ICE)	-	111%	92%	87%
HVO	Bio-Methanol (PEMFC)	-	121%	102%	97%
HVO	e-Methanol (ICE)	-	112%	93%	88%
HVO	e-Methanol (PEMFC)	-	123%	104%	99%
HVO	Hydrogen	-	-	-	87%
HVO	e-Hydrogen	-	-	-	91%
Methanol (ICE)	HVO	-	-	88%	84%
Methanol (ICE)	Methanol (PEMFC)	-	-	-	94%
Methanol (PEMFC)	HVO	-	-	144%	139%
Methanol (PEMFC)	Methanol (ICE)	-	-	-	139%
Bio-Methanol (ICE)	HVO	-	-	94%	88%
Bio-Methanol (ICE)	Bio-Methanol (PEMFC)	-	-	-	101%
Bio-Methanol (PEMFC)	HVO	-	-	150%	144%
Bio-Methanol (PEMFC)	Bio-Methanol (ICE)	-	-	-	146%
e-Methanol (ICE)	HVO	-	-	97%	90%
e-Methanol (ICE)	e-Methanol (PEMFC)	-	-	-	104%
e-Methanol (PEMFC)	HVO	-	-	152%	146%
e-Methanol (PEMFC)	e-Methanol (ICE)	-	-	-	149%

Table A.17: Yacht B TCO % variation compared to standard refit in the current scenario

Current scenario					
Propulsion	Hotel load	**Owner 1**	**Owner 2**	**Owner 3**	**Owner 4**
		TCO [%]	TCO [%]	TCO [%]	TCO [%]
HVO	HVO	119%	114%	94%	90%
Methanol (ICE)	Methanol (ICE)	-	-	-	91%
Methanol (PEMFC)	Methanol (PEMFC)	-	-	-	188%
Bio-Methanol (ICE)	Bio-Methanol (ICE)	-	-	-	101%
Bio-Methanol (PEMFC)	Bio-Methanol (PEMFC)	-	-	-	197%
e-Methanol (ICE)	e-Methanol (ICE)	-	-	-	116%
e-Methanol (PEMFC)	e-Methanol (PEMFC)	-	-	-	213%
HVO	Methanol (ICE)	-	114%	95%	91%
HVO	Methanol (PEMFC)	-	127%	108%	104%
HVO	Bio-Methanol (ICE)	-	119%	98%	94%
HVO	Bio-Methanol (PEMFC)	-	131%	111%	107%
HVO	e-Methanol (ICE)	-	125%	105%	100%
HVO	e-Methanol (PEMFC)	-	138%	118%	113%
Methanol (ICE)	HVO	-	-	95%	91%
Methanol (ICE)	Methanol (PEMFC)	-	-	-	104%
Methanol (PEMFC)	HVO	-	-	179%	175%
Methanol (PEMFC)	Methanol (ICE)	-	-	-	175%
Bio-Methanol (ICE)	HVO	-	-	103%	97%
Bio-Methanol (ICE)	Bio-Methanol (PEMFC)	-	-	-	114%
Bio-Methanol (PEMFC)	HVO	-	-	187%	180%
Bio-Methanol (PEMFC)	Bio-Methanol (ICE)	-	-	-	184%
e-Methanol (ICE)	HVO	-	-	116%	106%
e-Methanol (ICE)	e-Methanol (PEMFC)	-	-	-	129%
e-Methanol (PEMFC)	HVO	-	-	200%	190%
e-Methanol (PEMFC)	e-Methanol (ICE)	-	-	-	200%

Table A.18: Yacht B TCO % variation compared to standard refit in scenario 1

Scenario 1					
Propulsion	Hotel load	**Owner 1**	**Owner 2**	**Owner 3**	**Owner 4**
		TCO [%]	TCO [%]	TCO [%]	TCO [%]
HVO	HVO	123%	116%	98%	92%
Methanol (ICE)	Methanol (ICE)	-	-	-	89%
Methanol (PEMFC)	Methanol (PEMFC)	-	-	-	179%
Bio-Methanol (ICE)	Bio-Methanol (ICE)	-	-	-	103%
Bio-Methanol (PEMFC)	Bio-Methanol (PEMFC)	-	-	-	194%
e-Methanol (ICE)	e-Methanol (ICE)	-	-	-	110%
e-Methanol (PEMFC)	e-Methanol (PEMFC)	-	-	-	200%
HVO	Methanol (ICE)	-	115%	96%	91%
HVO	Methanol (PEMFC)	-	127%	109%	103%
HVO	Bio-Methanol (ICE)	-	121%	102%	96%
HVO	Bio-Methanol (PEMFC)	-	133%	114%	108%
HVO	e-Methanol (ICE)	-	124%	105%	99%
HVO	e-Methanol (PEMFC)	-	136%	117%	111%
Methanol (ICE)	HVO	-	-	95%	90%
Methanol (ICE)	Methanol (PEMFC)	-	-	-	101%
Methanol (PEMFC)	HVO	-	-	173%	168%
Methanol (PEMFC)	Methanol (ICE)	-	-	-	167%
Bio-Methanol (ICE)	HVO	-	-	107%	99%
Bio-Methanol (ICE)	Bio-Methanol (PEMFC)	-	-	-	116%
Bio-Methanol (PEMFC)	HVO	-	-	185%	177%
Bio-Methanol (PEMFC)	Bio-Methanol (ICE)	-	-	-	182%
e-Methanol (ICE)	HVO	-	-	113%	103%
e-Methanol (ICE)	e-Methanol (PEMFC)	-	-	-	122%
e-Methanol (PEMFC)	HVO	-	-	191%	181%
e-Methanol (PEMFC)	e-Methanol (ICE)	-	-	-	188%

Table A.19: Yacht B TCO % variation compared to standard refit in scenario 2

Scenario 2					
Propulsion	Hotel load	**Owner 1**	**Owner 2**	**Owner 3**	**Owner 4**
		TCO [%]	TCO [%]	TCO [%]	TCO [%]
HVO	HVO	114%	109%	90%	86%
Methanol (ICE)	Methanol (ICE)	-	-	-	85%
Methanol (PEMFC)	Methanol (PEMFC)	-	-	-	176%
Bio-Methanol (ICE)	Bio-Methanol (ICE)	-	-	-	92%
Bio-Methanol (PEMFC)	Bio-Methanol (PEMFC)	-	-	-	184%
e-Methanol (ICE)	e-Methanol (ICE)	-	-	-	96%
e-Methanol (PEMFC)	e-Methanol (PEMFC)	-	-	-	187%
HVO	Methanol (ICE)	-	108%	89%	86%
HVO	Methanol (PEMFC)	-	120%	102%	98%
HVO	Bio-Methanol (ICE)	-	111%	93%	89%
HVO	Bio-Methanol (PEMFC)	-	124%	105%	101%
HVO	e-Methanol (ICE)	-	113%	94%	90%
HVO	e-Methanol (PEMFC)	-	125%	106%	102%
Methanol (ICE)	HVO	-	-	89%	85%
Methanol (ICE)	Methanol (PEMFC)	-	-	-	97%
Methanol (PEMFC)	HVO	-	-	168%	164%
Methanol (PEMFC)	Methanol (ICE)	-	-	-	164%
Bio-Methanol (ICE)	HVO	-	-	95%	90%
Bio-Methanol (ICE)	Bio-Methanol (PEMFC)	-	-	-	105%
Bio-Methanol (PEMFC)	HVO	-	-	174%	169%
Bio-Methanol (PEMFC)	Bio-Methanol (ICE)	-	-	-	171%
e-Methanol (ICE)	HVO	-	-	98%	92%
e-Methanol (ICE)	e-Methanol (PEMFC)	-	-	-	108%
e-Methanol (PEMFC)	HVO	-	-	178%	171%
e-Methanol (PEMFC)	e-Methanol (ICE)	-	-	-	175%

Table A.20: Yacht B TCO % variation compared to standard refit in scenario 3

Scenario 3					
Propulsion	Hotel load	**Owner 1**	**Owner 2**	**Owner 3**	**Owner 4**
		TCO [%]	TCO [%]	TCO [%]	TCO [%]
HVO	HVO	111%	105%	88%	83%
Methanol (ICE)	Methanol (ICE)	-	-	-	82%
Methanol (PEMFC)	Methanol (PEMFC)	-	-	-	166%
Bio-Methanol (ICE)	Bio-Methanol (ICE)	-	-	-	89%
Bio-Methanol (PEMFC)	Bio-Methanol (PEMFC)	-	-	-	173%
e-Methanol (ICE)	e-Methanol (ICE)	-	-	-	92%
e-Methanol (PEMFC)	e-Methanol (PEMFC)	-	-	-	176%
HVO	Methanol (ICE)	-	105%	88%	83%
HVO	Methanol (PEMFC)	-	116%	99%	94%
HVO	Bio-Methanol (ICE)	-	108%	90%	86%
HVO	Bio-Methanol (PEMFC)	-	119%	102%	97%
HVO	e-Methanol (ICE)	-	109%	92%	87%
HVO	e-Methanol (PEMFC)	-	120%	103%	98%
Methanol (ICE)	HVO	-	-	87%	82%
Methanol (ICE)	Methanol (PEMFC)	-	-	-	93%
Methanol (PEMFC)	HVO	-	-	159%	155%
Methanol (PEMFC)	Methanol (ICE)	-	-	-	154%
Bio-Methanol (ICE)	HVO	-	-	93%	87%
Bio-Methanol (ICE)	Bio-Methanol (PEMFC)	-	-	-	100%
Bio-Methanol (PEMFC)	HVO	-	-	165%	159%
Bio-Methanol (PEMFC)	Bio-Methanol (ICE)	-	-	-	162%
e-Methanol (ICE)	HVO	-	-	96%	89%
e-Methanol (ICE)	e-Methanol (PEMFC)	-	-	-	104%
e-Methanol (PEMFC)	HVO	-	-	168%	161%
e-Methanol (PEMFC)	e-Methanol (ICE)	-	-	-	165%