The Yacht of 2030

Master Thesis by
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The Yacht of 2030

By

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ABSTRACT

Greenhouse gas emissions' reduction goals of a 50% reduction by 2050 were established by the IMO. As a first step to achieve this reduction already by 2030 this project uncovers how much of the CO_2 emissions it is possible to reduce by combining the available state of the art technology.

The reduction of CO_2 emissions is done in two steps. The first step consists in reducing the power demand in terms of auxiliary and propulsion systems. After that, cleaner power supply alternatives are considered to further reduce the emissions.

In terms of auxiliary power, heavy consumers such the air conditioning, the lighting or water systems are considered. The reduction of auxiliary power is not only achieved with the introduction of more efficient equipment but also by the introduction of passive design strategies that enhance savings by reducing the loading on the systems. Altogether it is possible to reduce the auxiliary power demand by 33% in comparison with the benchmark design. The reduction of auxiliary power demand has a significant impact on the yearly consumption due to the significant percentage of operational time spent at anchorage.

In terms of propulsion power demand, the reductions achieved are even more significant, 51% and 70% power demand reductions are possible at cruising and maximum speed, respectively. The introduction of the Van Oossanen's Fast Displacement Hull Form (FDHF), the reduction of displacement by making an aluminium hull and the application of the patented Hull Vane® are the main reasons for such a significant propulsion power demand.

Finally, the switch in power plant arrangement of the yacht results in further 10% reduction. In this case, simply the change from diesel direct arrangement to a hybrid arrangement leads to yearly savings, mainly because emissions at cruising are reduced due to the power take-off operational mode of the power plant, saving generator set emissions.

All in all, it is possible to already achieve a reduction of approximately 41% of the yearly CO_2 emissions on a 50 m motor yacht. One of the most important conclusions to be taken is that all these reductions are possible when finding the optimal interaction between components, from auxiliaries to power plant arrangement. Mainly, the CO_2 emissions reduction followed from a fuel consumption reduction, not yet introducing power supply from renewable energies nor alternative fuels which despite being the way to the future are not yet fully mature and suitable for this specific case.

Nomenclature

AC	Acquisition Cost	[€]
$B_{moulded}$	Moulded beam	[m]
B_{OA}	Beam over all	[m]
D	Displacement	[m^3]
$\overrightarrow{D_{HV}}$	Drag Force on Hull Vane®	[kN]
$\overrightarrow{F_{HV}}$	Sum of forces on the Hull Vane®	[kN]
FV	Future Value	[€]
g	Inflation Rate	%
i	Interest rate	%
i_{GB}	Gearbox ratio	-
IC	Investment Costs	[€]
$\overrightarrow{L_{HV}}$	Lift Force on Hull Vane®	[kN]
L_{wl}	Length on water line	[m]
L_{OA}	Length over all	[m]
n	Lifespan	years
$P_{auxiliaries}$ (P_{aux})	Auxiliary Power	[kW]
$P_{propulsion}$ (P_{prop})	Propulsion Power	[kW]
P_B	Brake Power	[kW]
P_{DE}	Power output of Diesel Engine	[kW]
P_{DG}	Power output of Diesel Generator	[kW]
$P_{EM,el}$	Electric power on e-machine	[kW]
$P_{EM,mec}$	Mechanical power on e-machine	[kW]
RC	Running Costs	[€]
T	Draft	[m]
θ	Trim angle	deg
B	Hull Vane® angle	deg
α	Hull Vane® inflow angle	deg
$\eta_{M/E}$	Efficiency of mechanical to electric energy conversion	%
η_{Fc}	Frequency converters' efficiency	%
η_{EM}	E-machine's efficiency	%
η_{TRM}	Transmission's efficiency (shaft and gearbox)	%

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and A-C Engineers
CFD	Computational Fluid Dynamics
EEDI	Energy Efficiency Design index
ELB	Electric Load Balance
FA	Fresh Air Unit
FDHF	Fast Displacement Hull Form
GHG	Greenhouse Gas
GT	Gross Tonnage
HFO	Heavy Fuel Oil
HVAC	Heating, Ventilation and Air Conditioning
IMO	International Maritime Organization
LED	Light Emitting Diode
LNG	Liquid Natural Gas
LY3	The Large Commercial Yacht Code
MARPOL	International Convention for the Prevention of Pollution from Ships
Max	Maximum
MCR	Maximum Continuous rating
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
PTI	Power Take-In
PTO	Power Take-Off
RC	Running Costs
RPM	Rotations per minute
Scn	Scenario
SFC	Specific Fuel Consumption
SOLAS	Safety of Life at Sea
UN	United Nations

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1. INTRODUCTION

1.1 INDUSTRY CONTEXT

The worldwide concern for the environment and the entry into force of the Paris Agreement motivated the MEPC to agree on a roadmap for developing a comprehensive IMO strategy on reducing greenhouse gas emissions from international shipping.

The shipping industry is accountable for 2% to 3% of global greenhouse gas emissions, which places the sector in the top ten of global emitters. The likelihood of an increasing share calls for immediate actions in order to reverse the trends.

In line with the goal of limiting the global temperature increase set by the Paris Agreement, the IMO defined emission reduction objectives to guide discussions on necessary measures to achieve reductions and to drive innovation and investment from the industry in new technologies.

The objectives are set in phases to be implemented over the years, recently a confirmation of the objective of a 50% reduction on global GHG emissions reduction by 2050 in comparison with the 2008 level was released. The first phases are mainly focused on international shipping and new built ships.

The emission levels are to be tightened from phase to phase. Currently, phase 1 is in place and phase 2 expected to be implemented between 2020 and 2025. The committee promised to start the revisions on EEDI phase 3 requirements in terms of reduction levels and ship types included. In addition, early implementation is projected already for the year of 2023.

The maritime sector is characterised by a significant emission reduction potential, allowing for emission reductions already with existing technology. Moreover, cost savings may be a consequence of the energy saving measures in the form of running cost reductions.

The yachting industry is not yet included in the requirements however the fact that requirements for phase 3 are being revised might implicate the sector as well. In addition, the yachting industry is regarded as a technology advanced sector of the maritime industry as it is related to the luxury market and benefits from the social awareness involved in emissions reduction.

1.2 VAN OOSSANEN NAVAL ARCHITECTS

This research is carried out in co-operation with van Oossanen Naval Architects, a company that since its early years focuses on finding excellence in performance in terms of efficiency, safety and comfort. Aiming to be on the forefront of progress, maintain its position in the market, van Oossanen Naval Architects invests in research and seeks for innovation in its designs.

Sustainability and energy saving are on the core of the company's designs by achieving high-performance hull forms, such as the Fast Displacement Hull form (FDHF) or by developing fuel saving devices, such as the Hull Vane®.

In line with the international industry trends, van Oossanen pretends to combine its knowledge in hull design with other energy saving measures in order to be ahead of competition in meeting the emission reduction levels as soon as possible, moving in the direction of zero emissions.

The company's international market position derives from its constant investment in innovations and excellence in sustainable yacht design. As a company van Oossanen motivates her employees to go off the beaten tracks in the search for improvements. This is done not only by putting aside employee working hours for research, but also in co-operation with universities as is the case of this project.

This project is developed with the aim to enlarge van Oossanen's portfolio and assuring its current market position as an innovative company, always on the forefront of technology.

1.3 ROADMAP OF THE REPORT

As a start, chapter 2 elaborates on the research objectives. During this chapter the research questions and sub-questions are presented. Furthermore, the method used to answer this questions and performance assessment method are clarified.

After that, chapter 3, elaborates on the operational profile definition based on Marine Traffic data. It defines the operating time percentages of each operational mode.

Chapter 4, describes and evaluates the benchmark design according to the performance parameters defined under chapter 2, energy efficiency, luxury and costs.

The first research sub-question is answered in chapter 5, where the analysis of the auxiliary power demand leads to energy efficiency improvements of the heavy consumers. Subsequently, the individual assessment of the heavier consumers is combined resulting in the reduction of auxiliary power demand.

Likewise, chapter 6 answers the second research sub-question, elaborating on the reduction of propulsion power demand, thus analysing the hull form design.

Chapter 7 gives the answer to the third research question. It looks into power supply alternatives with potential to reduce CO_2 emissions, assessing their feasibility and applicability to the case.

In chapter 8, the arrangement developed for the new design is described, presenting the changes in terms of layout between the benchmark and the new design.

Posteriorly, chapter 9 assesses the performance of the new design in terms of energy efficiency, luxury and costs in comparison with the performance of the benchmark given in chapter 4. Within this chapter the performance results of the new design according to the performance parameters are presented as well.

Finally, in chapter 10 the research questions are reviewed and a conclusion formulated. In addition, guidelines for future work are given.

2. RESEARCH OBJECTIVE

2.1 INTRODUCTION

This chapter elaborates on the research objective, the main research question, and the method derived through the answering of sub questions to achieve the end goal. Moreover, the scope of the assignment is defined.

Firstly, the background of the research is introduced in the following section based on the regulation's evolution concerning the air pollution due to the shipping sector. After that, the research questions are introduced and the method of approach to each one of the sub questions is explained. Lastly, the limits on the extent of the research are defined on the scope of the assignment.

2.2 BACKGROUND

The final text of the Paris Agreement in 2016 included no explicit reference to international shipping, which accounts for 2.2% of earth's man-made CO_2 emissions (1). The absence of shipping in the deal leaves the U.N.'s International Maritime Organization (IMO) as the sole governing body responsible for cutting greenhouse gas emissions from the sector.

The IMO, originally created for maritime safety (2), has also assumed the responsibility for the prevention of pollution. At first, the main issue considered was oil pollution, on the first MARPOL convention. However, the original convention has been amended several times to account for other types of pollution originated by shipping.

Annex VI adopted in 1997 considers air pollution and emissions by ships. The IMO division for air pollution is continuously working on new and stricter regulations regarding emissions, accounting for different fuels, propulsion arrangements and ship types.

In line with the Paris Agreement, the IMO developed a strategy to reduce the greenhouse gas emissions from ships by setting minimum energy efficiency levels per capacity mile for new build ships, this is known as the Energy Efficiency Design Index (EEDI). (1) The EEDI program is implemented in several phases and the level of emissions' reduction is tightened every five years to keep pace with new technology. The first phase started with a reduction of CO_2 emissions of 10%. Requirements have been established to achieve a reduction of CO_2 emissions of 50% in comparison with 2008's global levels by the year of 2050. (3)

A revision of phase 3 of the program is in progress and a prediction of earlier enforcement of this phase can be expected, 2023 instead of 2025. In this revision various criteria are going to be assessed as well as the introduction of different ship types. (4) Currently, the yachting industry is not included in the program, however it is unpredictable which decisions will come in to force already by 2023 given the increasing pressure on regulatory entities exerted by the public.

At the moment, only the most energy intensive segments of shipping are included in these regulations, leaving the yachting segment out of scope. Nevertheless, the IMO is currently working on new amendments and it is likely that yachting will also have to comply with similar regulations. (5) (6)

Although rules and regulations to come are uncertain, shipping and more specifically yachting will likely be affected. Van Oossanen's aim is to be well prepared for these regulations-to-come and to be on the forefront of new technologies.

2.3 RESEARCH QUESTION

Taking into consideration the above mentioned, together with the growing awareness of yacht owners for environmental issues, designing for higher energy efficiency and reduced emissions is the way to the future according to van Oossanen's experts.

Keeping in mind the IMO goals and striving to achieve a 50% reduction on the overall CO_2 emissions already by the year of 2030 the main research question is as follows:

> *"How much of the CO_2 emissions can already be reduced by combining the available state of the art technology in various areas and still have an attractive under 500 GT design for the market?"*

Being aware of how much is it possible to reduce the emissions by today is the first step towards achieving the goals established, reason why the research question focuses in available technology in the market. Furthermore, the goal is set to achieve an attractive design to the market as is the goal of van Oossanen to commercially market this design enlarging its own portfolio. Finally, the requirement of an under 500GT follows from the moderate regulatory framework in which this category is included, regarding the Large Commercial Yacht Code (7) and the exemption from complying with SOLAS's additional safety regulations. The reduced crew area requirements and lighter fire protection requirements, allow for a greater percentage of the interior volume to be assigned to guest activities which is more attractive to the market.

The gross tonnage constraint will represent a challenge when it comes to applying new technology as these normally take up a great amount of internal/external volume. The project aims to achieve the CO_2 emissions reduction by maintaining the functional specifications as much as possible and by keeping the yacht eligible for the under 500GT regulatory frameworks.

The main research question is divided in to two main topics, power demand reduction and power supply alternatives. From the first one two research questions are derived regarding the reduction of power demand, from the latter only one research question is derived. These sub questions address different ways of attaining the end goal of reducing CO_2 emissions:

1. *How much of the auxiliary power demand is it possible to reduce?*

This sub-question elaborates on reducing the power consumption of the auxiliary systems not only by introducing more efficient equipment but also by the introduction of passive design strategies in order to reduce the loads on equipment.

2. *How much of the propulsion power demand is it possible to reduce?*

This sub-question elaborates on the propulsion power reduction mainly by reducing the hull's resistance. It considers a change in hull form, material and the application of the energy saving device developed and patented by van Oossanen, the Hull Vane®.

3. *How much CO_2 emissions is it possible to reduce by considering power supply alternatives?*

At last, the final sub-question elaborates on the alternatives to reduce CO_2 emissions in terms of power supply. Either considering alternative fuels, renewable energies or alternative plant configurations.

The following sections elaborate on each question more in depth, clarifying the method followed to answer each one of them.

2.3.1 Sub Question 1: The Auxiliary power demand reduction

This sub-question follows form the fact that a great percentage of the operational profile of yachts is spent at anchorage (8), which results in a high percentage of yearly CO_2 emissions to be a consequence of the auxiliary power.

In addition, from the reference's electric load balance, over the whole operational profile of the yacht, the auxiliary's power demand is high, which points to the fact that possible reductions in consumption are possible.

To answer this sub-question, the first step is to identify the heavier consumers as these are the ones whose demand reduction will have a more significant impact to the overall demand. After that, the identified systems are analysed and possible strategies to reduce power demand are considered.

For this purpose, market research will indicate the newest available technology on the market that will improve energy efficiency of the heavy consumer systems. As a decision tool, a multi-criteria analysis based on cost, weight, size and benefit/contribution to energy reduction is used in order to select the most promising strategies to be applied.

2.3.2 Sub Question 2: Propulsion Power Demand

The second sub-question also considers power demand reduction. Following the auxiliary power demand reduction, there is the need to reduce the propulsion power.

The propulsion systems power demand is still the highest in comparison with other systems, especially at high speeds. Reason why the reduction of propulsion power demand has a substantial impact on yearly power consumption, thus fuel consumption, thus CO_2 emissions.

Reducing the propulsion power demand is often a goal in yacht design, either to reduce fuel consumption or to meet contract speeds. Mainly, to reduce power demand it is possible to focus on resistance reduction and efficiency of propulsion systems. In this case, the focus is given to the resistance reduction.

To answer this question, a benchmark design with a steel full displacement hull form is considered and compared to different hull forms previously designed by van Oossanen. Furthermore, the application of the Hull Vane®, an energy saving device is considered to further improve the performance of the yacht.

2.3.3 Cleaner Power Supply Alternatives

Finally, once the overall power demand is reduced, the third sub-question assesses how to supply the required power minimizing the resultant CO_2 emissions.

The answer to this sub question considers the implementation of new or more efficient technologies for power supply, such as alternative fuels, renewable energies and hybrid solutions.

In spite of the advantages offered by newer technologies, these are not always feasible or the best option regarding their size, cost etc. Furthermore, the maturity of technology combined with the functional specifications of the yacht determine the feasibility and applicability of each technology considered.

Once all sub-questions have been answered, there is the need to assess the quality of the new design encountered. For this reason three performance parameters and three different user profiles are defined. The assessment method description can be found on the next section, as well as the description of the performance parameters and user profiles.

2.4 ASSESSMENT METHOD

The assessment method is used to assess not only the final performance of the end design in comparison with the benchmark but also to assess and compare the feasibility of strategies to reduce power consumption in terms of auxiliary systems. The analysis is based on a multiple objective comparison function considering an additive aggregation model (9). In this way the strategies/designs can be compared in a mathematical way.

The criteria defined for the multiple objective comparison function are the performance parameters elaborated on the next sub-section. Nonetheless, some adaptation of the criteria is made when assessing the feasibility of strategies to reduce power consumption so to enable a better assessment, these are elaborated on section 5.2.

For each criterion (performance parameter), objective values are given *a priori,* and weights assigned according to the user's preferences since some criteria are perceived as more important than others. For each criterion *i*, the design *d (*or strategy *s)* is given an objective value $O_{I,d}$ ($O_{i,s}$). However, firstly the objective value is normalised according to Equation 2.

After being normalised, the objective value is multiplied by the weight factor $w_{u,i}$ depending on the user profile *u* (section 2.4.1*).*

Finally, the scores are summed to form a global performance parameter *P*. The global parameter *P* for design *d*, calculated for user *u* is calculated as follows in Equation 1.

$$P_{d,u} = \sum_{i=1}^{5} w_{u,i} * f(O_{i,d})$$

Equation 1

The need to normalise the objective values is common to various multi-criteria decision analysis methods. A normalisation procedure consists of carrying out a scale transformation so to convert all criteria to the same scale.

There are several options regarding normalisation procedures, in this case, there is the need to evaluate the difference between strategies, therefore a ratio scale procedure is considered. (9)

In this procedure, the best scoring strategy is awarded a value of 1 and the others scaled accordingly as a percentage of the leading strategy, as follows in Equation 2.

$$f(O_{i,s}) = \begin{cases} 1, & O_{i,s} = O_{i,max} \\ \dfrac{O_{i,s}}{O_{i,max}}, & O_{i,s} \neq O_{i,max} \end{cases}$$

Equation 2

In addition, the performance of the design is sensitive to the weights assigned by the decision makers, the users. This way it is possible to analyse the sensitivity of the multiple objective comparison function.

2.4.1 THE USER PROFILES

As stated before, in order to assess the sensitivity of the decision making process there is the need to define three different user profiles, which have different preferences, thus assign different weights to the criteria.

As different yacht owners have different requirements and prioritize different aspects of their yachts, different user profiles are created to assess the end design from different perspectives. Similarly to what has been done on the work of Kasper Uithof (10), the following users are considered:

1. *The Economist*, wants good value for his money
2. *The Family Man*, seeks space on board to comfortably have his family
3. *The Environmentalist*, prioritizes the environment and wants a green yacht

According to this preferences each user assigns a different weight factor to the performance parameters as displayed in Table 1.

Table 1: Weight Factors of the criteria according to each user profile

	The Economist	The Family Man	The Environmentalist
Energy Efficiency	0.3	0.2	0.5
Luxury	0.2	0.5	0.2
Costs	0.5	0.3	0.3

Taking this in consideration it will be possible to rank the new designs according to the different preferences of each user.

2.4.2 THE PERFORMANCE PARAMETERS

Three performance parameters to evaluate the new design and compare it to the benchmark design are created. These parameters assess not only how the design meets the goal of CO_2 emissions reduction but also how it performs in terms of attractiveness to the market, based on space and costs.

ENERGY EFFICIENCY

The energy efficiency is a measure of the CO_2 emissions. CO_2 emissions are measured in kg/h at each operational mode.

Taking in consideration the operational profile defined on chapter 3, thus the hours per year spent at each mode it is possible to define the amount of CO_2 emitted per year of the designs. Therefore, the energy efficiency of each design is measured in overall yearly emissions.

Nevertheless, when assessing the strategies or systems' feasibility the energy efficiency is a measure of power consumed instead of CO_2 emissions, as this allows for a better comparison.

LUXURY

Luxury is a measure of available space.

In terms of design's comparison it considers the interior deck area. Moreover, a comparison between exterior area available and guest areas available at each design is separately performed as to give a better indication of luxury.

In terms of strategies' comparison, this is an indicator of space and weight reservation that can be measured in terms of area, volume, thickness and/or weight.

Costs

Costs can be divided into investment and running costs.

Overall, it is expected that investment costs would be higher due to the implementation of alternative systems. Despite the potential increase in maintenance costs, the running costs are expected to be lower due to the enhancement of fuel savings, ultimately leading to running costs savings.

In terms of energy saving strategies the costs are mainly assessed with investment costs.

2.5 Scope

The goal of the project is to integrate several energy efficient systems into one design, therefore instead of intensely develop individual systems; use is going to be made of already performed research and van Oossanen's resources.

The focus will go to the impact of combining several different strategies and systems available in the overall CO_2 emissions and still have a super yacht to be marketed commercially.

This is a starting point to achieve the CO_2 emissions reduction goal for 2030, not only indicating of much is it possible to reduce today but also pointing out in which area more savings are possible.

3. THE OPERATIONAL PROFILE

3.1 INTRODUCTION

The end goal of the new design is to achieve a reduction of the yearly CO_2 emissions and simultaneously achieve an elegant form with a high luxury level to be commercialized.

The operational super yacht considers several different operating modes, ranging from sailing at cruising speed with guests on board to being at anchorage with only crew on board. Furthermore, the operational profiles are highly volatile not only in terms of power demand at each mode but also in terms of percentage of operational time. There are a wide variety of factors influencing the operational profiles, being the principal one the owner.

This chapter elaborates on the determination of the operational profile based on data from the Marine traffic database (11).

3.2 THE OPERATIONAL PROFILE

When considering the operational profile of a superyacht several factors should be addressed.

At first, it is important to define an area of operations. The Mediterranean, the Caribbean and the Bahamas are continuously the most popular destinations. Nevertheless, destinations that are more adventurous are appearing such as Antarctica. Nevertheless, the fact that Ice Classed vessel are a requirement makes these niche markets.

For the development of the project, the geographical profile assumes the most popular destinations, thus the Mediterranean for the summer season and the Caribbean for the winter season.

Regarding the Operational Modes, the following are going to be considered:

- Cruising
- Crossing
- Maximum Speed
- Manoeuvring
- Anchorage
- In Port

The definition of the operational profile of a super yacht can be very challenging since it depends solely on unpredictable patterns.

According to Roy et al. (12), one of the most important characteristics of a yacht is that it spends a significant percentage of time in port/marina or at anchor.

In order to find a more clarifying picture of current usage of yachts within the size range considered, thus between 40m and 60m, Marine Traffic data (11) was analysed and used as a base to define the operational profile considered for the project.

The fact that Marine traffic data is only available for the past 90 days forced the analysis of the operational profile to be based on vessels currently sailing on the Caribbean. Furthermore, it did not allow for a full year analysis.

Nevertheless, the conclusions taken for the winter season on the Caribbean are similar to the ones taken for the summer season in the Mediterranean regarding operational profile, since the trends in cruising in both areas are similar.

For this reason, eight yachts between 40m and 60 m on the Caribbean Sea area were randomly chosen and their itinerary history collect. The data collected can be found in Appendix A, meanwhile Table 2 presents the maximum, minimum and average percentage of time at each operational mode.

Table 2: Itinerary history collection based on Marine Traffic

	Cruising	Crossing	Maximum Speed	Manoeuvring	At Anchor	In Port
	%	%	%	%	%	%
Maximum	22.29%	18.58%	1.12%	3.36%	67.00%	78.04%
Minimum	1.80%	0.00%	0.14%	0.41%	10.21%	6.23%
Average	8.40%	8.03%	0.43%	1.30%	38.97%	42.86%

Figure 1 plots the amplitude between the maximum and minimum percentages for each modes, showing that in some cases this amplitude is rather significant. The highly volatile operational profile of a super yacht, varying from owner to owner and year after year is the main reason for these results. This presents a great challenge regarding operational profile prediction, reason why literature on the subject is so short and subjective.

Figure 2 represents the average operational profile that will be considered from now on, as an estimation for calculation purposes of emissions estimations. A full data set is not possible due to the constraints of data availability of the Marine Traffic, however these are assumed as a good representation of a yacht's operational profile, in line with literature. (12)

Nevertheless, more accurate operational profile predictions will lead to more accurate load profiles, which in turn will contribute for better optimizations.

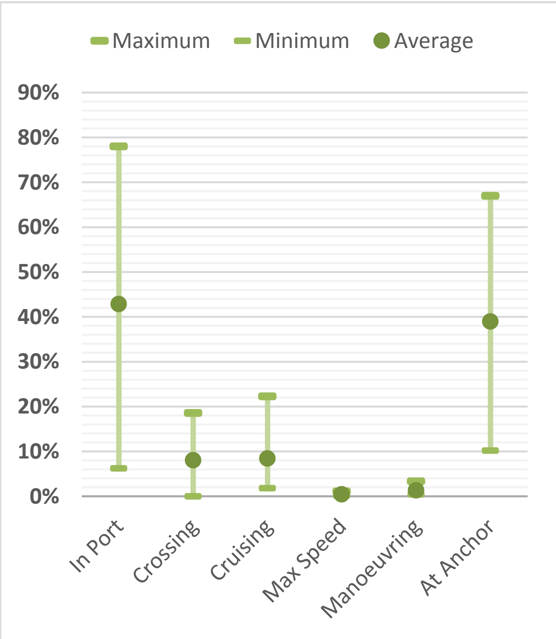


Figure 1: Operational Profile range per operating mode

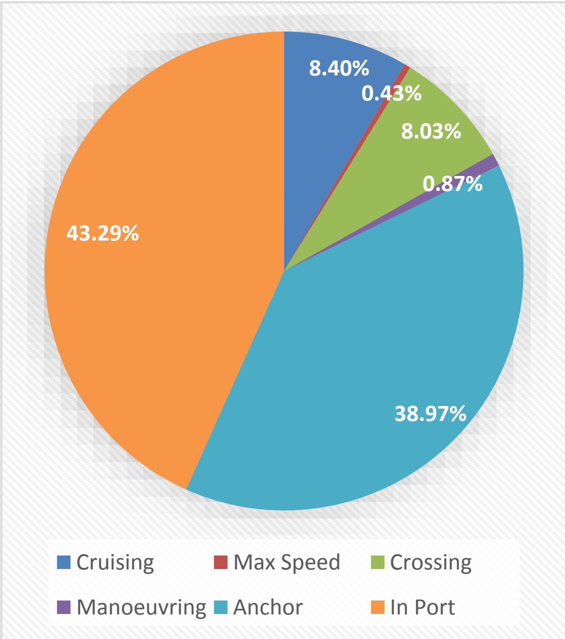


Figure 2: Operational Profile based on Marine Traffic

From Figure 2, it is possible to conclude that for approximately 80% of the time the yacht is either in port or at anchor, resulting in a significant impact of auxiliary loads on the total yearly power demand. After that, approximately 16% of the time is spent sailing at cruising speeds in operational modes such as cruising or crossing. Consequently, this leaves only a small percentage of time for both manoeuvring and maximum speed, which as it is going to be seen in the next chapter (chapter 4) are the ones with the highest power demand.

Following the assumption that when in port the yacht is on shore power, thus no CO_2 emission data is available to assess the impact of reductions; the operational mode is left out of scope concerning the emissions reduction assessment. Nonetheless, by reducing the overall power demand on the auxiliary systems will also result in savings when in port, however these will not be quantified.

Regarding the sailing modes, even though trends point to higher maximum speed requirements according to van Oossanen’s experience, these are sailed only for a short period of time as it can be seen from Figure 2. Therefore, in line with the chosen benchmark, the maximum speed is 16 knots. Furthermore, concerning the cruising speed, 12 knots are assumed, once more in line with the benchmark design.

4. THE BENCHMARK DESIGN

4.1 INTRODUCTION

As a starting point for the re-design and a reference for final evaluation of the new concept there is the need to choose a design from the company's portfolio.

This chapter describes the benchmark design chosen and evaluates its performance regarding the performance parameters.

4.2 THE MAIN CHARACTERISTICS OF THE DESIGN

Taking into consideration the market knowledge of Van Oossanen Naval Architects design no. 07-011 STORMAX 45m is chosen to be the reference design and start point for re-design considered throughout the entire project. The design is for a full displacement, steel hull with aluminium superstructure motor yacht with two diesel engines, MTU 12V 2000 M72 (1080 kW each). (Figure 3)

With the styling from Omega Architects and built by Laky Verf, a Russian Shipyard the STORMAX 45m is designed for a maximum speed of 16 knots and a cruising speed of 12 knots. The main Particulars of the yacht can be found on Table 3.

Figure 3: The Benchmark Design

Table 3: Main Particulars of Van Oossanen 07-011

L_{OA}	45.65	m
L_{wl}	39.05	m
B_{OA}	9.3	m
$B_{moulded}$	9.02	m
$T_{50\%}$	2.55	m
$T_{100\%}$	2.69	m
$Displacement_{50\%}$	420	Ton
$Displacement_{100\%}$	460	Ton
Tonnage	499	GT

4.3 Layout

The layout of the Van Oossanen 07-110 is regarded as conventional, guest accommodations, engine room and crew areas on the lower deck and owner's areas located in the Main Deck forward at a full beam extension.

The reference design is taken as a start point and minimum requirement for the layout design of the new yacht, however re-arrangements and changes are allowed for later stages of the project.

4.3.1 Lower Deck Accommodation

Figure 4: Lower Deck Layout

The lower deck is divided into four different areas (Figure 4). At the aft part, there is the tender garage and lazarette with a steam room and a lounge area located on portside. Forward to the tender garage, there is the engine room.

In front, there are four guest cabins with bathroom. Two VIP guest cabins with double beds and two twin cabins with single Pullman berth and a bathroom for each cabin. Moreover, there is an atrium with stair connecting to the main deck.

Forward on the deck, there is the crew area where a laundry room, a mess and four double cabins with bathroom are included.

Figure 5: Main Deck Layout

4.3.2 Main Deck

At the aft there is the bar area and the salon with dinning. In front of this, there is a corridor and atrium leading to the stairs, either downwards to the lower accommodation deck or upwards to the wheelhouse. Furthermore, there is also a day toilet in this area.

Forward to this, there is the Galley, Pantry, Walk-in cold room and Freezer and the stairs from the Crew's Area.

Finally is the owner's area. Staring with an office before entering the stateroom and bathroom, there is also a walk-in closet.

4.3.3 WHEELHOUSE DECK

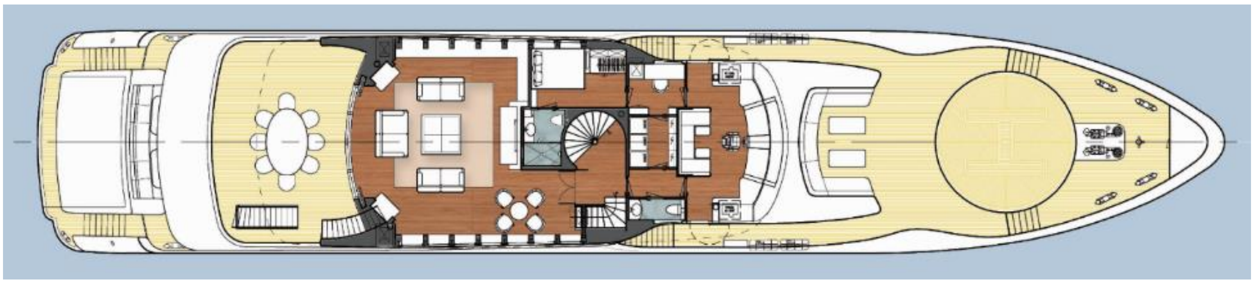


Figure 6: Wheelhouse Deck Layout

The aft part of the wheelhouse deck is a large partly covered are that can accommodate for instance an exterior dining area with a table.

In front of this, already on the interior there is a Sky Lounge with seating areas and entertainment equipment available (video and audio).

The wheelhouse deck contemplates a Sky Lounge at the aft part followed by a corridor and atrium where the stairs connecting to main deck and flying bridge are. Forward, there is a day toilet and pilot house.

Finally is the captain's cabin and bathroom. The captain's cabin has a double bed, wardrobe and desk.

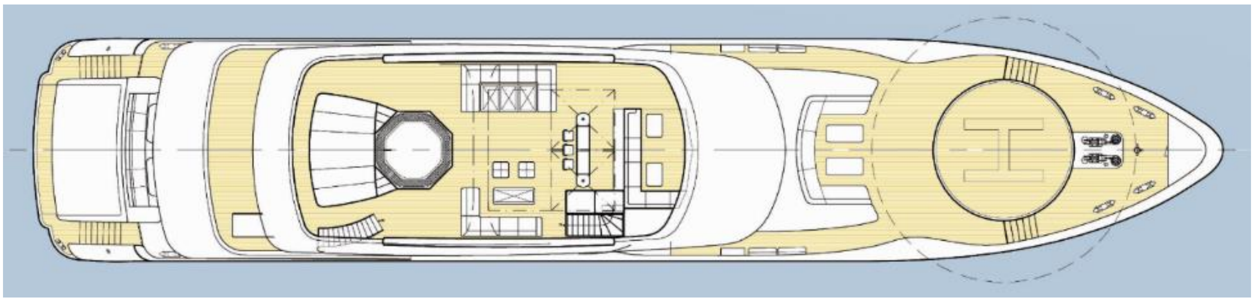


Figure 7: Flying Bridge Layout

4.3.4 SUN DECK

Finally, the flying bridge, also known as sun deck is an exterior lounge area where the most sunlight and privacy are provided to the guests. It is equipped with a Jacuzzi, several sunbeds and benches, a small dining with chairs, a side table, poufs and arm barstools.

In addition, there is a bar equipped with a counter, fridge, Icemaker and a BBQ/ electric grill. There is also the possibility of covering the areas with the two electrical sun awnings available.

On the main deck, there is a touch & go helicopter platform. Whenever there are no helicopters the area is covered with four outside sun loungers.

4.4 THE PERFORMANCE OF THE BENCHMARK DESIGN

As elaborated in chapter 2.4.2, there are three different performance parameters, the energy efficiency, luxury and costs.

4.4.1 ENERGY EFFICIENCY

The energy efficiency is a measure of the yearly CO_2 emissions. In the reference design this will depend on the power demand at each mode, specific fuel consumption of engines and generator set and finally on the operational profile drawn in chapter 3.

The auxiliary power demand follows from the electric load balance that can be found in Appendix B. While the propulsion power demand follows from the resistance and propulsion calculation analysis, chapter 6 provides more data on the analysis. Table 4 displays the power demand, fuel consumption, CO_2 emission rate and yearly CO_2 emissions of the yacht at each mode. In this case, propulsion and auxiliary power supply are independent, thus different calculations for each are presented.

Table 4: Yearly fuel consumption and CO_2 emissions of the benchmark design

	Annual CO_2 emissions from propulsion				Annual CO_2 emissions from auxiliaries			
	$P_{propulsion}$ [kW]	Fuel Consumption [l/h]	kg CO_2/h	ton CO_2 per year	$P_{auxiliary}$ [kW]	Fuel Consumption [l/h]	kg CO_2/h	ton CO_2 per year
Cruising	283	149	396	292	190	53	143	105
Max Speed	1062	515	1373	52	190	53	143	6
Crossing	283	149	396	279	155	44	119	83
Anchor	0	0	0	0	155	38	101	346
Manoeuvring	41	24	65	7	197	55	148	17
Port	-	-	-	-	-	-	-	-
Total				630				557

Figure 8 illustrates the distribution of emissions between auxiliary and propulsion systems at each operational mode. In the operational modes at which the vessel is sailing the propulsion power is responsible for the majority of the emitted CO_2. The exception to this is the manoeuvring operational mode, at which the speeds are low and the load on auxiliary systems is higher due to the use of bow thrusters, mooring systems, etc.

In addition, at anchorage 100% of the emissions are a consequence of the auxiliary power consumption. Reason why the reduction of auxiliary power may have a significant impact in the yearly emissions. Furthermore, the fact that the anchorage mode accounts for approximately 29% (Figure 9) of the yearly CO_2 emissions is another indicator of the potential of reducing power demand from auxiliaries when trying to reduce the yearly CO_2 emissions.

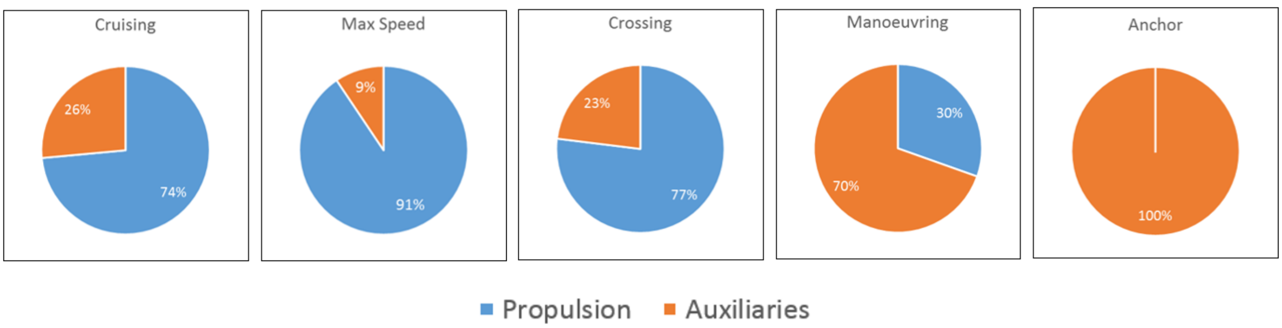


Figure 8: Distribution of emissions according to their origin at each operational mode

Figure 9 presents the share of each operational mode in the total yearly CO_2 emissions. Yearly the benchmark design emits 1187 ton of CO_2, from which cruising is responsible for the highest percentage, approximately 33%.

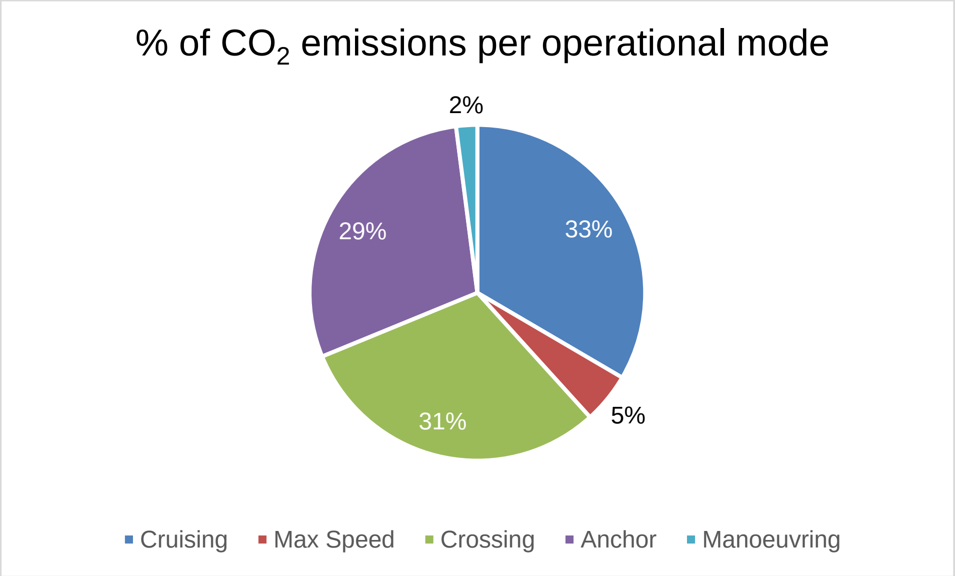


Figure 9: Percentage of CO_2 emitted annually per operational mode

It is noteworthy that despite the fact that maximum speed is the operational mode with the highest emission rate per hour, the fact that its percentage of operational time is so short results in only 5% of the annual CO_2 emissions to be a consequence of maximum speed operations.

4.4.2 Luxury

As defined under section 2.4.2, luxury is defined as the interior deck area. For this reason, the areas of all compartments are measured and presented in Appendix H.1.

The total area interior of the benchmark design is 501 m^2, Table 5 displays the internal area of each deck.

Table 5: Interior area available in each deck

	Benchmark
Lower Accommodation Deck	251 m^2
Main Deck	173 m^2
Wheelhouse deck	77 m^2
Total	501 m^2

4.4.3 Costs

The costs are divided into investment costs and running costs.

Investment Costs

The investment costs for a vessel are assumed to be the combination of the yacht's acquisition AC_Y and its berth acquisition AC_B, as presented in Equation 3.

$$IC_v = AC_{Y,v} + AC_{B,v}$$

Equation 3

The estimation of the yacht's acquisition price is based on van Oossanen's knowledge of the market together. Therefore, the benchmark design, a 45m 500GT steel design has an estimated acquisition cost of 30 million euros.

The berth acquisition price is assumed to be within the same category between 40m and 50m. According to (10), the berth costs for a 50m yacht are approximately 2.02 million euros based on an estimation based on data from (13).

Consequently, the acquisition price for the reference vessel is 32.02 million euros, following Equation 3.

RUNNING COSTS

Annual running costs are extremely difficult to predict since they are dependent on a wide variety of factors, ranging from the type and size of yacht to the owner's utilization.

The running costs encompass categories such as crew salaries, berthing fees, fuel consumption and outgoings.

The outgoings category includes a large variety of items such as, uniforms, food, drinks, toiletries, gadgets, electronics and AV equipment, Sports equipment, garage equipment, bridge equipment, paint, deck equipment, insurance and engine room & technical equipment.

Apart from this, the above mentioned categories follow from a survey by the Superyacht Intelligence (13). The figures are based on the estimation that the yacht spends 11 weeks in use, which means that guests are on board. For the other 41 weeks the yacht is not in use which in categories such as food translates in to lower costs.

The outgoing costs estimated based on the survey (13) are presented in Table 7. Included in these costs are the maintenance of engine and generator sets based on their yearly operational hours based on the operational profile defined in chapter 3. According to a market inquiry the maintenance costs are scaled based on the power output of these components, the maintenance for the engines and generators installed on the benchmark are presented in Table 6.

Table 6: Maintenance Costs of Main Diesel Engines and Generator sets of the benchmark design

Component	Number installed	Power Output	Maintenance [€/h]	Operational hours per year	Yearly Maintenance Costs [€/year]
Main engine	2	1080 kW	€4.84	1591.7835	€15,408.46
Generator set	2	99kW	€2.49	5005.8730	€24,929.25

Table 7: Outgoings estimated based on the Yacht Intelligence's survey (13)

	Monthly Costs [€/month]		**Yearly Costs [€/year]**
	In Use	Not in Use	
Uniforms	€5,113.00	€2,747.00	€38,970.00
Toiletries	€1,448.00	€966.00	€12,815.54
Food	€23.04	€9,458.00	€89,545.71
Drinks	€11,802.00	€4,086.00	€68,618.77
Gadgets, electronics and AV equipment	€8,228.00	€11,126.00	€126,155.54
Sports Equipment	€4,631.00	€2,921.00	€39,392.77
Garage (tenders & toys)	€16,037.00	€6,098.00	€98,405.77
Bridge Equipment	€4,827.00	€7,155.00	€79,950.46
Interior Maintenance	€4,469.00	€7,939.00	€86,459.54
Paint	€12,018.00	€15,844.00	€180,415.85
Deck Equipment	€7,561.00	€7,208.00	€87,392.08
Insurance	€60,051.00	€48,526.00	€611,567.77
Engine Room and Technical Equipment	€20,509.00	€35,313.00	€386,176.62
Total			€1,519,689.79

The salary of the crew represents a great part of the running costs; however it varies from yacht to yacht, depending on size, use and type of yacht, and also in the experience of the crew. (13) In this case, the expenditure on crew salaries is scaled by number of crew members and size of the yacht.

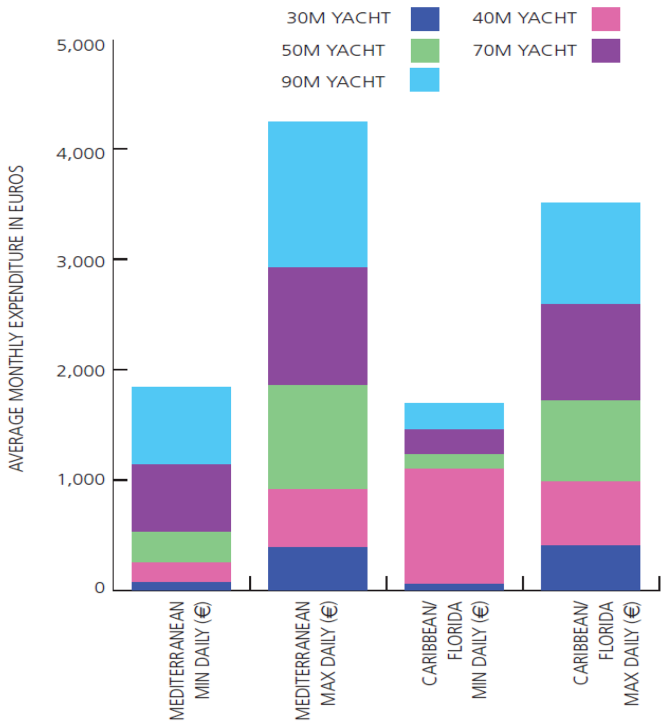


Figure 10: Breakdown of expenditure on berthing fees by yacht categories (13)

On average, each crew member on a 40-50m yacht earns 4,700.17 € per month, assuming 8 crew members plus captain and that every crew member earns the same, which in reality is true. Approximately, the annual crew salary costs are slightly higher than half a million euros (507,942.36€).

It is known that often yachts spend their time away from their home ports, either in anchorages or in other ports. (13) Therefore, there are some costs associated with staying in other ports, these are estimated for the two most popular areas in yachting, the Mediterranean and the Caribbean. (13) (Figure 10)

According to the survey, on average yachts spend 9.5 weeks in ports other than their home port. Assuming the vessel will spend half the year in the Mediterranean and the other half in the Caribbean, thus 4.75 weeks in each location.

Consequently, for a 40-50m yacht that spends 4.75 weeks in the Mediterranean and 4.75 weeks in the Caribbean the annual berthing costs are 90,606.25 €.

Finally, the last item of the running costs and the one with the highest fraction is the fuel consumption. Considering an annual fuel consumption of 311707.7 litres at the cost of 1.05€/litre the fuel costs are 327,293.09€ per year.

Altogether, the yearly running costs of the reference design are €2,506,079.90.

5. AUXILIARY LOADS ANALYSIS AND REDUCTION

5.1 INTRODUCTION

The reduction of power demand of the auxiliary loads can ultimately lead to the reduction of CO_2 emissions, by enhancing fuel savings. Since the goal is to maximize the power demand reduction, starting to reduce the power consumption of the heavier consumers is advantageous. To uncover which of the systems are the heavier consumers there is the need of building an electric load balance of the reference yacht.

Firstly, this section elaborates on the process followed for the selection of strategies implemented for the power demand reduction of each consumer group. After that, the first step of the analysis is presented, the identification of the heavier consumers from the electric load balance of the reference yacht and further analysing the consumption drivers of each of those systems.

In addition, it evaluates several strategies available in the market for the reduction of power consumption of the specified consumer groups. Moreover, presenting the strategy chosen and its impact on overall power consumption of auxiliaries

Despite the fact that power management systems are not consumer groups, they are shortly presented as a strategy that contributes to auxiliary power reduction.

Finally, the impact of the combination of all strategies is presented in terms of power demand. As in this chapter only power demand is considered, the power supply is assumed to be the same as in the reference design. Therefore, the reduction of CO_2 emissions is in the same order of the reduction in power consumption.

5.2 THE SELECTION PROCESS

The selection process of the possible strategies to reduce power consumption of the consumer groups analysed follows an additive aggregation model, as described in section 2.4.

While the end design is evaluated based on three different criteria, the different strategies require more detailed criteria for a more accurate comparison. Therefore, five criteria are developed based on the three performance parameters previously defined, energy efficiency, luxury and costs.

1. *Energy Efficiency*: in this case, the energy efficiency is measured in terms of power consumption
2. *Luxury:* in this case, the luxury category is divided in three sub categories:
    a. *Size,* that can be measured in terms of volume, thickness or area
    b. *Weight,* that is measure in kilograms (kg)
    c. *Quality*, quality is a subjective measure that provides indication on the comfort or state of luxury the strategies provide, this is mainly useful for strategies that directly influence the guest usage of appliances
3. *Costs,* in the same ways as before, costs are divided in terms of investment and running costs despite the fact that in the majority of cases the running costs will remain the same

In conformity, there is the need to define the weighting factors for the set of criteria according to the preferences of each user, these are displayed in Table 8.

Table 8: Weight factors for each criterion in the multi-objective comparison function by user profile

u	User Profile	Energy Efficiency	Luxury			Costs
			Size	Weight	Quality	
1	The Economist	0.15	0.1	0.15	0.1	0.5
2	The Family man	0.1	0.2	0.1	0.5	0.1
3	The Environmentalist	0.5	0.1	0.15	0.1	0.15

Having the criteria and weight factors defined, it is possible to start the analysis by identifying the heavier consumers from the reference electric load balance.

5.3 THE REFERENCE ELECTRIC LOAD BALANCE

As described under chapter 3, the operational profile of a super yacht has six main operational modes, cruising, crossing, maximum speed, manoeuvring, at anchorage and in port.

The Electric Load Balance of the reference design is developed based on data from suppliers, such as Heinen & Hopman, Hem, Nibe among others, and consumption figures from similar yachts designed by van Oossanen. The Electric Load Balance is built per consumer group so to identify the heavier consumer groups.

Table 9 presents an overview of the electric load balance of the reference design relevant operational modes and **Appendix B** presents the electric load balance construction per consumer group. In port operational mode is left out of scope since as stated before it is assumed that it is supplied by shore power, thus not included in the CO_2 emissions' analysis. Furthermore, maximum speed operational mode has the same auxiliary power consumption as the cruising mode, reason why it is left out of Table 9.

The first main distinction between the modes is whether there is or not the need for propulsion power. When there is the need of propulsion power the overall consumption of auxiliaries is higher, mainly due to intensive use of the steering systems, fuel and oil systems, and main machinery support systems combined with the other appliances.

Nevertheless, as uncovered in chapter 3 by the operational profile and later by assessing the performance of the benchmark in chapter 4, the share of time spent at anchorage results in a significant impact of the CO_2 yearly emitted due to the power consumption of auxiliary systems. As a result, even though the power consumption at anchorage is not the highest, its reduction has a great potential in reducing yearly emissions (12).

Table 9: General Overview of the Electric Load Balance for the Reference Design

spec.	Consumer	Total Actual Load (kW)	%	Cruising: Total Actual Load (kW)	Cruising: %	Crossing: Total Actual Load (kW)	Crossing: %	Manoeuvring: Total Actual Load (kW)	Manoeuvring: %	At Anchor, Day Duty: Total Actual Load (kW)	At Anchor, Day Duty: %	At Anchor, Night Duty: Total Actual Load (kW)	At Anchor, Night Duty: %
1	**Main Machinery Support**	17.77	3.3%	14.60	7.7%	14.60	9.4%	14.22	7.2%	0.82	0.5%	0.82	0.5%
2	**Steering & Manoeuvring**	82.56	15.2%	8.11	4.3%	8.11	5.2%	50.59	25.7%	0.00	0.0%	0.00	0.0%
3	**Stabilizing**	35.20	6.5%	21.12	11.1%	21.12	13.6%	17.60	8.9%	21.12	14.0%	21.12	13.3%
4	**Fuel & Oil Systems**	4.38	0.8%	3.53	1.9%	3.43	2.2%	2.71	1.4%	2.63	1.7%	1.19	0.7%
5	**Water Systems**	65.26	12.0%	25.95	13.7%	17.29	11.2%	11.21	5.7%	20.61	13.7%	27.30	17.2%
6	**Firefighting & Bilge Systems**	41.24	7.6%	5.36	2.8%	5.15	3.3%	5.36	2.7%	5.36	3.6%	5.36	3.4%
7	**Air Systems (HVAC)**	70.13	12.9%	66.47	35.1%	48.81	31.5%	57.98	29.4%	59.69	39.6%	54.37	34.3%
8	**Lighting**	69.87	12.9%	14.12	7.4%	14.35	9.3%	14.31	7.3%	13.26	8.8%	25.16	15.9%
9	**Domestic [Galley & Laundry]**	92.26	17.0%	12.20	6.4%	9.87	6.4%	8.63	4.4%	12.20	8.1%	10.83	6.8%
10	**Navigation & Communication**	8.00	1.5%	8.00	4.2%	8.00	5.2%	8.00	4.1%	0.80	0.5%	0.80	0.5%
11	**Entertainment**	10.62	2.0%	6.51	3.4%	1.27	0.8%	3.39	1.7%	6.62	4.4%	6.63	4.2%
12	**Mooring & Boarding & Others**	45.86	8.4%	3.60	1.9%	2.96	1.9%	3.06	1.6%	7.75	5.1%	5.11	3.2%
	Total	543.1673		189.57		154.95		197.06		150.71		158.67	

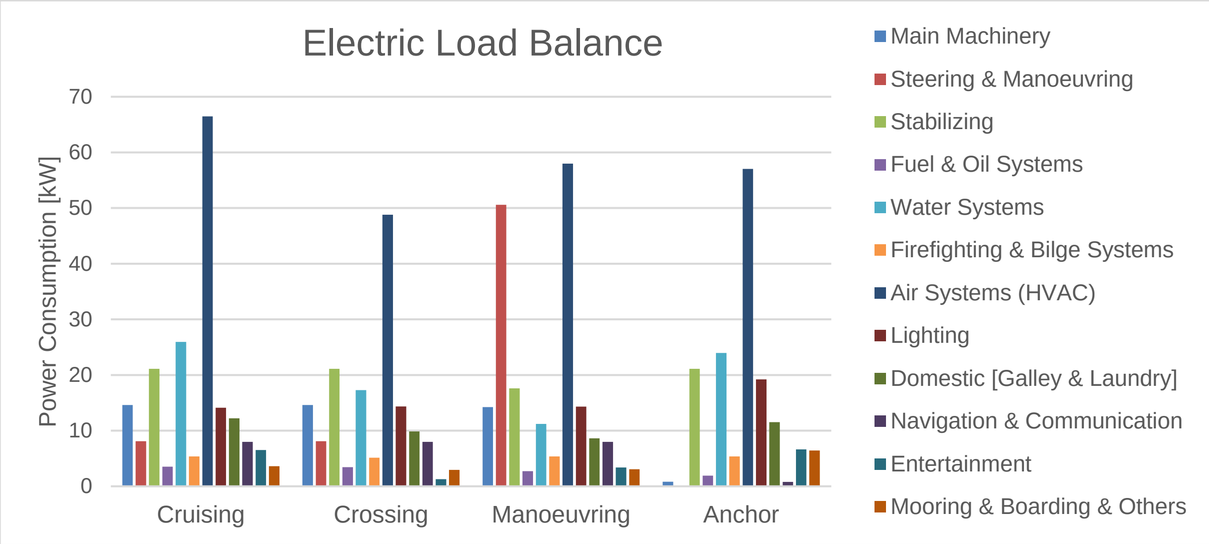


Figure 11: Electric Load Balance, consumer groups' consumption per operational mode

Figure 11 plots the data on Table 9, it represents the distribution of the loads of consumer groups in the different relevant operational modes, enabling the identification of the heavier consumers over the operational profile.

From Figure 11, the air systems (HVAC) can be unanimously identified as the heaviest consumer. Their consumption ranges approximately between 48kW and 66kW, which represents depending on the cases between 30% and 40% of the total consumption.

After that, it is possible to identify the peak consumption point of the steering and manoeuvring systems during the manoeuvring operational mode. As defined by the operational profile, manoeuvring covers only 1.3% of the operational time, which leads to a very low impact on yearly CO_2 emissions. For this reason, and considering the consumption of steering and manoeuvring systems is low on the other operational modes, these systems will not me further analysed.

The consumption of the remaining groups is lower than the one of the air systems, which indicates that reduction of power consumption of these groups will still have an impact on overall consumption, however not as significant as the one from the air systems.

Subsequently, the stabilizing systems can be identified as significant power consumers. The stabilizing market is dominated by two types of equipment, stabilizing fins and gyroscopes. The heated discussion of which of these is better is common in the market, especially due to their impact in the performance of the yacht.

Afterwards, the water systems' power consumption can also be pointed as in the same order of magnitude as the stabilizing systems, ranging from 11kW up to almost 30kW. From Appendix **B.2**, it is possible to identify the boilers as responsible for the majority of the power consumption, reason why the power reduction analysis in section 5.7 mainly focuses on these systems.

Finally, the lighting systems power consumption can be identified as significant, being on average around 14-15kW, except at night duty while on anchorage at which it increases to approximately 25kW, making it interesting to investigate.

All in all, four different consumer groups will be further analysed:

- The Air Systems
- The Stabilizing Systems
- The Water Systems
- The Lighting Systems

In addition, a short elaboration on power management systems takes place as a way to connect all consumer groups of the yacht. Moreover, through a better scheduling and monitoring achieve CO_2 emissions reduction.

Finally, the impact of all strategies combined is analysed, thus answering to the first research sub-question.

5.4 THE HVAC SYSTEMS

5.4.1 INTRODUCTION

The heating, ventilation and air conditioning systems (the HVAC) are one of the biggest consumers on board, mainly because they compensate for all the heat losses and/or gains on board in order to ensure a comfortable temperature inside.

In order to provide cooling to a space there is always energy expenditure, thus cooling always leads to CO_2 emissions (if considering conventional power means). Therefore, an effective way of reducing emissions besides more efficient equipment is to reduce the cooling loads on air conditioning system by reducing the heat absorbed by the spaces.

Taking into consideration the geographical operational profile of a conventional super yacht, the most common is to operate under summer circumstances. Therefore, the critical situation is the excess of heat absorbed by the spaces that need conditioning.

While in operations there are many possible heat sources, either external or internal. The heat from the exterior is absorbed by means of convection, conduction of radiation through the structures and windows. Internally, the heat is sourced by the operating equipment, by the lighting and by the people inside the spaces (14). Figure 12 shows a scheme of the heat sources considered.

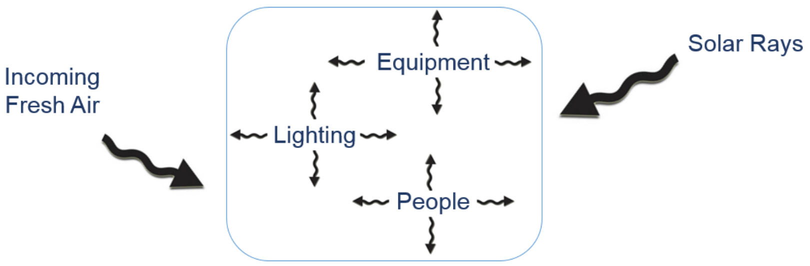


Figure 12: Schematic figure of the heat balance inside a yacht

As represented with larger arrows, the external heat sources, thus the incoming fresh air and the solar radiation have a bigger influence on the overall heat absorption. (15) (14)

This section firstly elaborates on different strategies to reduce the heat absorbed by the enclosed spaces in order to reduce the loads on the air conditioning systems. After that, it goes into detail in the equipment options available to reduce the power consumption.

5.4.2 REDUCTION OF THE ABSORBED HEAT

As stated before, the heat may enter the spaces either through incoming fresh air or through the structures and windows from the solar radiation.

The incoming fresh air is one of the most significant heat sources in a vessel, especially due to the regulations that define minimum standards for air changes. Minimum requirements for the air changes exist in order to maintain a healthy and clean environment inside spaces. In comparison with buildings, the requirements are somewhat stricter in the marine environment. (16) (7)

Reducing the number of required air changes, or adapting the number of air changes to the functionality of spaces might result in the reduction of the heat absorbed (14). However, regulations remain unchanged, requiring a minimum of 6 air changes per hour in all spaces. (7) Therefore, at the moment no savings can be achieved from the incoming fresh air.

The solar radiation penetrates the spaces through the structures and the glazing surfaces (the windows), resulting in the increase of the loading on the air conditioning systems. Insulation is the key to mitigate this effect, either on structures or glass. Furthermore, it is possible to reduce the radiation that actually reaches the surfaces by increasing the external shading.

In terms of structural insulation, despite the function of reducing the absorbed heat, the insulation should have fire protecting and sound insulating characteristics, which are often prioritized over thermal insulation. Furthermore, weight, thickness and corrosive behaviour of the insulation type used are fundamental in ship design as they have to be according to the restrictions, which vary from vessel to vessel.

Considering the current state of development of the insulation market for superyachts it is possible to say that the introduction of mineral wool brought the thermal insulation to a high performance standard. Therefore, no significant gains can be achieved by improving structural insulation.

Nevertheless, heat transferred by the incident solar radiation through the windows is more significant than through the structures, mainly due to the insulation resistance coefficients of both. (17) (18) (15) Moreover, this is aggravated by the reflectiveness and transparency of the glazing surfaces, which allows for a higher percentage of the radiation to penetrate the space.

As a consequence, glass surfaces, especially transparent ones, are critical from a heat gain point of view. However, yacht owners' value nature and experiences, thus the connection between the interior and exterior is vital when designing a modern super yacht. (19) Therefore, reducing the number of glass surfaces is not an option; actually, the tendencies are in the direction of increasing glass surfaces, however, improving their insulation and reflectiveness characteristics is vital.

In spite of being one of the most critical regarding heat absorption, it is possible to apply several mitigation strategies to reduce the heat absorption through windows. On the one hand, it is possible to improve the glass properties regarding insulation and solar protection characteristics. On the other hand, it is possible to increase the external shading of windows, thus reducing the solar radiation that reaches the glazing surfaces.

THE GLASS TYPE

Glass Surfaces are critical regarding heat gains. Not only because their insulating capacity is usually lower than for other structure materials, but also because glass surfaces allow the sun's radiation to penetrate the space increasing the heat gains.

For this purpose, the Solar Gain Coefficient is introduced as the fraction of radiation that enters through the surfaces, known as the G-value. The Solar Coefficient varies mainly with the internal shading factor of the glass, from 0 to 1, being 0 the completely dark glass types and 1 the completely transparent glass types.

In addition, the heat gain from radiation depends also on the solar radiation that reaches the surface, thus it depends on the position of the sun relatively to the position of the window, the time of the year, time of the day and location (longitude, latitude). The calculation of the solar radiation can be found on Appendix A.

The fact that glass surfaces are so critical in terms of heat gains challenges glass producers to search for better insulated glass and alternative strategies to mitigate the heat gain, since designers tend to increase the glazing surfaces' area more and more.

Nevertheless, the reduction of the heat gain comes at the cost of glass thickness, weight, price and colour. Consequently, the type of glass chosen depends on the preferences of the owner that will take in consideration all the factors. According to glass suppliers (20), Table 10 presents estimates of the characteristics for different general types of glass.

Table 10: Estimate on glass characteristics according to supplier

			U-value W /m^2 ºC	**G-value**	**Thickness** mm	**Weight** Kg/m^2	**Price** €/m^2
Single	Clear	Solar Protection	2.7	0.4	19	28.75	800
		Normal	5.2	0.7	19	28.75	600
	Dark	Solar Protection	2.7	0.25	19	28.75	800
		Normal	5.2	0.5	19	28.75	600
Double	Clear	Solar Protection	1.7	0.4	100	153.75	800
		Normal	1.7	0.7	100	153.75	600
	Dark	Solar Protection	1.7	0.25	100	153.75	800
		Normal	1.7	0.5	100	153.75	600

The fact that a vessel is constantly changing position and orientation makes the heat load analysis much more complex than the one for a building. In order to simplify this analysis, the heat load calculation is made for one position of the yacht. In reality the position of the yacht changes constantly, however since four orientations of windows have already been covered by assuming one position of the yacht it is possible to assume that due to the comparative character of this analysis the results provided are satisfactory.

Nevertheless, when deeply studying the effect of glass types (and also external shading effects) it might be valuable to develop a simulation model accounting for the constant changes. Moreover, for the realisation of such a model, more data on operational pattern is needed.

From the calculated solar radiation on a vertical surface (tilt angle of 90 º) (Appendix A) and the solar coefficient characteristics presented on Table 10 it is possible to calculate the average absorbed radiation throughout a summer day by a m^2 of the different glass surfaces, as displayed in Figure 13.

The double glass option has to be immediately discarded as it incurs such a significant weight increase that might not only lead to stability issues but also fail to get class approval. (21)

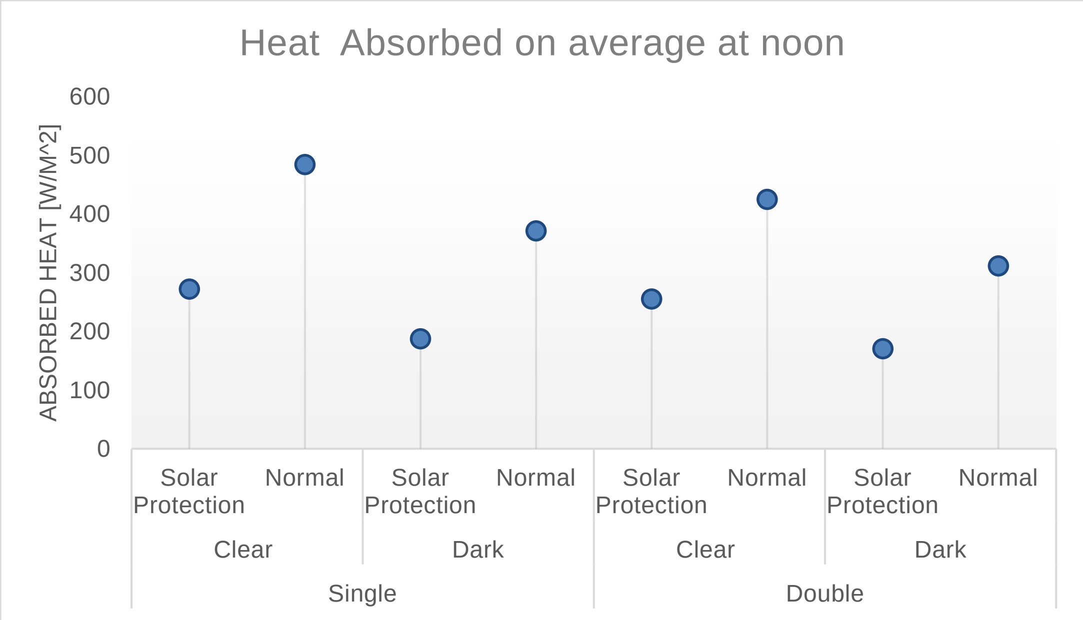


Figure 13: Average absorbed heat at noon on a summer day per type of glass

A 50 m yacht has a window area varying between 100 m^2 and 200 m^2, the reference yacht has a window area of approximately 100m^2, while the new design is expected to have a slightly higher window area, approximately 130 m^2. According to Table 10 the glass price varies between 600 €/m^2 for non-protected glass and 800 €/m^2 for the solar protected glass.

Considering the whole glass area on both cases, the reference vessel having non-protected glass would have a cost of 60,000 €, and considering the new design with non-solar protected glass would cost 78,000€, while with solar-protected glass this would result in 104,000€. The increase in glass area for luxury purposes has a cost of 18,000 €, the additional 26,000€ account for the cost of solar-protection. In comparison with the total value of the yacht, the increase in window costs does not have a great impact (21).

Finally, there is the need to select between clear and dark glass. The only different parameter between clear and dark glass is the absorbed heat since the thickness, weight and price are maintained. Therefore, dark glass is preferred as it results in lower heat absorption. In addition, most yacht owners claim to prefer privacy when inside their yachts, hence preferring a darker glass type, which contributes to the decision of installing a darker glass type.

Table 11 displays the results of applying the multiple objective comparison function presented in section 2.4 with the set of criteria presented in section 5.2. The choice of dark solar-protected glass is unanimous among the users.

Table 11: Result of Multi-objective comparison function on the feasible glass options

			The Economist	The Family Man	The Environmentalist
Single	Clear	Solar Protection	1.47	1.14	1.43
		Normal	1.45	0.64	1.23
	Dark	Solar Protection	1.61	1.67	1.67
		Normal	1.57	1.15	1.38

Once the glass type is chosen it is possible to look into other strategies that also contribute to the heat absorption reduction, thus the external shading devices.

External Shading

According to ASHRAE indications (16), shading is able to reduce solar heat gain by 80% in some cases. Moreover, Air Conditioning suppliers claim that savings up to 350 W per m^2 of glass are possible with shaded surfaces.

An optimal shading effect is the one that minimizes solar heat gain however at the same time maximises natural lighting (22). Shading can be static, by means of overhangs or static louvers, or dynamic by means of dynamic louvers.

The application of overhangs on superyachts is common. The combination of overhangs and “balcony depth” allows for some reduction of the heat gain (22). This combination not only avoids the direct exposure of structures to the sun’s radiation but also creates a “buffer” area where the air in contact with the structure is cooler.

According to McCartan & Kvilums (22), who tested balcony depths between 0 to 2.5 m, found that heat gains diminish with the increase of balcony depth. It was uncovered that between 0 and 1.5m the savings are quite significant; almost 30% less sensible cooling load for each 0.5m of balcony depth, after that the increments are reduced.

Balcony depth is space intensive strategy as it reduces the available interior area, thus a balance between space and savings is the end goal. Appendix D elaborates on the design of the overhang width taking into consideration the interior area reduction, by defining a maximum allowable area reduction.

Dynamic shading devices are investigated in the work of Aste et Al. (23), concluding that the inclination profile of the shading device is dependent on the systems geometrical profile, in terms of location, orientation and time of the year.

Optimising the form and inclination of louvers is a greater challenge for marine applications than it is for buildings since the orientation and location often change during an operational day. On their work, McCartan & Kvilums (22) compared the performances of static louvers, occupancy controlled (0^o when someone is inside and 90^o when empty) and solar radiation angle based control dynamic louvers. The results showed that occupancy based control dynamic louvers had a better performance in reducing cooling loads than solar radiation control based dynamic louvers.

Louvers are, in ship design, applied in combination with overhangs and not as a standalone measure. McCartan & Kvilums (22) consider its application in a cruise vessel case, which is functional and structurally different when compared to a superyacht. In that case, it was concluded that the effect on visibility of such systems is quite significant as even in the horizontal position their impact is noteworthy. Therefore, louvers were only applied to guest cabins where the occupancy rates are rather low throughout the day as guests are mainly on their cabins early in the morning and later at the end of the day.

On a yacht, the number of guest cabins is much lower than in a cruise vessel case. Moreover, the majority of these cabins are located in the hull and not in the superstructure. Additionally, the substantial effect on the yacht’s exterior styling works as a disadvantage for the application of this system. Moreover, the application of such systems breaks the interior/exterior environment connection, which is also regarded as a disadvantage.

As a result of these effects, the application of dynamic louvers was discarded. However, the idea of an alternative simpler system was developed.

Yet again, based on occupancy this alternative system is suitable to be applied to cabins and not to common areas such as saloons. This alternative system consists of rolling blinds that would be externally fitted in the window's structure. Producing the same effect as the dynamic occupancy based louvers would, i.e. completely shading the window surface whenever the cabin is not occupied. However, without damaging the interior/exterior connection when the guests are inside the cabin as they are completely rolled up in this case. In addition, the impact on the exterior style can be mitigated by making the "rolling blinds" either in the same style as the super structure (in white) or as fake windows, not altering the exterior styling.

Despite being able to reduce the required cooling capacity in some occasions, this system does not allow for a reduction on the size of required chiller, since the size of equipment is based on maximum load. Nevertheless, it is able to reduce significantly the loads on the air conditioning during the day at anchorage, reducing the heat absorbed by the conditioned spaces.

To sum up, the combination of three different strategies, the window type, the overhang and the "rolling blinds" it is possible to reduce the required cooling capacity by permanently reducing the heat loads and it is possible to reduce the loads while at anchorage, thus reducing the loads on the air conditioning system.

All factors considered and the required cooling capacity is 120 kW, according to an estimation by Heinen & Hopman (24). The required cooling capacity is a decisive parameter when choosing the air conditioning systems, namely the fresh air unit and the chiller unit. The next section elaborates on the choice of the actual air conditioning systems.

5.4.3 Cooling Supply systems: Energy Efficient Equipment

As aforementioned, in addition to reducing the heat absorbed by the spaces it is also possible to reduce the consumption of the air systems by implementing more efficient equipment or energy saving measures. Nonetheless, not all available systems in the market are suitable for a 50m yacht application due to the systems' characteristics.

Most energy saving systems developed up to date are for commercial shipping vessel's application where cooling requirements and available space for equipment are higher in comparison to the 50m yacht case. In the next paragraphs a number of systems are described and its suitability for the concept assessed.

Firstly, radiant cooling systems are assessed due to their good results in architecture. After that, the fresh air unit type that together with the cooling demand from the absorbed heat will determine the cooling requirements for the chiller unit.

Finally, several types of chiller units are compared and a system combination of fresh air unit and chiller unit chosen.

Radiant Cooling Systems

As increasingly applied in many buildings, the combination of air systems and radiant panel, thus hybrid HVAC systems, can provide advantages in terms of space and energy efficiency, the ASHRAE Handbook presents a few (25) (26).

Radiant cooling systems, are in general defined as systems in which radiant heat covers more than 50% of the heat exchange in the conditioned space. In comparison to all-air systems, radiant systems provide cooling by means of not only convection, but also radiation. (25) (27)

Firstly, the same thermal comfort is possible at higher temperatures due to the heat transfer process, Rhee et. All (27) claim that by making use of radiant heat transfer the human body is capable of the same thermal comfort for higher temperatures. Consequently, it is possible to reduce the cooling loads without reducing comfort level inside neither increasing air movement, on the contrary.

Secondly, radiant cooling systems enhance energy savings by utilizing the radiant heat transfer (27). The high thermal capacity of water compared to air reduces the transporting energy when compared to all-air systems (28). Furthermore, the higher temperature of water for radiant cooling enables the chiller, heat pump, boiler, etc to operate at higher efficiencies, directly influencing energy consumption.

Another advantage of the radiant cooling system is its compact design. Radiant cooling systems require less mechanical space and by reducing the airflow needs there is a reduction of the required space for the air systems. In some cases, the radiant ceiling systems also contribute to sound dampening and fire insulation, not critically contributing to an increase in ceiling thickness.

Overall, the advantages of radiant cooling encompass higher thermal comfort, potential space and energy savings (26). Nonetheless, the application of radiant cooling systems to super yachts has some disadvantages as well.

Firstly, due to the changing conditions in position and orientation of a yacht in operation, the cooling loads vary constantly and radiant cooling systems are slow to react to such changes. Secondly, the fact that the marine environment regulates the minimum amount of 6 air changes per hour (7) forces the capacity and size of the air systems leading to an extremely high volume and weight when combining the radiant system to the air systems required. Moreover, radiant cooling systems force the ceiling panels to be visible, interfering directly in the interior styling on the super yacht reducing the luxury level of the interior.

Finally, for marine applications the hybrid HVAC systems are only available in the market at a very high capital cost not only due to the equipment but also due to the highly complex control system it requires that is still not mature enough to be energy efficient.

Table 12: Advantages and disadvantages of Radiant Cooling systems

Advantages	Disadvantages
• Higher Thermal Comfort • Potential Energy Savings in stable conditions • Space savings • Fire and Sound Dampening	• Slow to React to condition changes (constant condition of a yacht in operation) • Visibility of ceiling panels • Need for combination with air systems which leads to: ○ Space intensive ○ High Costs ○ Complex Control systems ○ Lack of maturity in the technology control at an instable state

The advantages and disadvantages of radiant cooling systems applicable to super yachts are summarized on Table 12, where the disadvantages outweigh the advantaged. Consequently, ruling out the possibility of radiant ceiling panels at least in the near future as their potential is dependent on further technological developments.

As a result, all air systems are still the best option for yachts and its systems should be as efficient as possible. Two parts of conventional air systems are possible to improve. On the one hand, the type of chiller installed will influence the required power needed to produce the same cooling loads. On the other hand, by pre-cooling the incoming air it is possible to reduce the cooling capacity required. Therefore, the fresh air unit options are firstly analysed.

Fresh Air Units

Energy can be saved by pre-cooling the incoming air on the fresh air unit, making use of the air leaving the conditioned spaces.

A heat exchanger is used to extract the excess of heat from the incoming fresh air. As the heat flow is from higher temperatures to low temperatures, the excess of heat from incoming air will transfer to the exhaust air, thus reducing the temperature of the supply air.

For the pre-cooling of incoming fresh air, several types of heat exchangers may be suitable. On the one hand, there are plate heat exchangers that can be either counter or cross flow. On the other hand, it can be an enthalpy wheel heat exchanger in which not only sensible heat is transferred but also latent heat, improving its efficiency in reducing the cooling loads on the chiller and humidifier units. Figure 15 and Figure 14 show a representation of these two options.

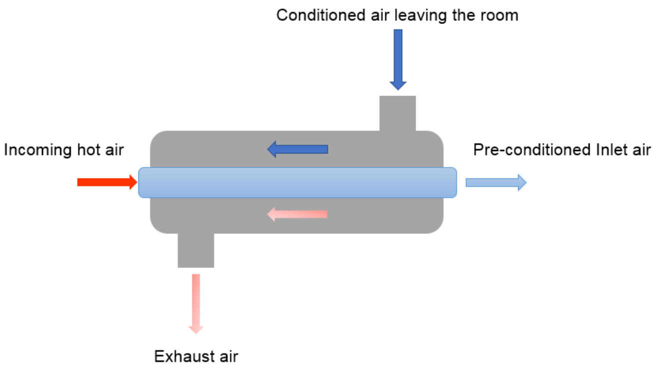


Figure 15: Scheme of a cross flow heat exchanger

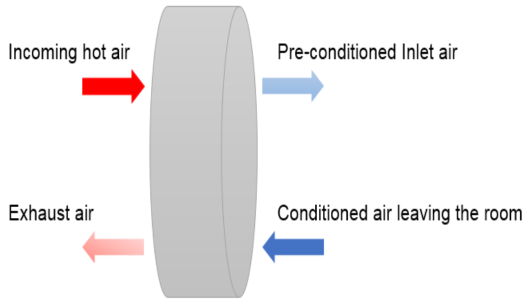


Figure 14: Scheme of a wheel heat exchanger

Depending on the amount of airflow and cooling loads, exhaust air re-circulation is a feasible option to substitute pre-cooling. Nonetheless, the benefits in terms of efficiency in pre-cooling the air are lower and highly dependent on the inlet fresh air flow. The efficiency of these systems depends not only on the temperature requirements but also on the outside air conditions.

In addition, to pre-heat the air through the exhaust air requires that both exhaust and inlet air are handled at the same unit which will not only increase the size of the air handling unit but also increase the complexity in the ducting system, as the exhaust as to be redirected to the unit. (29)

After consulting with air conditioning suppliers, two options for fresh air units were advised, either traditional fresh air unit with no pre-cooling or the fresh air unit fit with a heat wheel heat exchanger. The differences between both fresh air units are displayed on Table 13, a 90kW reduction in cooling capacity is possible at the cost of space, weight and price increase.

Table 13: Fresh Air Unit Characteristics (according to Heinen & Hopman)

	Length	Width	Height	Weight	Price Increment	Cooling Capacity Required
	mm	mm	mm	kg	€	kW
Traditional	2300	780	720	365	0,00	120
With Heat Wheel	2300	1100	1030	475	2.000	90

Afterwards, in order to design an air conditioning system, a fresh air unit has to be combined with a chiller unit therefore a number of chiller units are going to be assessed in the next paragraphs. After which, the complete combination can be assessed.

THE CHILLER UNITS

In terms of chiller units available in the market, two models stand out, the absorption chiller and the turbocor compressor chiller. On the next sections, a small elaboration of both types is presented. After that, traditional chillers are presented for the cases of the two possible fresh air unit.

ABSORPTION CHILLER

Absorption chillers are an alternative for vapour compressor chillers that present both economic and environmental benefits when waste heat is constantly available (30). Absorption chillers use heat to drive the refrigeration cycle.

Heat can be sourced either from waste heat of engines or directly from the sun's energy resulting in savings up to 95%, once only a small amount of electricity is spend to run the pumps of the unit (29). In addition, absorption cycles are advantageous due to their cycle's simple construction, reliability, long lifetime, low operating and conservation costs, low noise, vibration free and less replacement parts (30).

An absorption cooling cycle relies on a thermochemical "compressor" using two fluids: a refrigerant (usually water) and an absorbent. In a low pressure system the absorption fluid is evaporated removing heat from the chilled refrigerant. Based on this, the absorption chiller is capable of generating chilled water between 2ºC to 10ºC from low temperature energy, with incoming temperatures around 80ºC.

As for this chiller, heat needs to be available 100 % of the time. Since on a super yacht waste heat is not always available, an electric chiller is need as a backup what is going to have a significant impact in terms of size, weight and especially cost. (29)

In addition, the absorption chillers available in the market have a minimum cooling capacity of 176 kW, which is significantly higher than the one required. Moreover, suppliers confirmed that the application of absorption chillers is at the moment only suitable for commercial shipping applications.

TURBOCOR COMPRESSOR CHILLER

The turbocor compressor is a completely oil free compressor that is beneficial in terms of efficiency, sustainability and applicability for mid-range sized HVAC systems.

Making use of technology available in other industries, as the aerospace industry, the turbocor is equipped with magnetic bearings, variable-speed centrifugal compression and digital controls.

The most significant advantage is the fact that it has an oil-free operation, contributing not only to the efficiency but also to reliability, noise reduction and maintenance. The turbocor compressors are substantially smaller and lighter when compared with traditional compressors. Furthermore, the energy consumption can be reduced up 50%. (31)

In spite of being promising, these type of compressors have a start cooling capacity of 200 kW each, for this reason, its application is dependent on the cooling loads of a specific yacht. In the case considered of a 50m yacht where the maximum required capacity would be 120kW, turbocor compressors are not suitable. Nonetheless, they may be applicable for larger yachts or different case scenarios in which cooling requirements are higher.

TRADITIONAL CHILLER

Since more energy efficient chillers in the market are not suitable for this case, traditional chillers have to be considered. It is worth mentioning that common chiller units are also becoming more efficient. Nevertheless, considering that the application of two different fresh air units leads to two different cooling capacity requirements, two different chillers have to be considered, one for each case.

The fact that the cooling requirement is reduced by the application of a heat wheel exchanger leads to the possibility of installing a smaller chiller unit. As a result, part of the increase in weight and dimensions of the fresh air unit can be compensated by the decrease of the chiller unit.

The characteristics of the chiller unit are exhibited on Table 14 , where it can be seen that the reduction on the cooling capacity requirement from 120 kW to 90 kW results in the reduction of 8 kW of installed electric power. In addition to the power reduction there is also a slight reduction of dimensions, weight and price.

Table 14: Traditional chiller units characteristics based on installed fresh air unit (according to Heinen & Hopman)

	Length	Width	Height	Weight	Price Increment	Power
	mm	mm	mm	kg	€	kW
Traditional FA	2420	1934	1634	1080	2000	34.4
FA With Heat Wheel	2420	1880	1589	1050	0	26.4

The installation of the air systems has to be assessed as a whole, since the smaller chiller unit cannot be installed with the traditional fresh air unit. Therefore, Table 15 displays the characteristics of the combination of fresh air unit and chiller unit so that the choices remain feasible.

Table 15: Combined fresh air unit and chiller unit system's characteristics

	Length	Width	Height	Weight	Price Increment	Cooling Capacity	Power
	mm	mm	mm	kg	€	kW	kW
Traditional FA	4720	2714	2354	1445	2000	120	34.4
FA With Heat Wheel	4720	2980	2619	1525	2000	90	26.4

Looking at the system as a whole (Table 15) the fact that a heat wheel heat exchanger is fit to the fresh air unit is compensated fully in terms of price by the reduction on the chiller unit. Moreover, there are no changes in terms of systems' length, even though width, height and weight are slightly increased (between 5%-10%).

The reduction of 8kW in electric power consumption allied with the fact that there are no price increases and only marginal increases in dimensions points at the direction of the heat wheel fresh air unit as the best option for the design.

This line of thought is backed up by the results of the multi-objective comparison function (Table 16), where all users consider that the best option is the system fit with the heat wheel.

Table 16: Result of Multi-objective comparison function on the HVAC feasible systems

	The Economist	The Family Man	The Environmentalist
Traditional FA	1.48	0.65	1.31
FA With Heat Wheel	1.53	0.68	1.53

5.4.4 THE IMPACT OF CHANGES

By combining the reduction of the heat absorbed with the application of a heat wheel within the fresh air unit, the cooling requirement is instantly reduced to 90 kW, according to suppliers the lowest possible in a 50m super yacht.

In spite of not being possible to install an alternative chiller, the fact that the cooling requirement is reduced significantly, 30kW, allows for the installation of a smaller chiller unit. A smaller chiller unit results in a reduction of 8 kW in term of installed power, approximately a 23 % reduction in chiller unit installed power. As stated before, these changes are favourable to all three users therefore, definitely worth applying.

In addition, the reduction of heat loads, especially at anchor by introducing the rolling blinds lead to a reduction on the loads of both chiller and fan units, reducing the consumption of air conditioning system.

In terms of installed power, the air systems are reduced in about 47%. In terms of impact on overall consumption the reduction is between 12% and 13%. On Figure 16, it is possible to see the impact on power consumption at each operational mode due to the changes on the air systems.

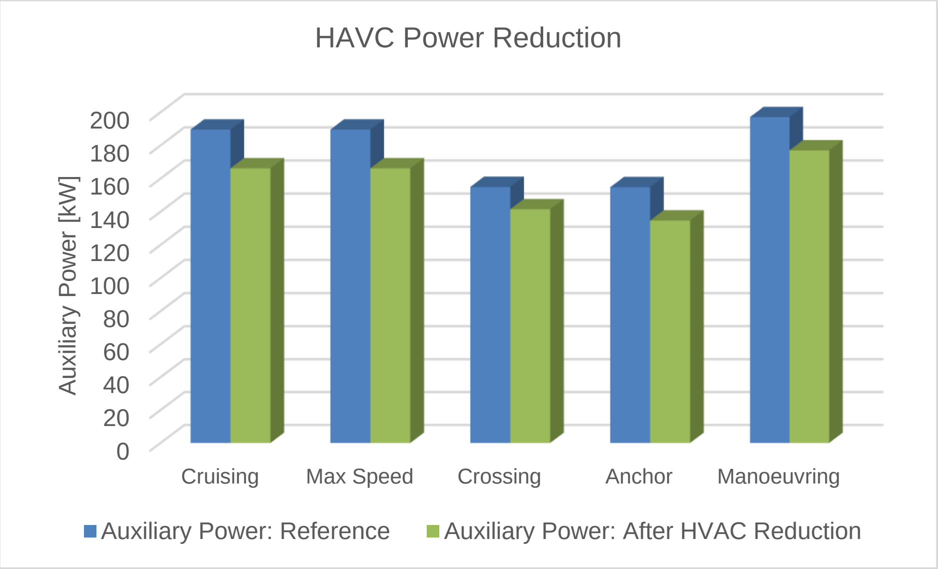


Figure 16: Comparison between Auxiliary power of the reference design and of the new design after HVAC power reduction

5.5 STABILIZING SYSTEMS

As stated before stabilizing systems represent between 10%-15% of the total power consumption, reason why are considered part of the heavier consumers. Two systems, the stabilizing fins and the gyroscopes dominate the stabilizing market today. Despite being very different, the systems go hand in hand in terms of overall performance.

The main goal of the stabilizing systems is to counteract the roll motions of the vessel, improving the comfort on board. In the first case, the counteracting moment follows from the moment generated by a pair of underwater fins. In the second case, the torque generated by the rotation of a flywheel counteracts the rolling moment.

The main difference between both systems is the fact that the stabilizing fins are located externally, thus leading to added resistance while the gyroscopes are placed internally. Nevertheless, the fact that the gyroscope units are significantly voluminous and heavy leading to an increase in displacement triggers an intensive discussion in the industry regarding their impact on resistance.

Mainly the sizing of the stabilizing systems depends on the parameters influencing stability, such as displacement, length, beam and transverse metacentric height. Furthermore, the operating conditions influence the sizing of the systems by determining the sea states to which the vessel will most probably be exposed.

In this case, coastal area operations are the most probable, thus corresponding to sea state 3 with wave heights up to 1.25m. From this, there are four different applicable solutions as displayed on Table 17. An option regarding stabilizing fins and three different configurations of gyroscopes.

Table 17: Stabilizing unit options and respective characteristics

Option	Number of units	Unit	Area [m^2]	Weight [ton]	€	Maximum Power [kW]	Operating Condition [kW]
1	2	Fins Naiad 720	3.49	2.1	€544,185.45	44.00	44.00
2	2	VG260SD	-	11.3	€726,564.63	68.13	58.13
3	3	VG145SD	-	9.0	€822,031.16	50.10	40.95
4	4	VG120SD	-	10.4	€832,111.39	65.60	54.80

In addition to the power consumed during the operations of the stabilizing systems, their indirect impact on propulsion power demand through the added resistance plays an important role in assessing these systems, especially since it is such a fracturing issue in the industry.

Consequently, there is the need to estimate the propulsion power demand that will follow from each option. This way it is possible to estimate, based on the same engine configuration the differences in fuel consumption that follow from the different case scenarios.

As a consequence of being internally placed, it is expected that the gyroscope options will have a lower impact on resistance in comparison to the stabilizing fins option. Data on the resistance and brake power requirements can be found in Appendix E.

All in all, stabilizing fins have a bigger impact on resistance, thus power requirements. Nonetheless, the difference between gyroscope options and stabilizing fins is not that severe. Due to the significant impact of gyroscopes on the displacement the potential of its internal placement is reduced, leading to a very small difference in terms of power requirements when comparing to stabilizing fins option, as it can be seen from Table 18.

Table 18 shows the percentage of power brake reduction of the gyroscope options in relation to the stabilizing fins options. As it can be seen, the reduction from having gyroscopes instead of stabilizing fins, in terms of power requirements is more significant when sailing at low speeds (3%-4%). At cruising speed the reduction lays between 1.41% and 2.13%, while at maximum speed falls to percentages going from 0.78% and 1.57%.

Table 18: Brake Power reduction comparison between gyroscope options and stabilizing fins option

	Option 1	Option 2	Option 3
D [ton]	321.19	318.89	320.29
Speed [knots]	**Brake Power Reduction [kW]**		
6	3.43%	3.94%	3.63%
8	2.60%	3.15%	2.81%
10	1.56%	2.26%	1.83%
12	1.41%	2.13%	1.69%
13	1.20%	1.95%	1.49%
14	1.09%	1.84%	1.39%
16	0.78%	1.57%	1.09%

From Table 17 it is possible to state that gyroscopes are generally more expensive than stabilizing fins. Moreover, gyroscopes have different maximum and operating power, i.e. they have a high starting power but when operating in calm sea states their power consumptions comes closer to mid-loading conditions. (Appendix E.2)

Differently than what happens with the other consumer groups, the weight of the stabilizing options affects the yacht's performance severely and the differences can be seen directly on fuel consumption. Therefore, the criteria for the assessment of these strategies can be resumed to energy efficiency, size, investment cost and running costs represented by the added fuel costs.

In order to equally evaluate all the possibilities, an extra scenario with no stabilizing feature is created so that the added fuel costs of all the options can be compared. Table 19 presents the performance of each stabilizing strategy regarding the added costs due to added resistance, thus the running costs.

Table 19: Performance of each stabilizing option

		Option 1	Option 2	Option 3	Option 4
Added Running Costs	€/year	€7,225.02	€5,218.02	€4,145.38	€4,797.63

By following the procedure elaborated under section 2.4 and respective weight factor for each user is it possible to rank the options according to each user's preferences as displayed on Table 20. Despite the fact that stabilizing fins have a higher impact on propulsion power demand, thus fuel consumption, their better performance on the other criteria leads to the unanimous choice of the users.

Table 20: Performance of stabilizing options for each user profile

	The Economist	The Family Man	The Environmentalist
Option 1	0.989	0.995	0.981
Option 2	0.691	0.726	0.622
Option 3	0.730	0.777	0.768
Option 4	0.677	0.730	0.634

5.5.1 The Impact of Changes

Taking into consideration that the reference design is already equipped with stabilizing fins, there is no impact on the new design from the conclusions taken in the previous paragraph. Therefore, there are no further power reductions following the choice of stabilizing system.

Nevertheless, it is worth noticing that a different design with different stability characteristics may have different requirements in terms of stabilizing configurations, thus power requirements for the latter. As a result, this conclusion is case based.

In addition, the development of more efficient systems may also lead to further reduction of power requirements regarding the stabilizing systems.

5.6 Lighting

Following the HVAC, the lighting systems have a significant impact on energy consumption. Moreover, lighting also contributes for the heat gains, so improving lighting will have a double effect on consumption on energy consumption.

The first strategy to reduce energy consumption from lighting is to consider low energy consumption light fixtures; LED lighting has proven to be the most efficient in the market in saving energy consumption of lighting systems. (14).

The two main options in the market for superyachts are Halogen and LED lighting bulbs, which representative characteristics are presented on Table 21.

In fact, the difference in power consumption of LED lighting is very significant, reason why it is nowadays commonly installed. Furthermore, the long lifetime of LED light bulbs reduces the maintenance costs over 50 000 hours by reducing the number of bulbs needed (1 LED bulb against 25 halogen bulbs). Consequently, the running costs are reduced by almost 90%.

Table 21: Lighting Systems Characteristics

	Cost		**Power Consumption**	**Lifespan**
	Investment	**Running**		
	€/bulb	€/50000hours	W	hours
Halogen	10,92	273	10	2.000
LED	30,6	30,6	1.3	50.000

Taking this into consideration, the choice of LED lighting instead of the halogen applied to the reference design is clear as it reduces both power consumption and maintenance costs. This result is also confirmed by the multi-objective comparison function, as presented on Table 22.

Table 22: Result of Multi-objective comparison function on the Lighting systems

	The Economist	**The Family Man**	**The Environmentalist**
Halogen	1.08	1.02	1.08
LED	1.33	1.14	1.55

In addition, other strategies contribute to energy savings regarding lighting, namely the use of occupancy sensors and dimming controls (32). The prediction of the energy savings from the latter strategies is dependent on factors such as usage, which varies from user to user. Previous studies and some suppliers estimate savings from occupancy sensors to be between 30-40% and dimming strategies to be between 6-9%. (33) (34)

5.6.1 THE IMPACT OF CHANGES

As stated before, the fact that the number of light bulbs on board is considerable (350 interior only), the impact on the lighting power consumption is also considerable even though apparently it is only about a few Watts.

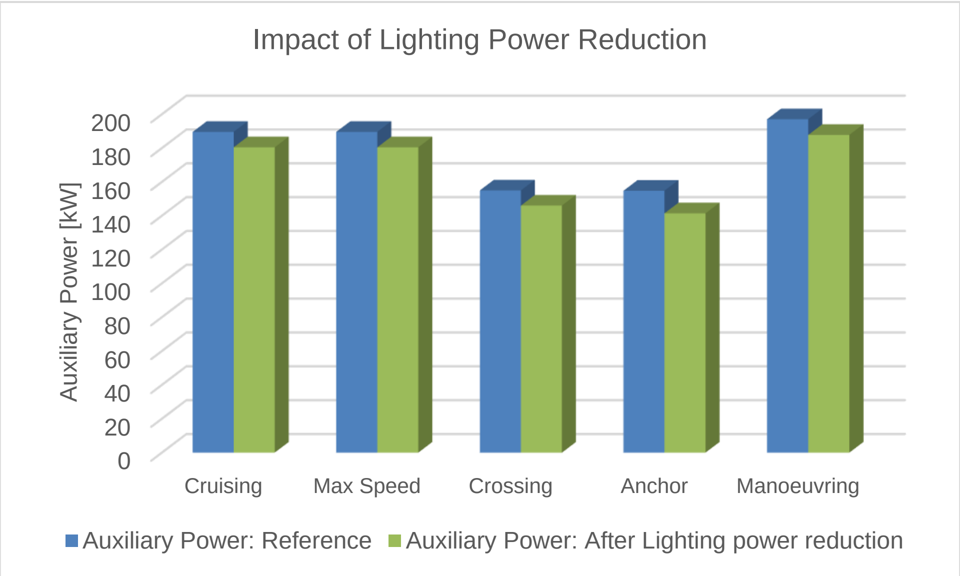


Figure 17: Comparison between auxiliary power of the reference design and of the new design after only Lighting power reduction

By changing the Lighting systems to LED lighting it is possible to reduce the installed lighting by almost 38%. This reduction alone has an impact on overall consumption that varies between 5% and 10%.

Figure 17 displays the comparison between the reference auxiliary power demand and the new design's power demand after only improving the lighting systems' consumption. This comparison is made by operational mode as the load profile varies.

5.7 WATER SYSTEMS

The power consumption of the water systems is mainly due to the excessive consumption of the boilers in combination with the high requirements of hot water.

For this reason, there are two possible strategies to reduce the boilers' consumption. On the one hand, by reducing the water consumption on board, thus reducing the load on the boiler, requiring less production rate and capacity. On the other hand, by improving the efficiency of the installed systems, optimizing the combination of boilers and cylinders.

The number of boilers plays an important role in defining the power consumption of the water systems. It is determined through the peak water consumption, thus dependent on the fixtures flow, reason why the reduction of the flow on the fixtures has an impact on not only water consumption but also energy consumption.

This sub-section elaborates on the improvements available for the boiler set systems and the possibilities in terms of fixture flow reduction. After that, it also assesses the possibility of heat recovery systems.

5.7.1 THE BOILER SET SYSTEMS

The boiler set is not only composed by the electric boiler but also by a cylinder, an expansion tank and a direct hot water recirculation pump among others. However the most important systems from an energy saving perspective is the combination of cylinder and electric boiler.

Depending on the yacht's demands and on the volume of the cylinders the number of boilers and capacity of boiler may vary. On the one hand one can have a smaller storage capacity with high power. On the other hand, one can have a larger storage capacity, thus requiring less power. To achieve an optimal combination is crucial, especially when the goal is to enhance energy savings.

In addition, the energy efficiency of the hot water cylinders contributes to the energy savings in this matter. New technologies have been developed in the industry to improve the efficiency of cylinders, mainly improving its thermal insulation. The most promising in the market is tank-in-tank technology that due to its capacity of storing water at high temperatures is installed together with a mixing valve, reducing the hot water requirements.

TANK-IN-TANK TECHNOLOGY

Tank-in-tank technology is an alternative to conventional storage tanks with heating elements. These enhance energy savings by reducing the static heat losses via the exterior walls. (35)

The inner tank, made of a stainless steel membrane that is designed to expand and contract with heating cycles, besides reducing the heat losses maintains the system clean, reducing the chances of water contamination by maintaining a temperature of at least 60ºC (36). By using domestic heating fluids that are non-toxic and environmentally friendly the heating systems will be kept clean, contributing to even higher energy savings. Overall savings can be up to 15%. (36)

As a consequence of a compact and energy efficient system costs will be reduced both in terms of energy consumption and in terms of maintenance and initial investment.

Increasing the insulating capabilities of the storage equipment it is possible to store hot water at higher temperatures, introducing mixing valves as energy saving devices.

MIXING VALVES

Mixing valves are devices provided and installed together with the boiler/accumulator unit, which follow from the fact that storage temperatures are increased (approximately at 80ºC).

Through the mixing valves, at the outlet of the cylinder, fresh water is mixed with the out coming water, at 80ºC, to be sent round the plumbing system to the outlets or returned to the cylinder via the recirculation pumps.

Mixing valves together with high temperature storage reduce the demand on the boiler, therefore reducing its power consumption. Considering this system, it is possible to dimension the boiler and cylinder (s) required capacities based on the peak water consumption depending on the flow of the chosen fixtures.

5.7.1 THE WATER CONSUMPTION ON BOARD: FLOW OF FIXTURES

The amount of water spent, both fresh and warm, depends on the type of fixtures used for shower, taps and hoses.

In terms of boiler, the water that is consumed, thus dependent on the type of fixtures is the water that needs to be heated to the desired temperature, usually between 37º and 40º. Moreover, the number of set of boilers needs to be able to provide enough water to satisfy the peak consumption.

The fact that it is a design for a super yacht implicates that comfort should never be disregarded, thus there are minimal standards that have to be met. To address this problem, suppliers created low flow fixtures that do not compromise the comfort while reducing the water consumption.

Table 23 presents seven different types of fixtures from different suppliers with respective consumption figures, resultant peak consumption and number of boiler sets required. The fact that the flow of the fixtures is reduced not always results in the reduction of the number of boilers. It is crucial for luxury purposes to reduce the least possible the flow on the fixtures.

It is also worth noticing that in a 50 m yacht it is advantageous two have more than one boiler set for redundancy purposes. Moreover, this will enable the use of only one boiler whenever the demand allows it, reducing the load on the boilers. In this case 320 L boilers are considered according to one market research (36), note that other size of boilers may be considered. Consumption and dimensions of the considered boilers may be found in Appendix F.

Table 23: Shower fixture types and respective consumptions

	Showerhead	Rain Shower Ceiling	Rain Fall	Rain Shower	Eco Joy	Eco Joy plus	Hand Shower
Consumption [l/min]	9.5	14	26.5	14.5	9.5	5.7	7.5
Peak Consumption [l]	1092.5	1565	2815	1615	1092.5	735	892.5
Nº of 320l boilers	2	3	5	3	2	2	2

Considering the minimal number of boilers 2, several types of fixtures are applicable for a 2 boiler configuration. Therefore, the choice should go in the direction of the one that allows for the higher level of comfort and luxury since cost and dimension differences are negligible.

In consultation with experts, the highest level of comfort may be achieved with the Eco Joy fixture type, since not only it has the lower flow reduction but it also offers a configuration of several usage modes in contrast with the showerhead type.

5.7.2 PRE-HEAT THE FEED WATER THROUGH WASTE HEAT RECOVERY

As an additional measure to reduce energy consumption of the electric boiler it is possible to pre-heat the feed water. This can be done by two different means, either by a smaller electric heater or by using waste heat.

The option of an additional heater was discarded since it incurs extra electric loads and according to the expertise of suppliers, only feasible when consumption is higher, thus larger yachts or commercial shipping vessels. Therefore, only waste heat recovery systems are considered.

The drain water heat recovery system brings still hot drain water through a pipe system adjacent to the incoming flow, pre-heating the incoming cold-water flow. (14) Assuming a drain water at the temperature of 40ºC, a cold water at the temperature of 20ºC and a heat recovery efficiency between 35% and 40%, savings between 5-10% in boilers consumption. (14) Besides the increased cost of the drain water system due to special plumbing, the high level of complexity required for the plumbing arrangement presents itself as a very significant disadvantage.

The relatively low consumption together with the fact that the price and complexity increase of drain water systems, does not compensate for the little electric power consumption savings (14) (36), thus it was decided to discard the drain water system heat recovery. It is however noteworthy that for cases in which space's availability is higher and water consumption more significant it might be worth implementing such a heat recovery system.

Regarding waste heat recovery from engines and generators, dependency on the availability of waste heat is determinant. Therefore, considering the operational profile as stated on chapter 3, the highest percentage of time is spent at anchorage reducing the available waste heat available at all times.

5.7.3 THE IMPACT OF CHANGES

Essentially, by reducing the fixtures consumption and inputting tank-in-tank technology considering a slightly higher cylinder capacity it is possible to decrease the number of boilers from 3 to 2. This is translated in approximately 35% savings in terms of boiler energy consumption.

In terms of overall energy consumption, the reduction is around 2% due to the relatively low load on the water systems in comparison to the ones assessed before. Furthermore, the reduction of water consumption slightly reduces the load on the water maker, contributing to extra 2% overall savings.

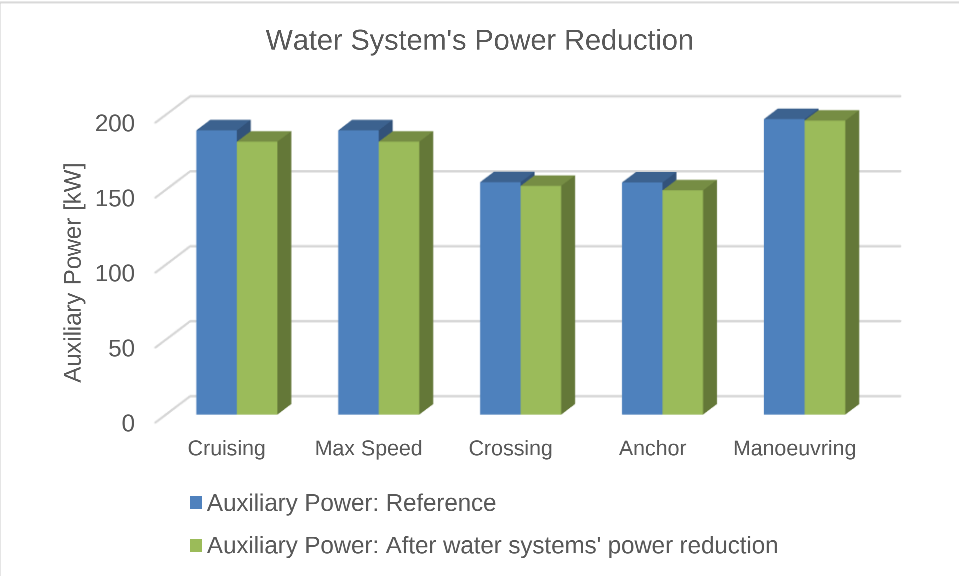


Figure 18: Comparison between auxiliary power of the reference design and of the new design after HVAC, lighting and water systems' power reduction

5.8 Power Management and Control

Energy management is the process of monitoring, controlling and conserving energy. The following steps are part of the energy management procedure:

1. Measuring energy consumption and collecting data
2. Analysing collected data, identifying and quantifying energy waste
3. Taking action to target the opportunities to save energy
4. Tracking process by analysing the energy-saving efforts

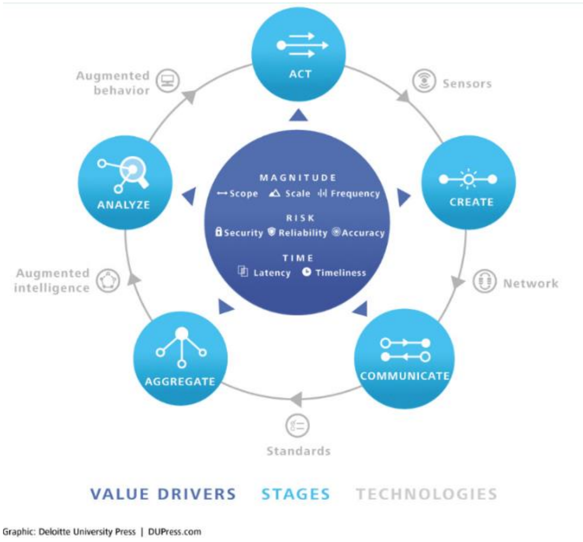


Figure 19: Drivers, stages and technologies related to the internet of Things (78)

Gathering detailed data for each individual consumer and correlating all possible measures to improve its energy efficiency will translate in to energy savings, since the energy waste is a consequence of poor energy use. (37) Energy management is a solution on the user demand side, involving the scheduling of certain appliances to reduce the impact of peaks both in terms of high and low demand.

In order to collect data the placement of multiple sensors is fundamental, from occupancy sensors to thermostats or voltage and current sensors. In addition to the typically controlled consumers if one management system controls all the consumers, further savings are possible avoiding energy consumption peaks.

This concept, known as the Internet of Things, already applied in private houses and office buildings as a tool for automated smart buildings, shows great results regarding energy consumption, hence energy costs and emissions. (38) The Internet of Things is a system of interrelated computing devices, mechanical and digital machines, objects or people that are provided with unique identifiers and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction. (39)

This concept moves the intelligence from the device level to the cloud level. The cloud provides the administrative interface and the data analytics function, which will be able to combine the analysis of the energy consumption and production, historical heating and cooling loads, weather forecasts and even work as a logbook. The combination of all functions in one through an interactive system leads to not only energy savings and easy management of the vessel but also it contributes to an increased awareness of crew and owner for the need of saving energy. With such a system, the integration of the monitor and control of the systems, allows to have a figure of the yacht's energy expenditure and emissions at each moment in time.

The main function of the power management system is to efficiently distribute the available power by the consumers, maintaining the engines and generators operating at an optimal point from a fuel consumption perspective, thus at maximum efficiency. Peak consumption points are reduced by delaying and reducing the power supply of low priority consumers during specific operational modes that have high power demands over short periods of time, such as manoeuvring.

In order to do so there is the need to rank the consumers in terms of priority. So that only low priority consumers will have their consumption reduced or delayed. Moreover, priority is dependent on the operational mode.

Power management systems require high level of programing and control systems. Nowadays, power management systems are being developed in order to improve the level of control do to achieve even higher energy savings. However, it is highly complex to determine the energy savings potential of such systems.

Power management is particularly useful for high consumption modes such as manoeuvring and maximum speed. During these specific operational modes part of the functionalities and equipment on board are not needed. Most probably the guests are around the main salons or even outside. Furthermore, these modes are sailed for very short times, as described under section 3.2, manoeuvring and maximum speed modes comply with 1.3% (approximately 19 min per day) and 0.43% (approximately 7 min per day) of the operational time, respectively.

Taking this into consideration, reducing the consumption of the consumers that are not in need for such periods of time has no impact on the comfort on board however it can reduce consumption significantly, especially at maximum speed where the reduction of loads leads to a 33% reduction on the overall consumption of auxiliaries. At manoeuvring further reductions on power consumption of 25% are achieved in comparison with the reference design.

5.9 CONCLUSION: HOW MUCH OF THE AUXILIARY POWER DEMAND IS POSSIBLE TO REDUCE?

Table 24 displays the comparison between reference and new design auxiliary power demand where it can be seen that the reduction of power demand is higher for higher consumption modes, the same can be visualised from Figure 20.

Table 24: Comparison between Reference and New Design Power Demand per operational mode

Operational Mode	Reference [kW]	New Design [kW]	Difference [kW]	Power Demand Reduction
Cruising	189.57	149.46	40.10	21%
Max Speed	189.57	126.58	62.99	33%
Crossing	154.95	130.08	24.87	16%
In Port	117.84	79.57	38.27	33%
Anchor	154.78	116.05	38.73	25%
Manoeuvring	197.06	166.72	30.34	15%

The savings achieved are not only dependent on the power consumption of systems but also on their loading and servicing time, which varies from one operational mode to another. The maximum reduction occurs while at maximum speed. Nonetheless, it is worth noticing that the modes with high operational percentages, cruising and at anchorage have a reduction of approximately 40 kW in terms of demand.

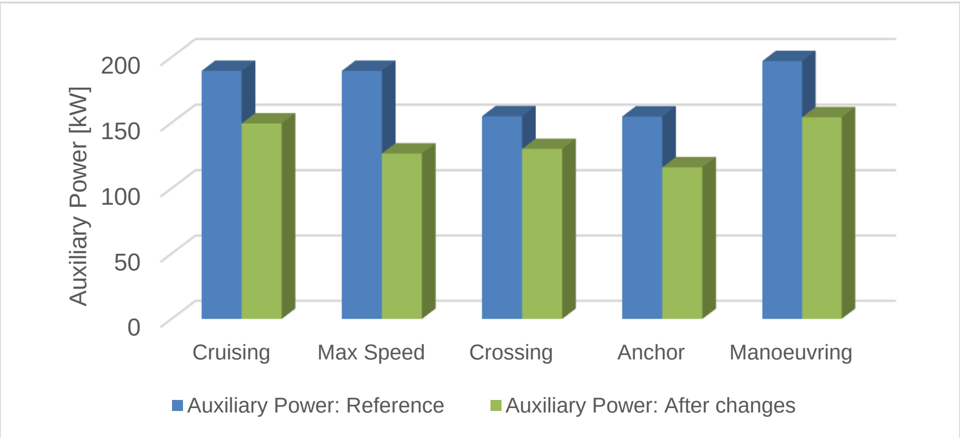


Figure 20: Comparison between auxiliary power of the reference design and of the new design after all changes and introduction of power management affect at maximum speed

EXCELLENCE IN PERFORMANCE

In addition, the peak consumption moment, hence the one defining the size of auxiliary power supply is also reduced by 30 kW, allowing a reduction on the size of equipment, hence further reduction of emissions depending on the fuel consumption rates.

Moreover, even though the emissions in Port cannot be quantified due to lack of information on shore power, the reduction of 33% on consumed power will have an impact on emissions as well.

Finally, the fact that all users prefer the same set of strategies is a consequence of the maturity of the strategies presented. The availability in the market plays a decisive role in the selection process, as it leads to options that do not present significant disadvantages in terms of any of the criteria.

As a result, it is possible to achieve by now a combination that leads to an energy saving solution without significantly compromising cost, size, weight or luxury. Table 25 presents the impact of the selected strategies in terms of investment costs, size (volume) and weight.

Table 25: Impact of the selected strategies

Strategy	Investment Cost Variation	Size Variation	Weight Variation	Power Consumption Variation	Absorbed Heat Variation
	€	m^3	kg	kW	kW
Glass	44,000	-	-	-	-36.76
Cooling Supply System	0	0.90	80	-8.00	-
Lighting	6,888	-	-	-3.05	-
Boiler Configuration	-6,800	-2.00	-421	-15.00	-
Total	44,088	-1.10	-341	-26.05	-36,76

The impact of the power savings on the overall consumption of the auxiliary systems is dependent on the load and service timing of each consumer group, as presented on Table 24, thus the cost/benefit analysis of the combination of strategies varies between operational modes as shown on Table 26.

Table 26: Cost Benefit Analysis of strategies per operational mode

Operational Mode	Power Savings	Investment Cost per energy benefit	Volume Cost per energy benefit	Weight Cost per energy benefit
	ΔkW	€/kW	m^3/kW	kg/kW
Cruising	40.10	1,099.18	-0.027	-8.50
Max Speed	62.99	699.92	-0.017	-5.41
Crossing	24.87	1,772.74	-0.044	-13.71
In Port	38.27	1,152.03	-0.029	-8.91
Anchor	38.73	1,138.34	-0.028	-8.80
Manoeuvring	30.34	1,453.13	-0.036	-11.24

On average the cost per kW saved is about 1,110 €, depending on the savings achieved on each mode. Due to the positive impact of the water systems on weight and volume, there is a benefit regarding these two criteria in applying energy saving measures, so the overall volume and weight is reduced per kW saved.

Finally, to answer the first sub-question there is the need to combine all the strategies selected over this chapter. By combining a multitude of strategies that alone have little influence in overall demand, however when combined are able to significantly impact overall power demand. In this case, it is possible to reduce the power demand at all modes up to 33%. The next chapter will answer the second sub-question on how much it is possible to reduce the propulsion power.

6. PROPULSION POWER DEMAND ANALYSIS

6.1 INTRODUCTION

Propulsion power demand is driven by multiple factors, such as hull resistance (friction and wave making), propulsive efficiency, etc. The reduction of power demand results in the reduction of fuel burnt, thus reducing the emitted CO_2.

As stated before, use is made of the Van Oossanen's expertise in designing performance-optimized hulls. For this reason, their database and existing designs are the start point for the resistance comparison to the benchmark design.

Firstly, the chapter elaborates on the Fast Displacement Hull Form developed by van Oossanen Naval Architects as in previous research it shows promising results in similar conditions to the ones considered. Furthermore it elaborates on the patented energy saving device, the Hull Vane® also developed by van Oossanen Naval Architects. Afterwards it briefly elaborates on the choice of going from steel to aluminium in terms of hull form material.

After that, the chapter elaborates on the method and iteration process used for the resistance comparisons and hull form selection. Furthermore, it gives and outline of the database used.

Finally, the results of resistance and power requirements for the chosen hull are compared to the ones of the benchmark so to quantify the improvements in terms of propulsion power demand, thus answering the second sub-question.

6.2 THE FAST DISPLACEMENT HULL FORM

6.2.1 INTRODUCTION

Nowadays, higher speeds are often the focus on the design of luxury motor yachts (40). Despite this, maximum speeds are hardly ever sailed. Instead mega yachts' typical load profile consists of cruising at lower speeds since this is translated into a more pleasant and comfortable ride for people on board. (41) (40)

Consequently, the higher the difference between cruising and maximum speed is, higher is the design challenge of optimizing performance for the complete speed range. Shifting the focus from maximum to cruising speed optimization will allow for savings during a higher percentage of the operating time. However it is important that no significant penalties to maximum speed occur as these still need to me met.

Design briefs cover from typical displacement speeds up to typical semi-displacement speeds, creating a dilemma regarding which type of hull form to choose. Considering the length range of the reference design to be between 40 to 50 meters, the latter speeds correspond to Froude numbers ranging from approximately 0.3 at cruising speeds to 0.5 at maximum speeds.

By making use of the combination of features that influence resistance, such as immersed transom area, bulbous bow design, trim control and spray rails, Van Oossanen designed a new concept, The Fast Displacement Hull Form (FDHF).

The Fast Displacement Hull Form is designed to be a semi-displacement form that is able to achieve an over-all good performance. Regarding resistance, it is able to achieve better results than conventional semi-displacement vessels, even being comparable to full displacement vessels at displacement speeds. (40).

This chapter describes the design features of the fast displacement hull form concept that allow it to have a better resistance performance, thus justifying its suitability for the new design.

6.2.2 DESIGN FEATURES

In order to achieve an optimal performance over the whole speed range, advantage is taken of not only one but the combination of various design features.

Typically, full displacement hull forms have better performance capabilities when sailing at lower speeds, thus design characteristics of the latter are applied to the FDHF concept in order to achieve performance advantages at lower speeds.

Likewise, features from semi-displacement hull forms, known to perform better at higher speeds, are introduced to achieve higher speeds.

ROUND BILGE VS HARD CHINE

Extensive research has been carried out comparing advantages and disadvantages of both forms. (42) (43) (41)

Among the literature there is no consensus regarding which form is the best concerning seakeeping behaviour. Nevertheless, literature states that hull dimensions and parameters have a higher influence on seakeeping behaviour when compared to the section shape (42).

In addition, the utilization of centreline skeg, bilge keels and stabilizing fins, which are standard features for all types of yachts, improve the performance of the round bilge form at higher speeds, making it comparable to the hard chine form.

Considering the significance of the improved resistance and seakeeping behaviour at displacement speeds of the round bilge form, the FDHF adopts a round bilge form assuming well designed the above-mentioned features for the performance at semi-displacement speeds (40).

TRANSOM AREA

The immersed transom area has two different effects at displacement and semi-displacement speeds.

On the one hand, at displacement speeds, the immersed transom generates a considerable amount of resistance, proportional to the immersed area. This resistance constitutes a large fraction of the total resistance at displacement speeds, as it is translated in added wetted surface.

On the other hand, at semi-displacement speeds, the immersed transom area generates an upwards pressure on the aft part of the hull leading to a reduction of the running trim angle. The consequently more level attitude of the hull reduces resistance especially around the primary hump and lower end of the semi-displacement speed range.

In order to decide which of the factors would have a dominant effect, Van Oossanen compared the effect of the immersed transom area at cruising range (Froude number 0.35) and at semi-displacement speed (Froude number 0.60). (Figure 21) (40)

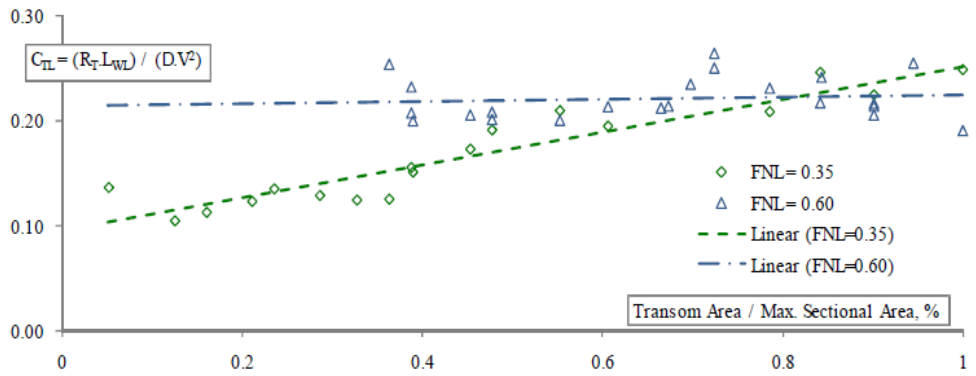


Figure 21: Dependency of resistance (in form of C_{TL}) on the immersed transom area at Froude number of 0.35 and 0.60 (40)

From Figure 21 it is possible to conclude that the impact of the immersed transom area is dominant at displacement speeds rather than at higher speeds. The FDHF has a small immersed transom area, around 20% to 30% of the maximum sectional area.

TRIM CONTROL AND SPRAY RAILS

In terms of trim control, interceptors are well known for their effectiveness in improving overall resistance by reducing the running trim. Moreover, an adjustable interceptor can be beneficial for all speeds.

Spray rails are common in semi-displacement yachts. Spray rails are beneficial especially above certain speeds by providing additional lift in the forward part of the hull and reducing the wetted surface area of the hull by breaking the spray sheet of the bow wave. Furthermore, spray rails are practical in keeping the deck dryer and avoiding spray to sweep over the deck in beam winds and waves.

THE BOW SHAPE

The bulbous bow is a common feature on displacement yachts since long ago. Bulbous bow have a positive effect on resistance, from low speeds up to speeds around Froude number of 0.55 (43). The reduction of pressure resistance of the fore body, reducing the bow wave height and lowering the running trim are some of the causes for the resistance reduction of applying a bulbous bow (40).

The fact that the bulbous bow is only fitted when the stem shape allows, results in some fast displacement hull forms to be featured with vertical bow lines. A vertical bow shape also presents some advantages in terms of buoyancy and especially seakeeping behaviour by reducing the pitching motion of the yacht. Furthermore, a vertical bow creates more internal space as the crew area can be moved forward.

The latter advantage of a vertical bow shape is especially important as the internal area can be critical due to the finer waterline entry of the concept. In order to counteract this issue, besides having a vertical bow shape, an enlarged concept of the fast displacement hull form was developed.

ENLARGED CONCEPT OF THE FAST DISPLACEMENT HULL FORM

The FDHF has a finer waterline entry when compared to other hull forms, namely hard chine and typical round bilge forms. Consequently, the lack of interior space can become rather critical.

For this reason, there was the need of finding an enlarged concept for the Fast Displacement Hull Form that would be able to have the required interior space and still encompass improvements in terms of resistance performance and meet the gross tonnage requirements.

This is achieved with the combination of increased slenderness and overall length of the FDHF. The increased slenderness allows the designer to increase dimensions without significant penalties in terms of resistance. (40) This way, the loss of area due to the increased slenderness is compensated by the increased length and vice-versa so that a compromise is achieved.

Especially at higher Froude number the increased slenderness ratio contributes to the resistance reduction through the reduction of the wave making resistance, dominant fraction of the total resistance at high speeds.

In addition, the wetted surface is relatively reduced with the increased slenderness, contributing for the resistance reduction at lower Froude numbers when viscous resistance is dominant. In this case, since the overall length is also increased due to the internal area issue, the wetted surface remains the same.

6.3 THE HULL VANE® [1]

6.3.1 INTRODUCTION

The Hull Vane® is a patented device by van Oossanen, developed by Dr. Ir. Pieter van Oossanen.

The Hull Vane® is described as a fixed foil below the waterline of a non-planing hull. It is located at the aft part of the hull, influencing the stern wave pattern and generating hydrodynamic lift, therefore contributing for an improved performance in terms of resistance and seakeeping behaviour. Nowadays, Hull Vane B.V. works independently of Van Oossanen.

This section outlines the working principles of the Hull Vane®.

6.3.2 WORKING PRINCIPLE

Four interrelated effects of the Hull Vane® can be found, a thrust force, a trim correction, the reduction of waves and the reduction of motions in waves (44).

Firstly, based on foil theory, a thrust force is provided by the Hull Vane. On Figure 22 a schematic overview of the forces on the Hull Vane® is given.

The foil creates a lift force $\overrightarrow{L_{HV}}$ which is perpendicular to the water flow, and a drag force $\overrightarrow{D_{HV}}$ in the direction of the flow. The sum of these two forces is $\overrightarrow{F_{HV}}$ that can be decomposed in x and z direction as follows:

$$\overrightarrow{L_{HV}} + \overrightarrow{D_{HV}} = \overrightarrow{F_{HV}} = \overrightarrow{F_{x,HV}} + \overrightarrow{F_{z,HV}}$$

Equation 4

[1] Hull Vane® is a registered trademark of Van Oossanen & Associates b.v.

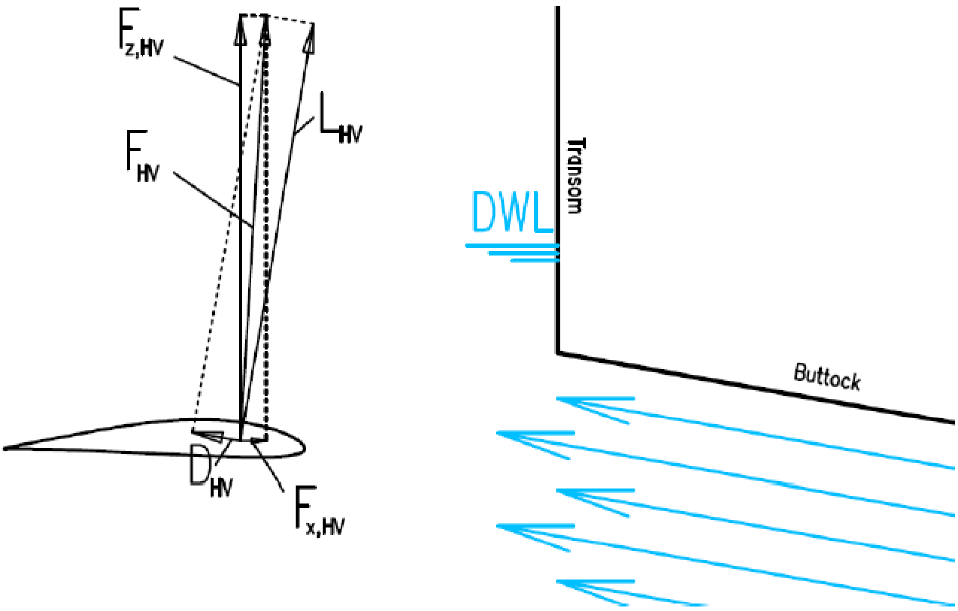


Figure 22: Schematic overview of the forces on the Hull Vane® in a section view of the aft ship

If the x-component of the lift force is greater than the x-component of the drag force the resultant force $\overrightarrow{F_{HV}}$ provides a thrust force. The lift and drag forces are not only dependent on the shape of the Hull Vane®, but also on other factors, such as the vicinity of the free surface.

If θ is the defined as the trim angle, β the Hull Vane® angle and α the Hull Vane® inflow angle, then the thrust forced generated by the Hull Vane® is described as follows:

$$\overrightarrow{F_{x,HV}} = \overrightarrow{L_{HV}}\sin(\alpha+\beta+\theta) - \overrightarrow{D_{HV}}\cos(\alpha+\beta+\theta)$$

Equation 5

Secondly, the resultant force in z-direction also contributes for the resistance reduction by affecting the trim, especially at higher speeds. Furthermore, the trim reduction influences the angle of the buttocks relative to the design waterline, hence the angle of attack of the water flow on the Hull Vane®.

$$\overrightarrow{F_{z,HV}} = \overrightarrow{L_{HV}}\cos(\alpha+\beta+\theta) + \overrightarrow{D_{HV}}\sin(\alpha+\beta+\theta)$$

Equation 6

Thirdly, by creating a low pressure region on the top surface of the Hull Vane® that interferes favourably with the transom wave system a significantly lower wave profile can be achieved. The reduction of the wave system contributes not only to the total resistance reduction but also leads to less noise and vibration on the aft deck and to a lower wave system.

Finally, the Hull Vane® dampens the pitch and heave motions of the vessel. The lift force produced by the Hull Vane® counteracts the pitch and heave motions reducing them.

By reducing the motions the added resistance due to waves is also reduced, which contributes to a higher effectiveness of the Hull Vane® in waves. Moreover, benefits as increased comfort on board, safety and range of operability are a consequence of the reduced motions.

6.3.3 THE INFLUENCE OF HULL VANE LOCATION, SHIP SPEED AND HULL SHAPE

During the past years much research has been done on the optimal position of the Hull Vane® relative to the ship's hull. The main considerations were found by Moerke in his CFD analysis (45), showing that if fitted too close to the hull, the Hull Vane® might be positioned in the boundary layer, thus reducing the lift it creates.

Due to the effect of 'pressure reflection', the total resistance of the combination hull and Hull Vane® is increased when the Hull Vane® is fitted directly below the hull. In order to solve this problem the Hull Vane® has to be placed behind the transom of the vessel, leading to a slight reduction in Hull Vane® thrust (44).

In addition, in order to place the Hull Vane® one has to consider the angle of the water flow near the stern of the vessel. Regarding the angle of attack the optimal position of the Hull Vane® is highly dependent on the wave length, thus on vessel's speed.

In his research, Moerke also noted that the Hull Vane® results improve with increasing speed (45). Advantages are achieved for Froude numbers between0.2 and 0.7 with an optimum around 0.35.

At lower Froude numbers, when friction resistance is dominant, the increased wetted surface due to the Hull Vane® has a negative effect on total resistance. However, taking into consideration that those slow speeds are only relevant during manoeuvring, thus small percentage of operational time, the negative effect of the hull vane at lower Froude number can be neglected when compared to the potential fuel savings at higher speeds.

Regarding the Hull Shape (45) noted that if the buttock angle is increased, the angle of attack of the flow to the Hull Vane® is increased, and the lift force directed more forward, increasing the resulting decomposed force in x-direction.

Considering all the above, not every ship type is suitable for fitting a Hull Vane®. The ideal candidates are medium and large sized vessels operating at moderate or high non-planing speeds.

6.4 STEEL VS ALUMINIUM

Reducing the vessel's displacement is a way of enhancing resistance reduction. Among others, this can achieved either by reducing dimensions or by opting for lighter building materials. Therefore, aluminium is considered. Moreover, there are many advantages of considering the use aluminium alloys over the use of mild steel in the construction of vessels. (46)

The first and more important advantage is the high strength to weight ratio leading to lightweight vessels. The fact that lighter structures are possible allows for higher speeds and fuel savings. Furthermore, by having lower structural weight allows for increased dimensions and more accommodation space.

In addition, the lightweight of hull and superstructure allow for lower gravity centres, thus enhancing stability.

Secondly, the high resistance to corrosion of aluminium makes it attractive for applications in the maritime sector since this characteristic is decisive when choosing hull and superstructure materials.

For all the above stated, especially due to the ability of reducing displacement, thus resistance, the use of aluminium for both hull and superstructure is attractive when focusing on the CO_2 emissions reduction from the vessel's operation point of view. The processing and recycling of the materials is left out of scope in this research.

The increased fuel efficiency due to the reduced weight as well as the possibility of increasing dimensions and accommodation space are very attractive. The latter might become significantly important, as more space may be required for the application of newer technologies in terms of energy saving devices and power production techniques.

6.5 THE DATABASE, THE METHOD AND THE ITERATION PROCESS

Van Oossanen's database consists of gathered data on resistance and performance of the previously designed vessels. The resistance data of the various vessels is based on either empirical data, CFD or tank testing or both. Furthermore, the database is able to scale the existing designs and corresponding data based on either length or displaced volume.

In addition to Van Oossanen's designs, the database also includes "public" designs, extending the range of data and comparison options. As the range of possibilities is so broad, several search filters are possible so to make the comparisons as fair as possible.

The definition of the parameters to filter the results presented by the database varies from case to case. In this case, based on the proven knowledge that FDHFs have a superior performance when compared to full displacement hull forms (40), the search was restricted to Van Oossanen's previously designed fast displacement hull forms.

On a first iteration, aiming for an improvement in resistance due to difference in hull form, the building material and displaced volume are kept the same while the other main dimensions kept within similar ranges.

Scaling in terms of displaced volume, targeting for the cruising speed the database provides the results in which the length to displacement and length to beam ratios are as close as possible to the ones of the benchmark design.

When comparing the benchmark performance to the hull forms presented by the database it is possible to see that there are some improvements in terms of performance. However, these are relatively small and mainly at higher speeds.

Figure 23 presents the resistance over the speed range of the reference and three designs suggested by the database. The reason for such similar performance results lays on the fact that the benchmark was already very close in terms of design concept to the FDHF.

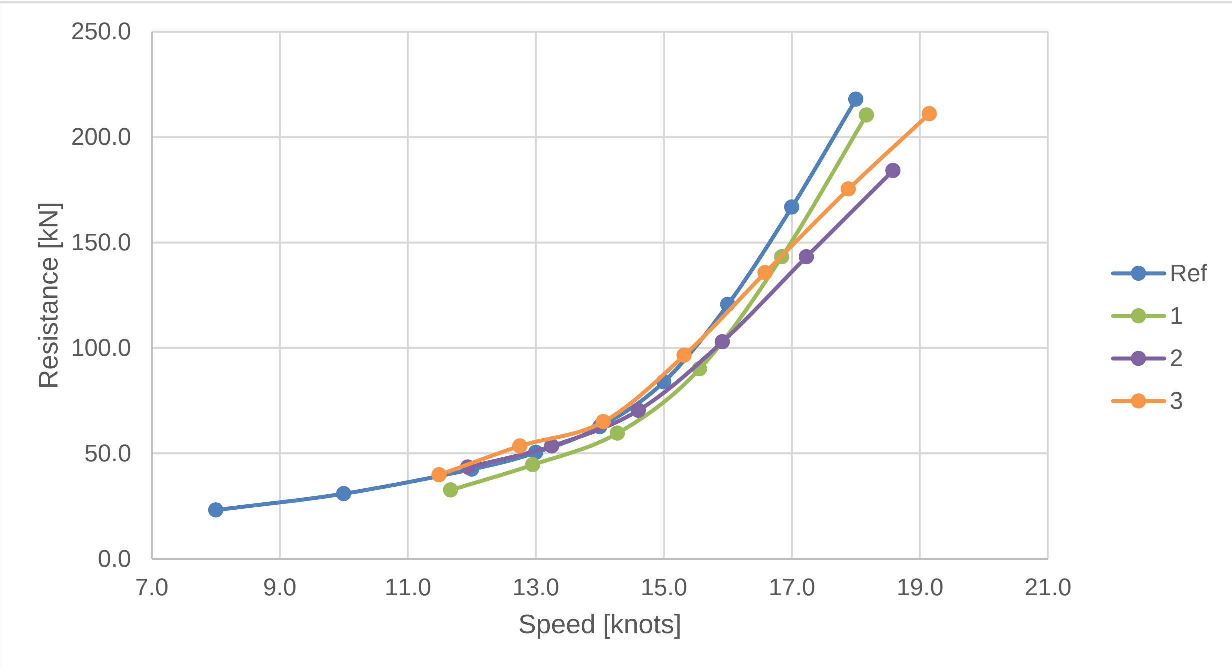


Figure 23: Performance comparison between reference design and steel fast displacement hull forms from database

Consequently, in this case, reducing displacement is the next step for further resistance reduction. In order to do so the building material goes from steel to aluminium. In order to obtain a fair comparison, the hull's dimensions are kept the same and only the structural weight is changed. In this case the displacement goes from 460 ton to 256 ton, which is a significant difference, thus significant resistance improvements can be expected.

Figure 24 shows the resistance curves of the benchmark design against the ones of two designs suggested by the data base having the same dimensions of the benchmark, however being built of aluminium as previously elaborated. As expected, the resistance is significantly reduced in this case over the whole speed range.

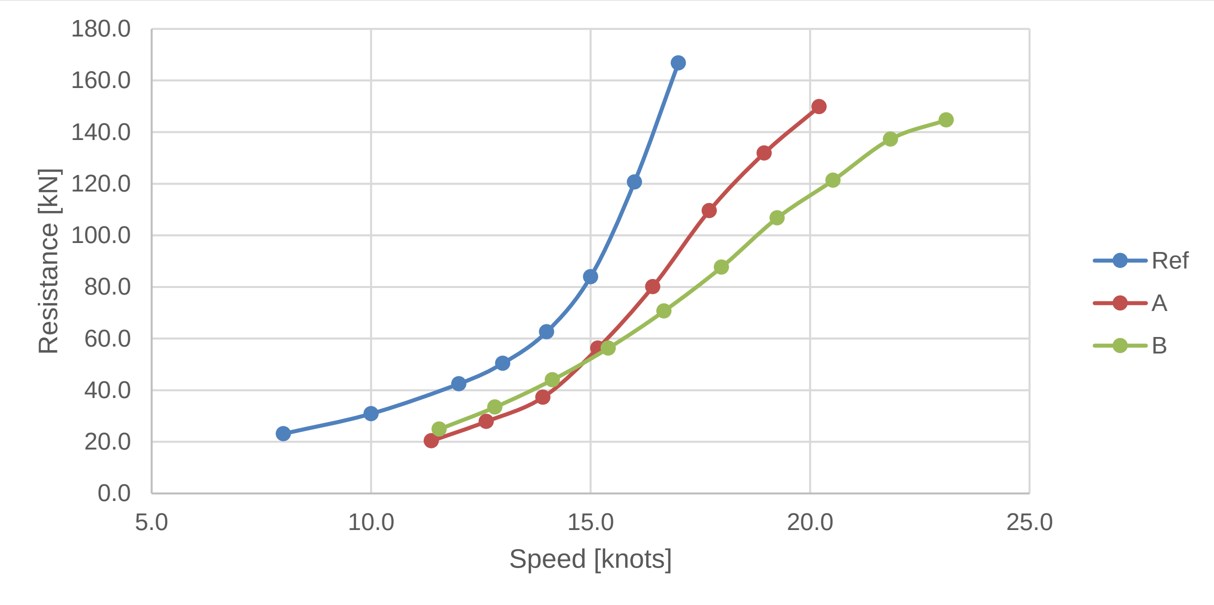


Figure 24: Performance comparison between reference design and aluminium fast displacement hull forms from database

As stated before, interior area is a critical issue in this assignment. As energy saving technologies are usually associated with space intensive devices and guest areas must not be reduced for the sake of comfort and luxury on board the super yacht.

Consequently, one of the decisive parameters for the choice of hull form is the interior area, thus the second step after verifying the performance improvements is to verify that the interior area available. As a reference, a 10% interior area reduction from the benchmark is taken as acceptable, however larger reductions would lead to unfeasible and unattractive designs.

As explained in section 6.2, the fact that the slenderness of the fast displacement hull is increased relatively to a full displacement hull presents an issue in terms of interior area available. Reason why the enlarged version of the FDHF is becoming more popular.

As expected, the interior areas of the new aluminium designs presented by the database were critical in terms of lower deck area, not respecting the 10% difference allowance established, as displayed on Table 27.

Table 27: Lower Deck Area Comparison between reference design and Aluminium FDHF designs from database

	Reference Design	**A**	**B**
Lower Deck Area [m^2]	231.68	140.82	138.86

Consequently, there is the need for a third iteration. In order to go around the interior area problem without sacrificing a great deal of the performance improvement achieved before, thus the enlarged concept is considered. According to section 6.2, it is possible to slightly increase length without significant penalties to performance, this due to the slenderness increase brought by this concept. Moreover, the increased dimensions do not translate into increased tonnage, so the design will remain under the 500 GT category.

For this purpose an increase in length was allowed up to an overall length of 50m as this is still in the range attractive to the market according to van Ossanen's experts and will still be able to provide with favourable regulatory standards of a yacht under 500GT.

This new input to the database led to a new design, which not only had better performance but also met the interior area requirements, thus being chosen for new concept.

The next section describes the new hull form found through the database. In addition, it presents a comparison between the performance of the benchmark and the new hull form in terms of resistance, power requirements and interior space.

6.6 NEW HULL FORM VS BENCHMARK

As stated before the new hull form suggested by the database has a better performance in terms of resistance when compared to the benchmark, as it can be seen for Figure 25.

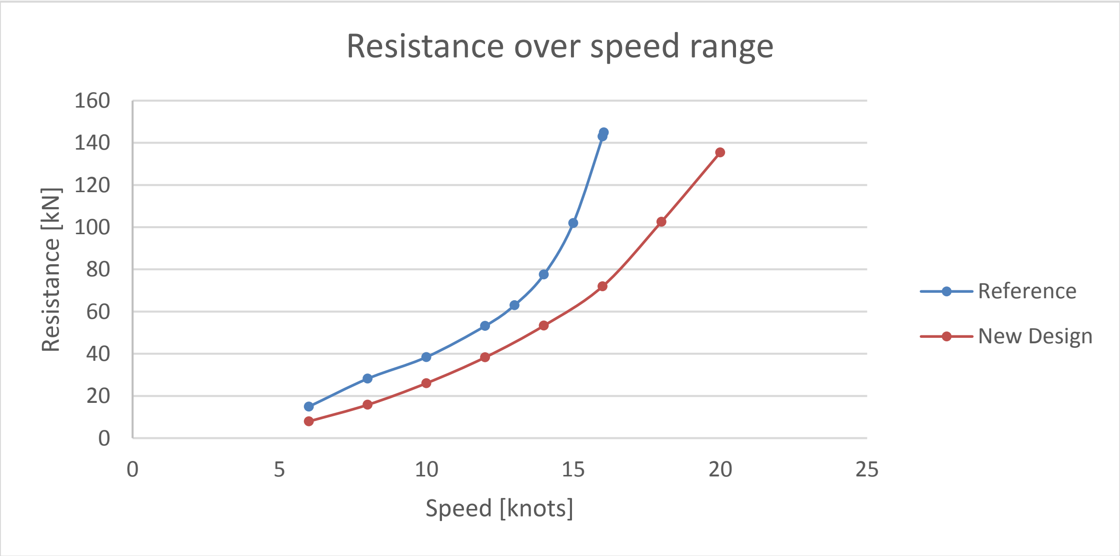


Figure 25: Resistance comparison between benchmark and new hull forms over the speed range

From Figure 25, it is possible to see that the new hull form performs significantly better over the whole speed range, especially after the primary hump. The changes to the hull form, i.e. the introduction of the FDHF prove to have a beneficial effect on the resistance curve, which is the start for the reduction of propulsion power demand. Nevertheless, the most significant effect is indeed the reduction of displacement weight due to the change in building material, which proves the importance of lightweight building materials.

In addition, the slight change on the main particulars also has an impact on the resistance reduction. The increased slenderness of the hull is as stated before one of the main characteristics of the fast displacement hull form that contributes to this reduction.

The main particulars and coefficients of both the benchmark and the new design can be compared on Table 28. The most significant differences between both designs are the increased length and slenderness ratio (Equation 7), and the reduction of displaced volume.

$$Slenderness\ Ratio = \frac{L_{wl}}{D^{\frac{1}{3}}}$$

Equation 7

Table 28: Main particulars and design coefficients of benchmark and new design

	Reference Design	New Design
L_{OA} [m]	45,65	50
L_{WL} [m]	39,05	48,9
B_{WL} [m]	8,93	8,36
T [m]	2,55	1,85
D [m^3]	409,76	304,4
L/B	4,373	5,849
B/T	3,502	4,519
Slenderness Ratio	5,257	7,269
C_B	0,461	0,402

The draft reduction resulted on the reduction of the propeller diameter, which in turn influences the propulsive efficiency, thus propulsion power demand. Therefore, there is the need to assess how significant is the impact of the draft reduction and propeller diameter reduction.

The reference design is equipped with two propellers of 5 blades and 1.6m of diameter. The new design is also equipped with two propellers of 5 blades; however the propeller diameter is 1.5m.

The propeller characteristics define the hull efficiency, through the trust deduction coefficient and the wake fraction, the relative rotative efficiency and the open water efficiency that have a direct influence on the RPM and power demand.

In addition, by adding a Hull Vane®, further resistance reduction is achieved at cruising and maximum speed in comparison with the new design without Hull Vane®. At low speeds, the Hull Vane® results in a slight resistance increase as it can be seen from Figure 26.

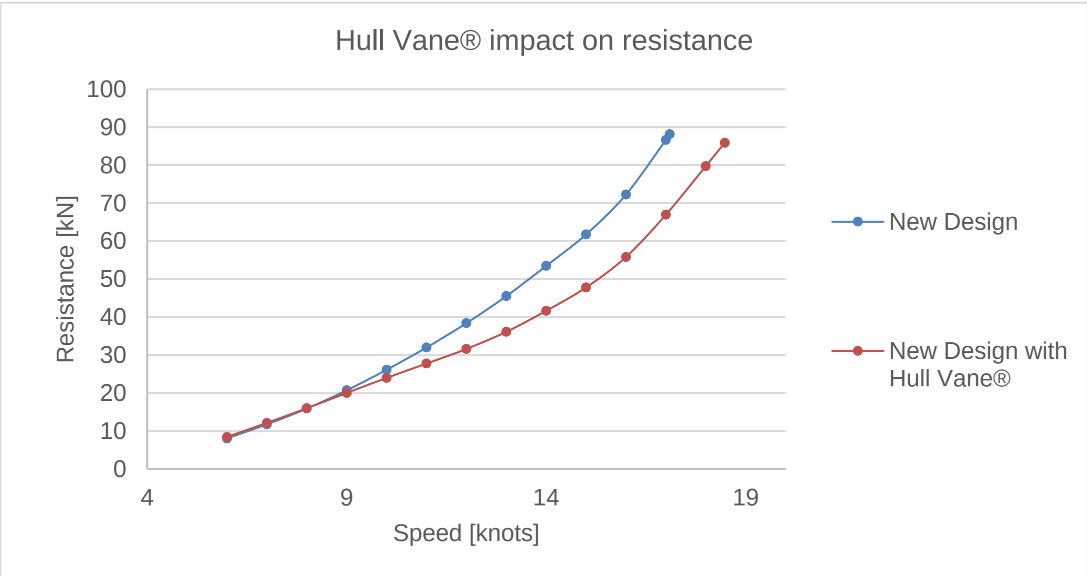


Figure 26: Resistance comparison between new design with and without Hull Vane®

6.7 CONCLUSION: HOW MUCH OF THE PROPULSION POWER DEMAND IS IT POSSIBLE TO REDUCE?

Figure 27 displays the power brake curves over the whole speed range for the benchmark design, the new design encountered by the data base and the new design featured with a Hull Vane®. As plotted in Figure 25, the new design has a lower power consumption curve over the whole speed range.

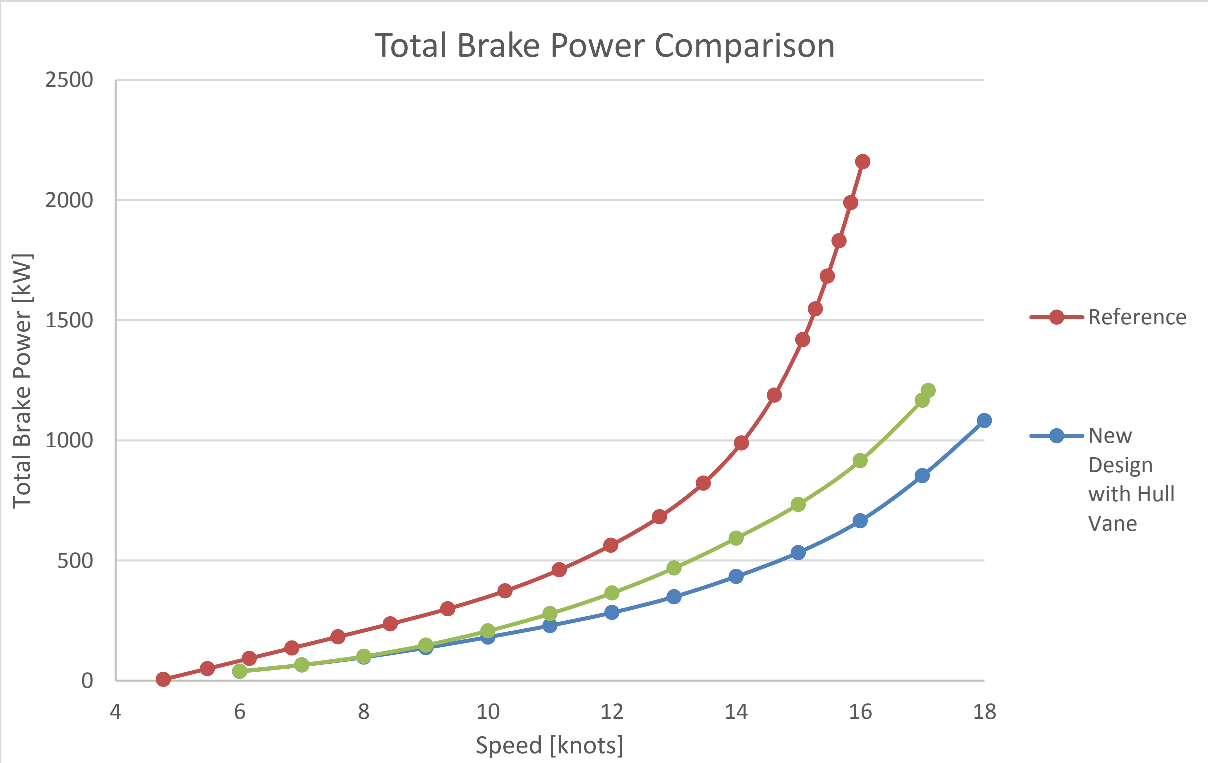


Figure 27: Total brake power demand comparison between the benchmark and the new design with and without the Hull Vane®

Regarding the Hull Vane®, the brake power demand is reduced at cruising and maximum speed, however as stated before, the same way with the resistance, at low speeds the brake power demand is slightly increased.

To answer the second research sub-question, how much of the propulsion power demand it is possible to reduce, Figure 23 displays the brake power demand and percentage of reduction in relation to the benchmark of the two options considered of the new design.

Table 29: Propulsion Power Reduction: Brake power demand and reduction percentage

	New Design		New Design with Hull Vane	
	Brake power demand[kW]	**% reduction**	**Brake power demand[kW]**	**% reduction**
Manoeuvring	38.15	56.2%	38.49	55.9%
Cruising	364.58	37.7%	283.14	51.4%
Maximum Speed	915.23	56%	665.27	67.6%

Finally, in the next section the last sub-question will be answered, elaborating on the power supply systems and resultant emissions.

7. SUPPLY ALTERNATIVES

7.1 INTRODUCTION

Once the power demand has been analysed and reduced, the next step is to answer the last sub-question: How much CO_2 emissions is it possible to reduce by considering power supply alternatives?

There are mainly two ways of reducing emissions. On the one hand, the use of clean ways of supplying energy, such as alternative fuels or renewable energies result in CO_2 emissions reduction or even elimination. On the other hand, the efficiency of the power plant plays a decisive role regarding emissions' reduction since the reduction of fuel consumption leads to a reduction of the CO_2 emissions.

The Paris Agreement has challenged the industries to join efforts and work together to the overall reduction of emissions in the years to come. (47) The standards established lead to the development of renewable energies, energy storage and alternative power supply forms in general as they promise to provide cleaner energy. (48)

Zero emission yachts are on the agenda (49) however the current stage of mature technology does not allow for a feasible and reliable application in this 50m yacht case as it will be demonstrated throughout this chapter.

Like the Energy Observer (50), it is possible to have zero emission vessels if the power demand is low and operational times relatively short. In general, these are normally prototype projects to attract the eye of the public and governments to invest in the development of cleaner technology.

Alternatively to zero emission, it is possible to already reduce CO_2 emissions to some extent by improving the efficiency of the power plants. Furthermore, transitional strategies such as hybrid power supply concepts, utilizing several ways of supplying power, can be a first step in reducing emissions.

Despite the fact that hybrid strategies' popularity is growing, in the marine industry diesel direct traditional power plants with traditional diesel oil are still the most popular alternative due to its reasonable efficiency and reliability relative to its investment cost.

This chapter briefly elaborates on the different emission reduction strategies above mentioned, however it focuses on the hybrid power solution.

7.2 ALTERNATIVE FUELS

In the maritime industry, heavy fuel oil (HFO) and marine diesel oil (MDO) are still the most common fuel types when compared to other types of fuel, mainly due to their attractive price, efficiency and physical properties, such as heating value, viscosity, energy density and density at ambient conditions, etc.

However, the stricter regulations concerning the environment encourage ship owners and designers to look for different options in order to meet the new emission levels, hence alternative fuels that potentially lead to lower emissions are many times considered.

The effectiveness of alternative fuels in reducing the CO_2 emissions is highly dependent on the production process of these fuels (51). In many cases, as it is for biofuels and hydrogen, the levels of CO_2 emitted during the production process are higher than the levels saved in the energy production process from these fuels.

Natural Gas, usually in the liquefied form (LNG) is the one which application is more mature, already being applied in some cases, mainly in the commercial sector.

In the natural gas and hydrogen case, the physical properties at ambient conditions are the major drawbacks of these types of fuel, especially regarding bunkering and storage. (52) Both fuels occupy large storage volumes as they are very light. Furthermore, among other options, they require either liquefaction or gasification in order to be stored.

In the hydrogen case, there are two main processes, liquefaction through the storage at cryogenic temperatures (-253ºC) or gasification through the compression at 350 bar or 700 bar, either way a considerable amount of energy is spent in storage.

In addition, the existence of bunkering stations throughout the world is still very scarce, especially due to the complexity of bunkering systems and storage of large quantities of these fuels. Another disadvantage of such fuels lays on safety issues; both hydrogen and LNG are highly combustible, therefore the risks associated with leakage are noteworthy.

In terms of equipment, internal combustion engines are the most common in the industry as they are the ones commonly operating on diesel oil. It is still possible to operate them on alternative fuels even though they require some alterations. Furthermore, the possibility of having dual fuel engines is becoming more common and available in the market, which has a positive impact on emissions however does not eliminate the storage issue related with light fuels. Dual fuel engines may be considered a transitional strategy towards zero emission or emission reduction.

Alternatively, equipment like fuel cells are many times associated with alternative fuels. Nevertheless, they are not yet fully mature since energy density is low and investment costs very high which leads to very space and cost intensive power supply alternative. (52) (48) (53)

As a result of the interest in reducing emissions of a series of industries besides the maritime industry, e.g. automotive, progress associated with hydrogen and fuel cell solutions can be expected for the coming years with the goal of making zero emission vehicles and ships a reality.

For now, diesel is still the preferred option, especially in this case of space restrictions due to a maximum gross tonnage of 500GT. However, for larger designs, alternative fuels are on the edge of being feasible, as there are actually concepts being developed. (49) (54)

7.3 Renewable Energies

Renewable energies have the particularity of being available at almost all times, especially considering the operational areas. Moreover, renewables are a clean energy source that increasingly provides electricity at costs competitive with or lower than fossil-based power. (55)

The most competitive renewable energy sources, especially in the maritime industry are solar and wind power as these are both widely available at sea.

Currently, renewable energies on ships are characterized by high investments and low energy density, which all together results in reduced feasibility for their application in a 50m yacht as a standalone power supply.

Mainly, the restricted space hinders large scale installations, which together with the fact that energy density is low due to low conversion efficiency, especially regarding solar energy, results in non-significant achievements as will be demonstrated further in this section. Nevertheless, renewables, especially solar energy has a great potential to reduce vessel's emissions and meet the requirements of greenhouse gas emissions set by the IMO. (1)

The potential of renewable energy has led to developments over the past few years, further improvements are still promised for the years to come as continuous technological innovation remains a constant in the renewable power generation market. (55)

The competitiveness of renewable energies in meeting the generation needs is dependent on the technology improvements as these are able to unlock efficiencies in energy conversion, improving the power generation performance. Moreover, as the manufacturing efficiency is increased and installation costs decreased the renewable energy power supply option becomes more competitive. (55)

Taking into consideration the current stage of technology, in the marine industry the attention goes towards solar and wind energy. The better efficiency, energy density and simplicity of installations makes solar energy more attractive than wind energy. Consequently, only the solar energy was investigated as an option. However, in case there is the opportunity, it might be interesting to investigate the combination of renewable power sources on board.

Firstly, there is the need to determine the area available for the installation of solar panels. As stated before, the energy density of solar energy is rather low, thus maximizing the installation area results in maximizing the power output from solar energy.

The ideal areas for the installation of solar panels are the roofs, for this reason, a rearrangement of the superstructure in order to maximize available roof area was performed. The rearrangement of superstructure did not lead to internal area variations nor it lead to significant issues. In depth elaboration on the rearrangement is provided in the next chapter (Chapter 8) and the drawings can be found in Appendix G.

As a result of the increase in available roof area, the available area for solar panels increased from 100m^2 to 158.55 m^2. Taking into account the calculation methodology elaborated in Appendix A and the collected solar radiation data (56), assuming once more that the yacht is at the same position and orientation, an average energy production for a summer day in a random location in the Mediterranean is calculated.

In addition, the solar panel characteristics displayed in Table 30 are based on high efficiency solar panels available for maritime applications. (57) Moreover, it presents the characteristics of the installation considering that all the available area for solar panels is covered, which in reality is not feasible.

Table 30: Solar Panel average characteristics and installation characteristics

	Panel Characteristics	**Installation Characteristics**
Installed Area	-	158.55 m^2
Installation Cost	1,054.29 €/m^2	€167,157.81
Peak Power Output	148.24 W/m^2	23.50 kW
Installation cost per power output	-	7,111.97 €/kW

Accounting for all this, and a panel efficiency of 24% (57) as these are high performance solar panels. Figure 28 represents the power output per hour of the installation. The highest production is between 10am and 1pm when the position of the sun is higher and the radiation intensity is higher.

In total, in an optimal situation this will lead to 180.6 kWh/day, admitting an average of 12 hours of sun per day in summer, this production rate translates in 15.05 kW.

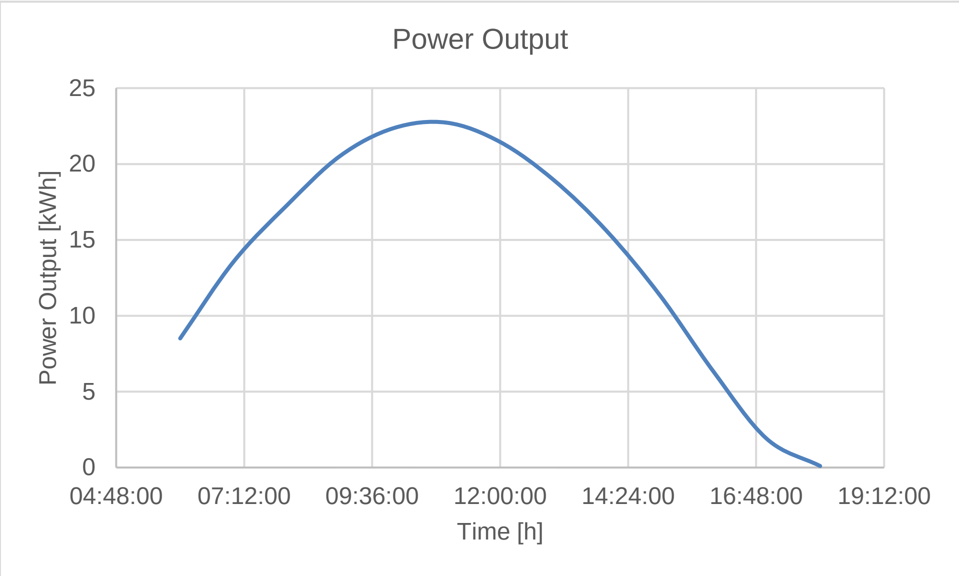


Figure 28: Power Output in optimal conditions of the total installed solar panel area

At anchorage the yacht has a consumption of 116.049 kW and while cruising of 149.465 kW. (Section 5.9) Therefore, the total solar power installation is only capable of meeting 12.97% or 10.07% of the demands, respectively.

It is worth mentioning that the production estimated in this calculation is higher than in reality for a number of reasons. Firstly, the installed area is generally reduced to at least 80% of the available area, for the installation of other components such as electric cables. Secondly, the yacht is not in a static position, therefore the dynamic operational profile will have an impact on the power output. Finally, the calculation method does not account for external environmental conditions such as dust, wind or shadows, all of which also contribute to the reduction of generated power by solar panels.

In addition, a major drawback of the solar power production is, as it can be seen from Figure 28, the fact that production is not constant therefore cannot be directly input into the grid. Therefore, requiring the installation of storage systems and converters.

Lastly, the fact that installation costs are high together with the fact that the only very low percentages of demand are met through solar panel are the reason why the attractiveness of such an option is so reduced.

7.4 Power Plant Configuration

The optimisation of fuel efficiency through the optimisation of the power plant configuration results in fuel cost and emissions reduction as these are dependent on the amount of fuel burnt.

In addition, the efficiency of the vessel not only lies in the efficiencies of the single components, but there is also efficiency potential in the synergy between components, i.e. if the interaction between the components results in a better fuel efficiency when they are combined rather than when they operate separately.

Traditionally, yachts are featured with diesel direct propulsion plants. However, alternative power plants are growing in popularity, especially hybrid configurations. Hybrid configurations seek to find the optimal interaction between diesel engines and generators in order to achieve the optimal synergy between components with the goal of reducing the fuel consumed per kW delivered.

The specific fuel consumption curves of diesel engines and generators have similar trends. However, the fact that extra conversion is necessary inside the diesel generator, from mechanical to electric energy, there are extra losses (~8% (58)) in comparison with the diesel engine. Therefore, the specific fuel consumption of a generator is generally higher for the same percentage of MCR when compared to the specific fuel consumption curve of a larger diesel engine.

Nevertheless, when considering a generator smaller in size in comparison with the engine, at higher percentages of MCR the difference in specific fuel consumption is reduced as shown in Figure 29. The specific fuel consumption figures are in relation to the output of the machines, thus output of diesel engine and output of diesel generator (electric kW).

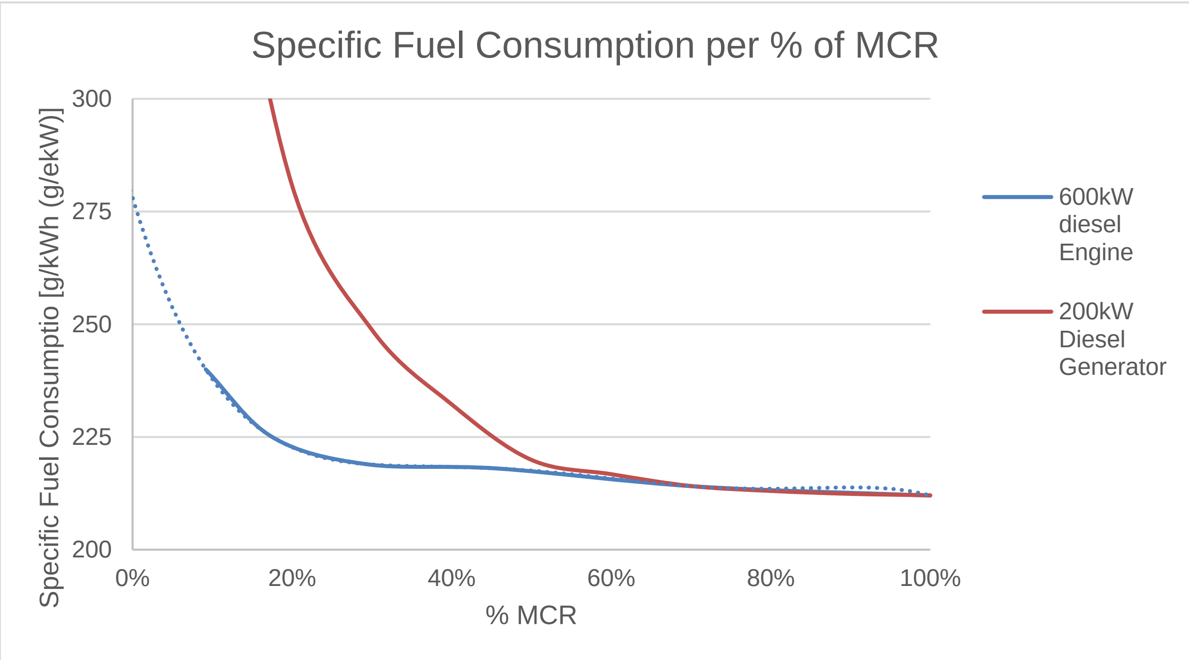


Figure 29: Specific fuel consumption comparison between medium size diesel engine and smaller diesel generator per percentage of maximum continuous rating

In both cases, when operating at low loading conditions the specific fuel consumption characteristics are poorer than when operating at higher loading conditions. This is where the potential benefits of a hybrid configuration lay.

Consequently, when combining a large diesel engine with a smaller diesel generator in a way that the high loading zone of the generator overlaps the low loading zone of the diesel engines it is possible to find the synergy between the components. Nevertheless, this is highly dependent on the installed engines and generators as it is not true for all cases.

Figure 30, illustrates this situation for a certain combination of engine and generator, in which operating the diesel generators at high loads is potentially more advantageous than operating the diesel engines at low loads. In this case, this happens between 70kW and 200kW. When operating near the 200kW, approximately 1.5 kg of fuel per hour are saved which can be translated in approximately 4.5 kg of CO_2 per hour saved, which can be quite significant depending on the operational profile.

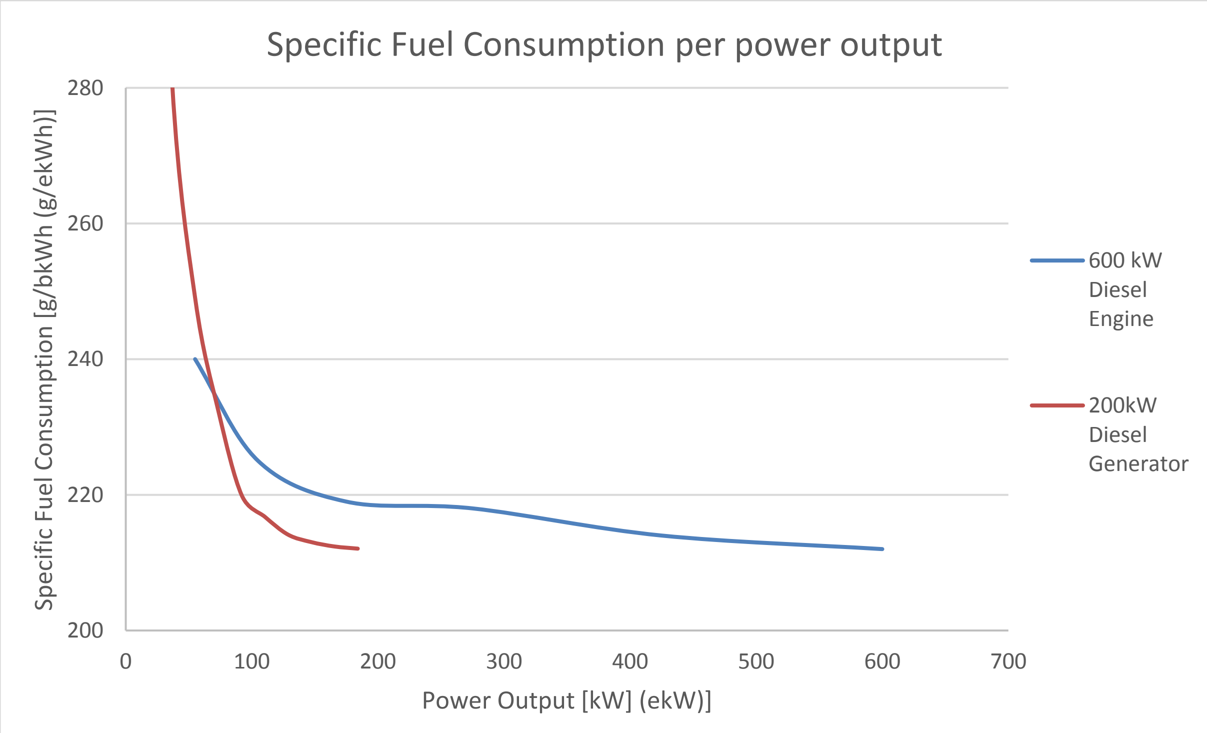


Figure 30: Specific fuel consumption per power output of medium size diesel engine in comparison with smaller generator

Usually, the low loading of diesel engine corresponds to low speed sailing, when the propulsion power demand is lower and forces the main engines to operate at less efficient conditions. Nevertheless, the potential savings are dependent on the synergy between the components and power demand of auxiliary and propulsion systems at each operational moment. In addition, they are also dependent on efficiencies of the electric motor and converters installed

Regarding the synergy between components, the high load zone of the generators should overlap, as much as possible, the low loading zone of the diesel engine. Moreover, the difference in specific fuel consumption needs to be such that makes up for the additional conversion losses on the generator set.

Nevertheless, as speed increases, the power demand also increases, until reaching the point at which is no longer advantageous to have the generator sets to be the only prime movers, since the difference in specific fuel consumption is no longer enough to make up for the extra conversion losses.

Careful matching and designing of power plants is needed to make sure that benefits are achieved by changing the plant configuration, as the benefits depend on the consumption characteristics of the chosen engines and generators.

The following sub-sections briefly elaborate on three different configurations, diesel direct (7.4.1), diesel electric (7.4.2) and hybrid (7.4.3).

7.4.1 Diesel Direct Propulsion

Diesel Direct, also known as mechanical propulsion is the most common in the maritime industry, and the yachting industry is not an exception.

Typically yachts use conventional diesel systems driving fixed propellers via a gearbox. Separately, the generator set supplies the electrical power for auxiliary systems. (59)

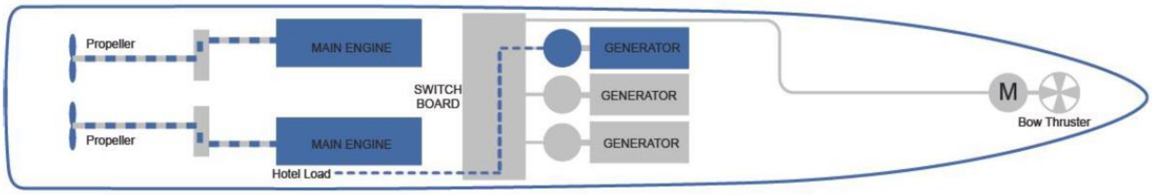


Figure 31: Diesel Direct typical configuration (8)

Figure 31 shows a classic configuration of this type of power plant. The attractiveness of such a configuration follows from the fact that it contains fewer components when compared to other arrangements, thus leading to lower investment and maintenance costs.

In terms of system efficiency, besides the efficiency of the engines, the only additional losses are regarding transmission, shaft and gearbox. Usually, these losses lay around 4%. (59)

The major drawback of this arrangement is the limited flexibility of operations allowed, thus reducing efficiency at off-design conditions. This is aggravated by the requirement of having to fulfil the demand of the operational mode with the highest demand, increasing installed capacity and off-design condition range.

7.4.2 Diesel Electric Propulsion

Alternatively to what happens in the conventional architecture, in diesel electric both propulsion and auxiliary are connected in the same network driven by multiple generator sets. Figure 32 represents the typical configuration of diesel electric propulsion arrangement.

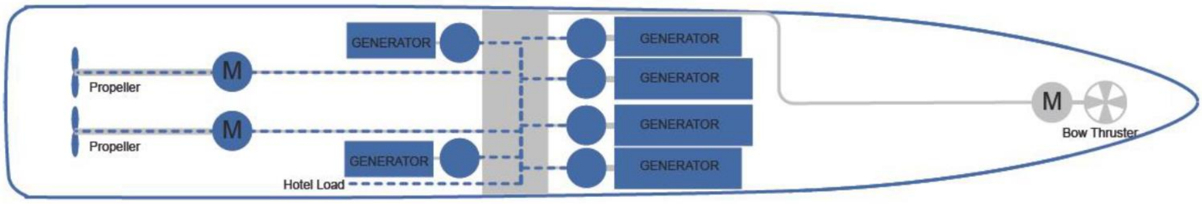


Figure 32: Diesel Electric Typical Configuration (8)

In this case, there is no mechanical transmission, reducing noise, vibration and transmission losses. Nonetheless, extra conversion stages are added to the architecture in comparison with the diesel electric case, which in turn incurs additional losses (10-20%). (8)

7.4.3 Hybrid Propulsion

The hybrid propulsion concept consists in combining the advantages of both diesel direct and diesel electric propulsion in one power plant, taking advantages of the synergy between engines and generators as previously explained (Figure 29 and Figure 30). Therefore, extending the economically and environmentally attractive operating area of the vessel. (59)

This is possible through an electric machine connected at the gearbox that is able to act as either a power take-in (PTI) or power take-off (PTO). Therefore, it is possible to combine electric and mechanical propulsion depending on the demand of each operating moment.

As previously stated, diesel engines operate at maximum efficiency around 85% loading condition and when operating at part-load the efficiency is significantly reduced. Especially, below approximately 50% loading when incomplete combustion starts, the environmental and engine maintenance issues are more severe.

The main goal of hybrid propulsion is to keep the engines operating close to their maximum efficiency point. Therefore, there are three main operating modes in hybrid propulsion, as shown in Figure 33, Figure 34 and Figure 35.

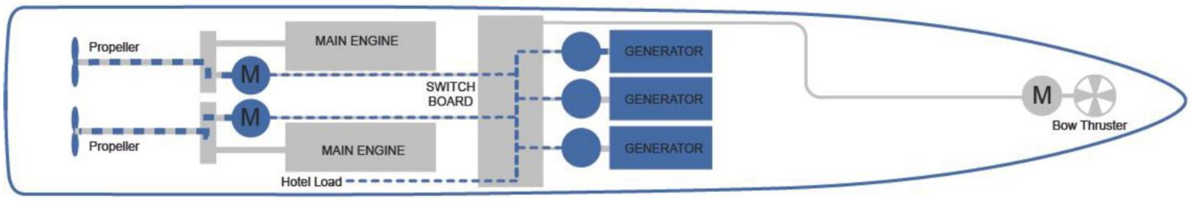


Figure 33: Hybrid propulsion arrangement in slow PTI mode (8)

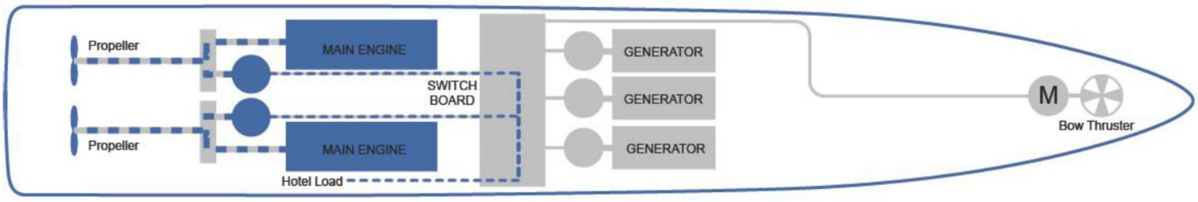


Figure 34: Hybrid propulsion arrangement in PTO mode (8)

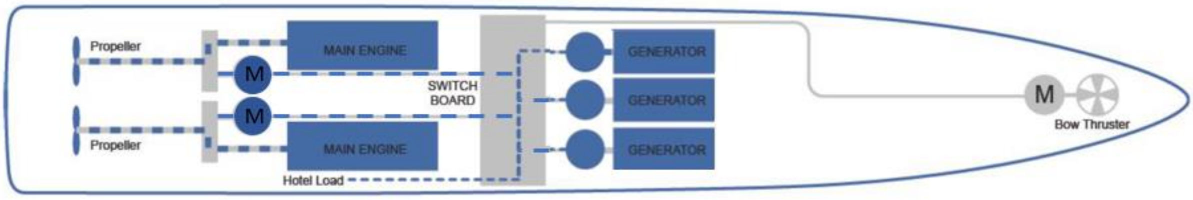


Figure 35: Hybrid propulsion arrangement in Boost PTI mode (8)

Slow Power Take-In (Slow PTI)

The slow PTI mode corresponds to the mode at which it is advantageous to have the generator sets operating as the only prime movers, supplying both auxiliary power and propulsion power through the electric machine connected to the gearbox working as an electric motor. (Figure 33)

As stated before, this mode is associated with sailing at low speeds, manoeuvring or slow cruising. During these modes propulsion power demand is low resulting in less efficient low loading operation of the diesel engines. In this case, it is possible to take advantage of the better specific fuel consumption conditions on having a smaller generator set operating at high loading conditions and supplying the full power demand.

POWER TAKE-OFF (PTO)

In this mode, the main engine is the only prime mover supplying power to the vessel. By having an electric machine connected to the gearbox generating electric power to supply the auxiliaries it is possible not only to increase the loading on the main engine to its high efficiency point but also to eliminate the low loading operation of the generators since the auxiliary power is supplied by the main engines.

PTO mode is often associated with transit speed operational modes, in this case cruising and crossing. During these modes, propulsion and auxiliary power demand are not enough to fully load engines and generators operating separately, which results in low load operation of both.

In this case, the propulsion power demand is higher than at low speeds which results in overall higher power demand, at which the specific fuel consumption of diesel engines has better characteristics than the ones of the diesel generators.

Consequently, during this operational mode, the generator sets are turned off and the diesel engine apart from supplying the propulsion power also supply the auxiliary systems through the electric machine connected at the gearbox that this time operates as a generator.

The fuel efficiency per kW delivered is improved by making use of all the power available at each engine speed. Therefore, it is possible to eliminate the operation of low loaded generators and make a better use of the diesel engines' power availability.

To sum up, the PTO mode results in better fuel efficiency per kW delivered during transit, especially appreciated given the operational profile of the yacht, in which cruising speed modes make up for the majority of the sailing period.

BOOST POWER TAKE-IN (BOOST PTI)

As speed increases, thus the propulsion power demand increases, the diesel engines are not capable to supply both propulsion and auxiliary systems without being excessively oversized. Therefore, the diesel generator sets will start operating in parallel with the diesel engines.

Depending on the maximum speed requirements and the diesel engines installed, the power plant may operate as diesel electric configuration, thus diesel engines supplying the propulsion systems and generator sets supplying the auxiliary systems.

Alternatively, in case the diesel engine is not able to supply all the demanded propulsion power, the electric machine is once more used as an electric motor supplying the remaining propulsion power that is not supplied by the diesel engine. This mode is known as boost PTI mode.

In this case, the diesel generators will supply the auxiliary systems and the part of the propulsion systems that the diesel engines are not capable of supplying. As a result, both generators and diesel engines will be operating in high load conditions.

7.4.4 COMPARISON BETWEEN ARRANGEMENTS

The diesel direct arrangement is characterized by having average efficiency, low complexity and thus relatively low investment costs. However, this arrangement provides low flexibility of operations, resulting many times in poor efficiencies at off-design conditions.

The diesel electric arrangement's main advantage to the yachting industry is the fact that it reduces noise and vibration due to the lack of mechanical transmission, increasing the comfort on board. Moreover, optimal loading by matching size and number of generators leads not only to fuel efficiency but also minimizes sooting and wear of engines, reducing the maintenance load. (8)

If propulsion and auxiliary have a high power demand on the same operating mode, as is the case of cruising for instance, this will lead to a high number and size of installed generators to meet the total demand.

Another drawback associated with the high power demand case is the fact that power plants would require more space, weight and cost. Nevertheless, when high auxiliary and high propulsion power demand happen in different operational modes, an electric arrangement has the opposite effect, thus leading to smaller volumes and weights when compared with conventional arrangements.

All in all, electric propulsion arrangements can be advantageous when the vessel has several operating modes with different power requirements, especially if the auxiliary loads are high in comparison to propulsion loads.

Electric propulsion has proven to be successful in passenger ships, cruise vessels and ferries. Moreover, DP drilling vessels, cable layers, icebreakers and capital naval vessels have followed the trend mainly due to their wide operational profile, contemplating low speed operations with high auxiliary power demand and need for redundancy.

Despite the significance of auxiliary power in a super yacht, propulsion power demand is still a higher fraction of demand for a significant part of the operating time. By comparing the results obtained in chapter 5 and chapter 6, it is possible to calculate the significance of the auxiliary power in relation to the total power. During cruising, maximum speed and crossing the auxiliary power demand is approximately 30%, 12% and 22% of the total power demand, respectively.

Contrarily, during manoeuvring the auxiliary power is 81% of the total power demand. In addition, at anchorage 100% of the power demand is from the auxiliaries as there is no propulsion.

As a result, the advantages of electric propulsion in terms of fuel consumption are not enough to make it much more attractive comparatively for the superyacht case. (8) Nonetheless, some yachts have electric propulsion systems for comfort purposes due to their noise and vibrations characteristics.

Finally, the hybrid power plant becomes attractive in three main situations: (59)

1. When the operational profile has large variations in propulsion and auxiliary power demand
2. When the maximum power in terms of propulsion and electric loads do not occur at the same time
3. When the electric power demand is not constant neither it is enough to make diesel electric propulsion a feasible solution.

Taking into consideration its operational profile (Chapter 3), this case fits all three categories above mentioned, thus to which hybrid propulsion may be attractive.

The fact that the difference in propulsion and auxiliary power demand between the main operational modes, manoeuvring, cruising and maximum speed, is so pronounced together with the fact that maximum auxiliary power occurs at minimum propulsion power are the main characteristics that make a super yacht suitable for hybrid propulsion application.

With the application of a hybrid arrangement it is possible to increase the plant's fuel efficiency, thus it is possible to reduce the CO_2 emissions once these are dependent on the amount of fuel burnt. Furthermore, in comparison to full electric power plants, hybrid power plants translate into lower volume, weight, complexity, and therefore also lower investment for this case, since for a full electric configuration the installed generator power would have to meet the maximum demand of about 1010kW. (59)

In addition, by installing a hybrid system it is possible to reduce noise and vibrations when sailing at lower speeds, hence increasing the comfort on board. Likewise, the fact that both main engines and generators are not always in operation, and when they are, they operate at more favourable loading conditions, reduces the required maintenance.

7.5 THE NEW CONCEPT'S HYBRID ARRANGEMENT

This section will elaborate on the choice of equipment, main engines and generators installed for a possible hybrid configuration, and a comparison in terms of fuel consumption between several solutions, including the reference's solution of diesel direct arrangement.

As previously elaborated (section 7.4.3), there are three possible modes, power take-off, boost power take-in and slow power take-in. Figure 36 displays the Energy Flow diagram of the architecture.

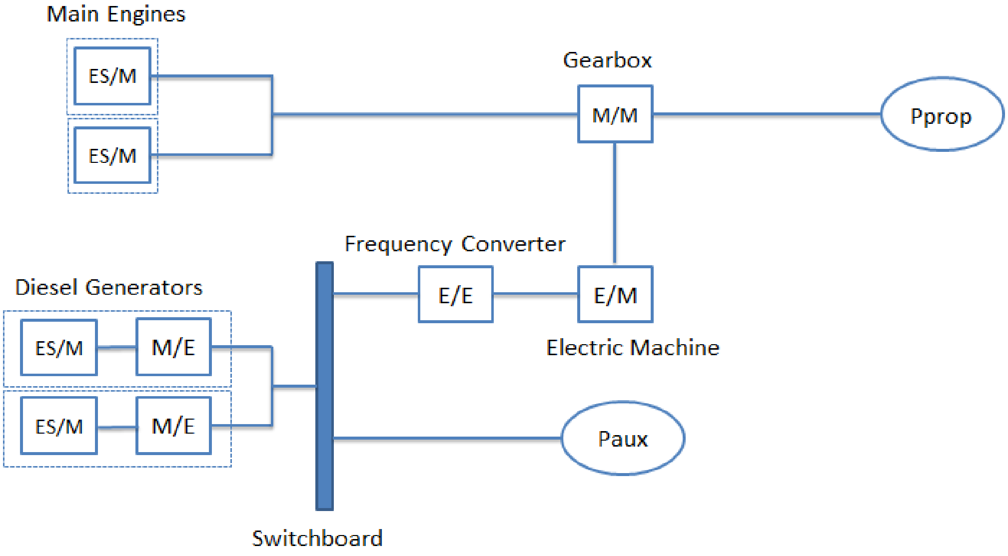


Figure 36: Energy Flow Diagram of the power plant of the new concept

During slow PTI mode, the diesel generator is the only prime mover, thus supplying all the power, for propulsion and auxiliaries. As a result, it is possible to have the main engines off, avoiding harmful low loading operation. Therefore, the load on the generator set is defined by the propulsion power demand and auxiliary power demand, accounting for the losses at the frequency converter, the electric machine and the transmission losses at the gearbox and shaft (59), as formulated in Equation 8.

$$P_{DG} * \eta_{\frac{M}{E}} = P_{aux} + P_{EM,el} = P_{aux} + \frac{P_{EM,mec}}{\eta_{FC} * \eta_{EM}} = P_{aux} + \frac{P_{prop}}{\eta_{TRM} * \eta_{FC} * \eta_{EM}}$$

Equation 8

In the PTO mode, the main diesel engines supply both propulsion and auxiliary power while the generator sets are turned off. Equation 9 defines the load on the diesel engine during the PTO mode.

$$P_{DE} = \frac{P_{prop}}{\eta_{TRM}} + \frac{P_{aux}}{\eta_{TRM} * \eta_{EM} * \eta_{FC}}$$

Equation 9

As the speed increases, the propulsion power demand increases, therefore the diesel engine is not able to meet the total power demand. Generally, this is the case when approaching the maximum speed. In this case, the diesel generators will supply the remaining power needed for auxiliaries or the vessel will switch to diesel direct mode until the maximum speed.

In case the diesel engine is not able to fully meet the power requirements for propulsion at maximum speed the boost PTI mode is activated.

In the first case, the available electric power from the diesel engine to power the auxiliaries is defined by Equation 10 while the load on the diesel engine is defined by Equation 11.

$$P_{EM,el\ available} = (P_{DE,max} * \eta_{TRM} - P_{prop}) * \eta_{EM} * \eta_{FC}$$

Equation 10

$$P_{DG} * \eta_{\frac{M}{E}} = P_{aux} - P_{EM,el\ available}$$

Equation 11

In the case of boost PTI mode, all the diesel engine power is directed to the propulsion systems while the generator sets will power the auxiliaries and the remaining power needed to achieve the maximum speed. Equation 12 and Equation 13 define this case.

$$P_{DE} = P_{DE,max}$$

Equation 12

$$P_{DG} * \eta_{\frac{M}{E}} = P_{aux} + \frac{P_B - P_{DE}}{\eta_{EM} * \eta_{FC}}$$

Equation 13

As stated before, the gains associated with the hybrid arrangement lay on the synergy between components, so that during the PTI mode the specific fuel consumption of the generator sets is indeed lower than the consumption of the diesel engines. Therefore, the potential improvements in fuel consumption depend on the installed diesel engines and generators.

As a start point, the MTU 12V 2000 M61 1800RPM 600kW as the one able to supply the power demand for the whole speed range, thus the engine needed for a diesel direct configuration. This is already a reduction from the reference which was an MTU 12V 2000 M72 2250RPM 1080kW.

In order to define the generator set size there is the need to define the minimum requirements the generator sets should be able to meet. In addition, for redundancy purposes a minimum of 2 generator sets are considered.

Firstly, the generator sets should at least be able to provide enough power to sail under PTI mode for manoeuvring at 6 knots which corresponds to a total demand of approximately 216kW. In this case, the main engines are able to fully meet maximum speed propulsion power demand, thus there is no need to consider boost PTI mode.

A minimum demand of 216kW can be translated in two generator sets of 109kW each (60). However, as stated before, the advantage of a hybrid propulsion systems lays on the interaction between the components, thus the interaction between the specific fuel consumption curves of installed engines and generators.

According to what is elaborated on section 7.4, for the benefits of the hybrid arrangement it is advantageous that the generator is able to cover the high specific fuel consumption operation range of the engine during its low specific fuel consumption range.

The minimum required generator sets of 109kW will indeed reduce the fuel consumption, however this reduction is nearly insignificant since the PTI mode lasts only very short period, which does not cover for the high specific fuel consumption operation range of the engine. Consequently, slightly increasing the generator size will allow better coverage of the low efficiency operation range of the main engines.

Nevertheless, if the generator sets are oversized, no benefits are attainable, as specific fuel consumption of the generators grows closer to the one of the engines. Furthermore, increasing the size of generators leads to an increase in volume and weight, which can become so high that the savings in emissions do not make up for this increment.

Four different configurations were tested for the MTU 12V2000 M61 engines, considering two generator sets of 109kW, 160kW, 200kW and 250kW. Two generator sets are considered for redundancy purposes Figure 37 presents the results obtained with each configuration. Despite presenting similar results, the 200 kW generators are a slightly more advantageous in terms of fuel consumption, especially considering the minimal requirement of two generator sets of 109kW.

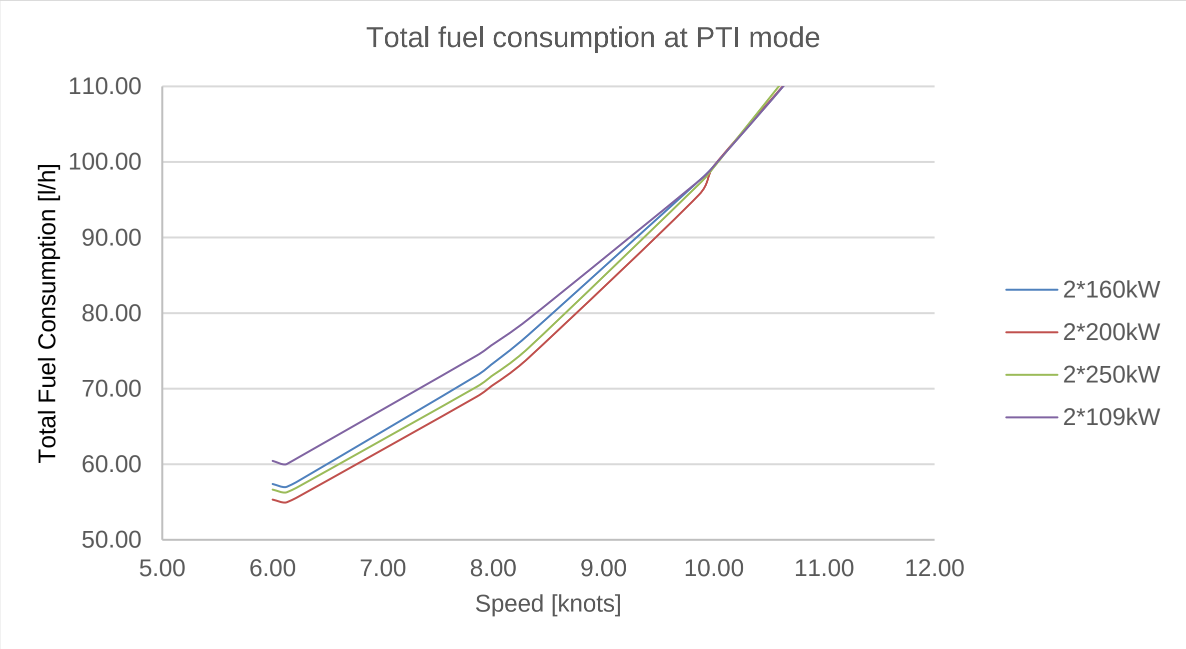


Figure 37: Total fuel consumption during PTI mode over the speed range for the four considered configurations

Consequently, the 200kW generator sets are going to be considered to assess the other possibilities. Nonetheless, it is worth mentioning that generator sets in between these capacities or from other suppliers might have different consumption curves, thus leading to a different outcome.

In this case, the diesel engines are capable of supplying power for the whole speed range in PTO mode which indicates that it might be possible to reduce the engine size and fully take advantage of the hybrid power plant by operating all possible modes, including boost PTI.

Therefore, the engine is reduced to a MTU 8V2000 M61 400kW 1800RPM. In the same way as before, the 200kW generator sets result in better fuel economy, thus are chosen for the configuration.

Figure 38, displays the CO_2 emissions in kg per hour over the whole speed range for the diesel direct configuration and for the two hybrid configurations derived. The diesel direct arrangement is composed of two diesel engines MTU 12V2000 M61 600kW 1800RPM and two diesel generators of 99kW.

As presented in Figure 38, changing from a diesel direct configuration to a hybrid configuration keeping the same diesel engine, thus not fully taking advantage of the operational modes of hybrid does not translate in significant changes, being the maximum savings in CO_2 emissions about 2%. However, when reducing the engine size it is possible to achieve further savings, especially during cruising at which savings in CO_2 emissions are approximately 8.5%.

During boost PTI mode the emissions are in fact higher than in diesel direct or in a hybrid configuration considering a diesel engine capable of fully meeting the power demand as is the case of the MTU 12V2000 M61. Nevertheless, according to the operational profile (section 3.2) maximum speed is only sailed over 0.43% of the operational time, thus this increase in emissions at maximum speed as a reduced impact on the yearly emissions of the yacht.

In addition, it is possible to eliminate this effect by considering the installation of batteries to supply the remaining power that the main engines are not able to supply. However, this will increase the electric power demand during cruising. The consequences of the introduction of batteries are further elaborated on section 7.5.1.

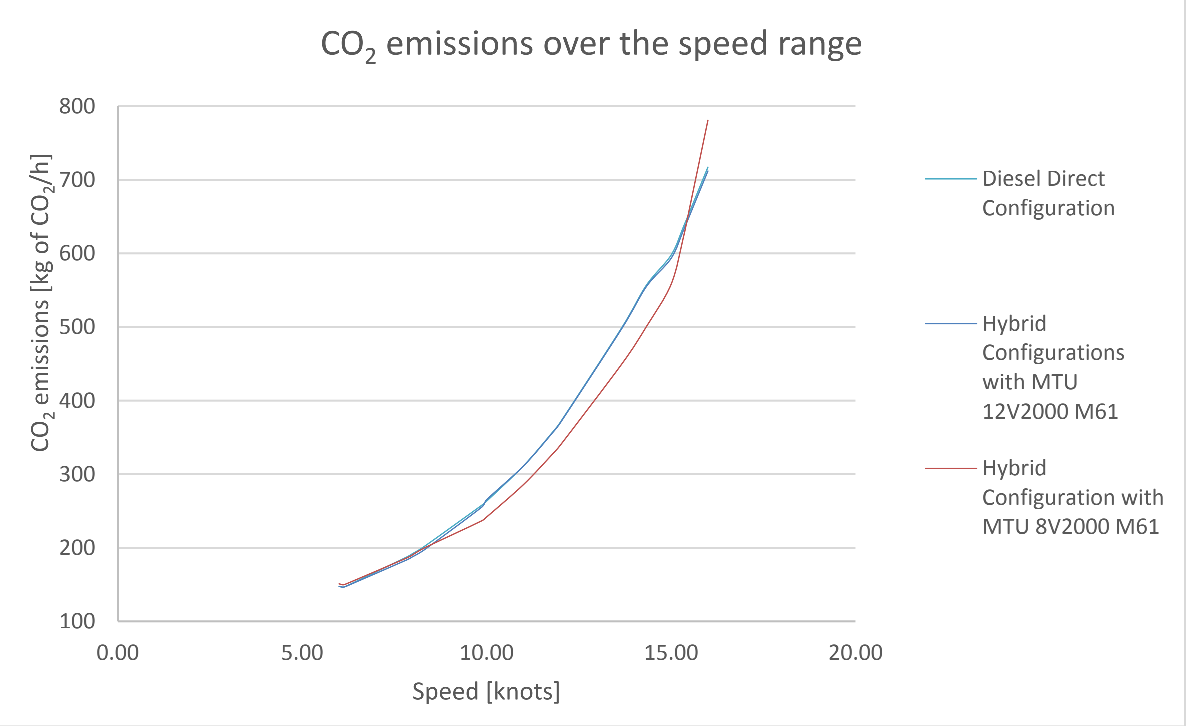


Figure 38: CO_2 emissions over the speed range for the three different configurations

Table 31 displays the resulting fuel consumption and CO_2 emissions in kg per year correspondent to each operation mode. Apart from reducing the fuel consumption at the sailing operational modes, the fact that the generator size is increased results in the reduction of fuel consumption at anchorage since it is possible to supply the auxiliary systems operating only one generator set, which reduces fuel consumption.

Table 31: Yearly Fuel Consumption and CO_2 emissions per operational mode

	Diesel Direct Configuration		Hybrid Configuration With MTU 12V2000 M61		Hybrid Configuration With MTU 8V2000 M61	
Operational Mode	**Fuel Consumption [l/year]**	**CO_2 emissions [ton CO_2/year]**	**Fuel Consumption [l/year]**	**CO_2 emissions [ton CO_2/year]**	**Fuel Consumption [l/year]**	**CO_2 emissions [ton CO_2/year]**
Cruising	102299	273	102091	272	93703	250
Max Speed	10215	27	10141	27	11058	30
Crossing	102190	273	87329	233	79687	213
Anchor	101309	270	99125	264	99125	264
Manoeuvring	6295	17	6307	17	6222	17
Port	0	0	0	0	0	0
Total		860		813		774

All in all, comparing the hybrid solution with the diesel direct solution it is possible to reduce the yearly CO_2 emissions by 7% if the same engine is chosen or in the case of choosing the smaller engine savings of approximately 13.5% are possible. Furthermore, in relation to the benchmark design these changes translate in a reduction of CO_2 emissions of about 32.6% and 37.4%, respectively

The change in propulsion arrangement not only leads to changes in fuel economy but also in space, weight and cost of the power supply systems. Table 32 shows the characteristics of the principal equipment that is part of the different architectures.

Despite having a different gearbox ratio, the gearbox model is kept the same on the three configurations, thus its dimensions are the same, only the price is slightly increased due to the PTI/PTO option.

When switching to a hybrid configuration the electric machine is introduced which translates in additional cost and space as it can be seen from Table 32. Nonetheless, the most significant changes in terms of space and weight are due to the changes in the main engines and generators.

In comparison to the reference design's main engines, the extra generator size translates into 1016 kg extra and approximately 2.96 m^3 per generator. However, when downsizing the main engines this is compensated. In this case, the change in engine results in a reduction of 1255 kg and 1.16 m^3 per engine, which altogether does not result in significant changes, even leading to a weight reduction.

By comparing the hybrid options one to another in terms of all the parameters, the hybrid option 1 does not have significant advantages in terms of emissions and still increases the investment costs, size and weight. For this reason, from now, in terms of hybrid arrangement only option number 2 is going to be considered.

Table 32: Characteristics of the main equipment of the power plants[2]

		Reference	Diesel Direct	Hybrid 1	Hybrid 2
		Engine			
		12V 2000 M72	12V 2000 M61	12V 2000 M61	8V 2000 M61
#		2	2	2	2
Power	kW	1080	600	600	400
RPM		2250	1800	1800	1800
Length	mm	2685	2711	2711	2051
Width	mm	1295	1400	1400	1216
Height	mm	1385	1290	1290	1465
Volume	m^3	4.82	4.90	4.90	3.65
Weight	kg	3680	3290	3290	2425
Price	€	€422,426.71	€234,681.51	€234,681.51	€156,454.34
		Generator Set			
#		2	2	2	2
Power	kW	99	99	200	200
RPM		1500	1800	1800	1800
Length	mm	2286	2286	2720	2720
Width	mm	1067	1067	1420	1420
Height	mm	1067	1067	1400	1400
Volume	m^3	2.60	2.60	5.56	5.56
Weight	kg	1844	1844	2860	2860
Price	€	€52,110.61	€52,110.61	€105,273.96	€105,273.96
		Gearbox			
Model		ZF 3351	ZF 3311	ZF 3311	ZF 3311
ratio i_{GB}		4.72	4.727	4.727	5.04
Difference in Price	k€	-	-	20	20
		E-machine			
	k€	-	-	140	140
Length	mm	-	-	480	480
Width	mm	-	-	380	380
Weight	kg	-	-	387	387

[2] Dimensions for main engines include gearbox and dimensions for generator sets include sound enclosure

7.5.1 COMBINING A HYBRID POWER PLANT WITH OTHER STRATEGIES

As elaborated on chapter 6, by featuring a Hull Vane® in the design it is possible to further reduce the resistance, thus the propulsion power demand. By combining the Hull Vane® with a hybrid power plant it is possible to further decrease the CO_2 emissions as shown on Figure 39.

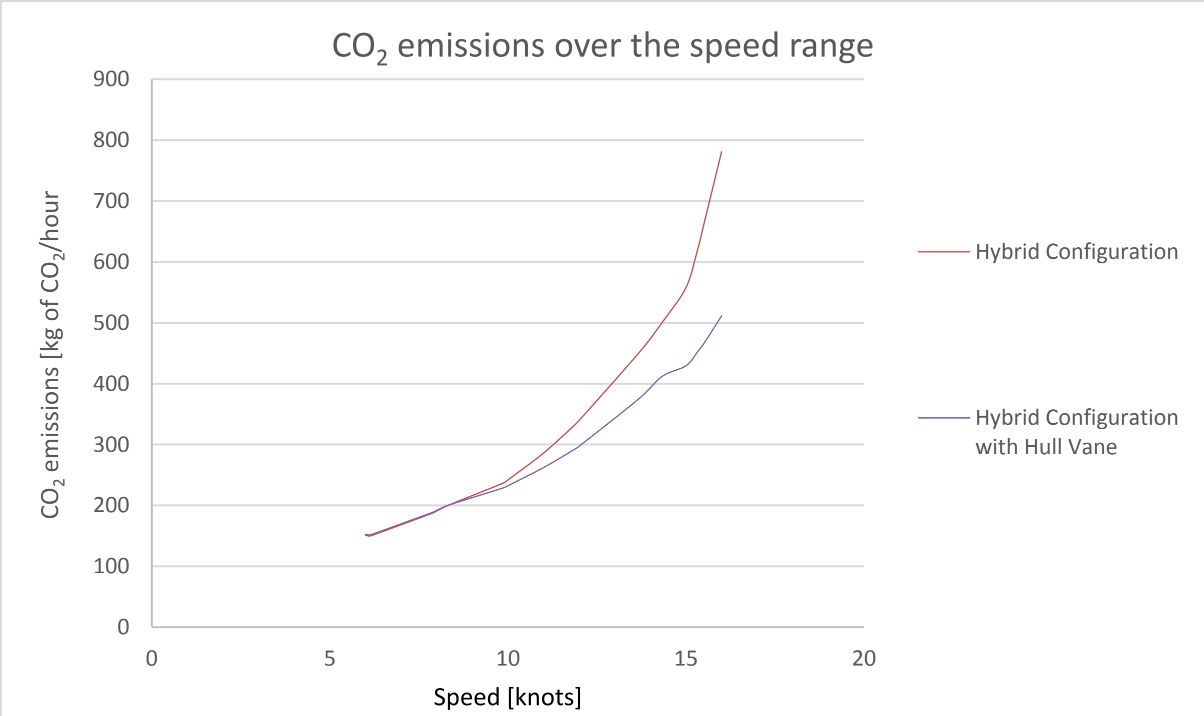


Figure 39: CO_2 emissions over the speed range of a hybrid configuration with and with Hull Vane®

The introduction of the Hull Vane® has a greater impact on higher speeds, actually presenting some minor increase in resistance, thus power demand at lower speeds compared to the hull without Hull Vane® as elaborated on section 6.6

On a yearly basis, the introduction of the Hull Vane® results in savings of about 14% when compared to the solution without the Hull Vane®. However, when compared to the reference design the yearly savings are approximately 46%. Table 33 displays the yearly CO_2 emissions of this solution for each operational mode of the Hull Vane® option.

Table 33: Yearly Fuel Consumption and CO_2 emissions of the configuration featuring a Hull Vane®

Operational Mode	**Fuel Consumption [l/year]**	**CO_2 emissions [ton CO_2/year]**
Cruising	82021	219
Max Speed	7283	19
Crossing	68274	182
Anchor	99125	264
Manoeuvring	6514	17
Port	-	-
Total		701

In addition, it is possible to introduce batteries to power either the manoeuvring or to supply the boost power for the maximum speed. In this way, either there is a zero emission operational mode or the extra emissions that were found at maximum speed are reduced. Nevertheless, this translates into extra electric power demand during cruising to re-charge the batteries.

Table 34 presents the characteristics of the battery pack considered for this application. For zero emission operation at manoeuvring, thus at the speed of 6 knots and with an auxiliary power demand of approximately 155kW, considering manoeuvring time is about 20 min (1.3% of 24 hours) together with the battery discharging capabilities there is the need of having 3 battery packs.

Table 34: Battery Pack Characteristics

Capacity	42	kWh
Charging	1.8C	
Discharging	1C	
Capacity	75.6	kW
Length	1241	mm
Width	860	mm
Height	786	mm
weight	670	kg
Cost	€72,000.00	euros/bat

In addition, for the option without Hull Vane®, boost power is needed to achieve the maximum speed. It is also possible to use the batteries to make up for this demand instead of using the generator sets. The electric power in this case is 184 kW. Taking into considering an operational time of 6 min (0.43% of 24 hours according to the operational profile) and the power demand three battery packs are needed for boost PTI.

In order to recharge these battery packs the auxiliary power demand is increased during cruising mode. Cruising makes up 8.40% which can be translated in approximately 2 hours. To fully recharge the battery packs in two hours an extra load of 63kW is needed. In case the batteries are needed for both manoeuvring and boost power within a shorter interval of time it is possible to increase electric power in order to have a shorter charging time. However, on a first analysis it is assumed that manoeuvring and maximum speed will be operated only within this interval.

Table 35 displays the resultant yearly fuel consumption and CO_2 emissions of the introduction of three battery packs to make up for manoeuvring and boost power for maximum speed. The fact that the introduction of the battery packs increases the load at cruising speed that has a significant percentage of operational time, especially when compared with manoeuvring or maximum speed modes results in higher yearly CO_2 emissions.

Table 35: Yearly fuel consumption and CO_2 emissions comparison between Hybrid configuration with and without batteries

		Hybrid		**Hybrid with Batteries**	
Operational Mode	**% operational time**	**Fuel Consumption [l/year]**	**CO_2 emissions [ton CO_2/year]**	**Fuel Consumption [l/year]**	**CO_2 emissions [ton CO_2/year]**
Cruising	8.40%	93703	250	106487	284
Max Speed	0.43%	11123	30	9155	24
Crossing	8.03%	79687	213	79687	213
Anchor	38.97%	99125	264	99125	264
Manoeuvring	1.30%	6453	17	0.00	0.00
Port	42.86%	0	0	0	0
	Total		774		785

Despite reducing the emissions during manoeuvring and maximum speed, the increase in emissions during cruising is such that it is not advantageous to introduce the battery packs.

In addition, it is possible to consider the application of solar panels to make up for the extra power demand for charging the batteries. As elaborated under section 7.3, the production of the solar panels is on average 15kW is the whole available area is taken. By adding this power supply to charge the batteries, the load to recharge the batteries in the same two hours is reduced from 63kW to 48 kW.

In this case, the increase in CO_2 emissions at cruising are not as significant as before. Nonetheless, the overall yearly emissions are still higher by approximately 4.15 tons of CO_2 per year when compared to the case without batteries.

7.6 CONCLUSIONS

There is a great potential to reduce CO_2 emissions in terms of power supply. However, the current state of development of such strategies results in the lack of feasibility for their application to a 50m yacht. In addition, the operational profile defined has a great impact on the decision making, especially in the application of batteries and solar panels, as it directly influences the yearly emissions resulting of each operational mode.

By implementing a hybrid power plant arrangement it is possible to reduce the overall yearly emissions by approximately 37% in relation to the benchmark design. Furthermore, when combining this with the application of the Hull Vane®, the emissions are further reduced by 14%.

As previously stated, the introduction of batteries considering this operational profile and demand pattern is not advantageous since the impact of increasing loads during cruising is greater than the benefits achieved by the manoeuvring zero emission operational times. Nevertheless, a different operational profile, power demand characteristics or battery characteristics may lead to a different outcome. The same can be concluded for the solar panels application.

In order to fully assess which configuration is the better solution for each user there is the need to assess the running costs in the long term. As the hybrid power plant configurations have the potential to reduce fuel consumption up to the point that the initial investment cost is compensated by the reduction in running costs due to fuel consumption.

Consequently, in chapter 9 the performance of three different configurations, diesel direct, hybrid and hybrid together with Hull Vane® will be evaluated according to the three performance parameters defined in chapter 2.4.2. However first, in the next chapter, the general arrangement of the new design is compared to the one of the benchmark design.

8. The General Arrangement

8.1 Introduction

At this point, the three research questions have been addressed; however there is the need to combine the resulting answers into one arrangement and compare it to the reference arrangement presented in chapter 4.

Following the choice of hull form described in chapter 6, there is the need to define the general arrangement that features the new components and meets the requirements imposed, taking into consideration the new main particulars of the vessel.

According to chapter 6, a fast displacement hull form with an overall length of 50 m is chosen to substitute the reference design's full displacement hull form. As a result of this change, the hull is now longer and more slender which requires some re-arrangement in terms of internal spaces.

The main requirements regarding the general arrangement involve the real estate area, as this should not deviate much from the one of the benchmark; and the gross tonnage that should remain below 500GT for regulatory purposes.

The new hull form follows from a previous project of van Oossanen, thus structural and stability calculations have already been performed once. However, the new concept developed for this project introduces some changes in comparison with that project, which will be assessed throughout this chapter.

This chapter mainly elaborates on the general arrangement and introduction of the new auxiliary equipment and power plant components.

8.2 The General Arrangement

As elaborated on section 4.3, the reference design has four decks: the lower accommodation deck, the main deck, the wheelhouse deck and the sun deck. Despite some re-arrangements, the same configuration is kept in the new design.

Considering the changes that have to be implemented, the main changes in the arrangement occur in the engine room and beach club on the lower accommodation deck, and in the wheelhouse deck.

This section describes the changes carried at each deck, but firstly it briefly provides an overview of the changes that have to be introduced.

All drawings can be found in Appendix G as well as throughout this chapter.

8.2.1 Overview of changes

By answering the first research question regarding the auxiliary systems some changes were introduced in an attempt to reduce energy consumption on board.

On the air systems consumption, firstly measures were taken to reduce the absorbed heat, reducing the load on equipment and after that changes in equipment took place to reduce the energy consumption (section 5.4).

- Absorbed Heat Reduction
  - Windows: color and solar protection changed occurred, however maintaining the single glass type, thus maintaining the thickness of the glass (section 5.4.2)
  - Overhang: the new design's superstructure had already a larger overhang when compared to the benchmark design; hence the still remaining increase was marginal which does not translate into structural nor weight significant impact.
- Equipment changes
  - Fresh Air Unit: larger and heavier unit has to be installed, however to compensate for this in terms of stability the unit is placed on main deck instead of being placed in the wheelhouse deck, which contributes to lowering or maintaining the centre of gravity, not leading to critical stability issues
  - Chiller unit: The chiller unit is reduced in size and weight, the fact that it is placed in the engine room allows for space savings.

After the air systems, the only other significant changes are in terms of the water systems as instead of 3 boilers of 200 L there are now 2 boilers of 300L. The change in boiler sets does not have a significant impact on the design as the changes in volume and weight are not very significant, as elaborated on section 5.7.

In terms of auxiliary systems, these are the only changes that will have a direct impact on the design as the change in light bulbs has no impact on space neither on weight. Moreover, the stabilizing systems are not altered.

In terms of power supply, the changes have a larger impact when comparing to the auxiliary systems, especially in terms of engine room and wheelhouse roof area.

- Engine Room
  - The main engines' size is reduced, thus are the systems linked to the main engines, which allows for some space savings
  - On the contrary, the main generator sets are increased, thus occupying more space
  - Electric machines and converters have to be added to the engine room thus requiring some space
- The Wheelhouse roof area is expanded in order to fit solar panels, even if solar panels are not considered in the end, the roof area is still expanded to allow for possible refit or installation upon owner's requirements

The fact that the extra weight is added on the lower deck and close to mid-ship ensures that no stability issues will arise from the power plant configuration changes as the centre of gravity is being lowered.

8.2.2 THE LOWER ACCOMMODATION DECK

The new hull form resulted in a more slender and longer design, thus some re-arrangements are needed in order to keep the interior areas close to the ones in the benchmark design, resulting in narrower but longer compartments. Figure 40 shows the lower deck layout of the new design.

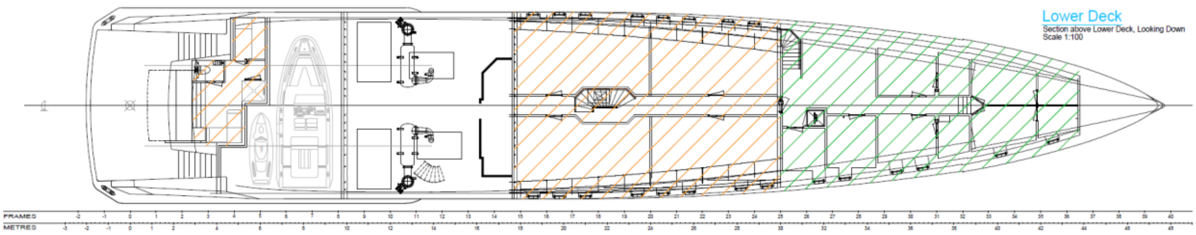


Figure 40: Lower Deck layout of new design

Starting from the forward end there is the crew area. In the same way of the benchmark there are four en-suite cabins which accommodate eight crew members. However the need to comply with the LY3 resulted in the need to slightly increase the available areas (7).

In addition, the crew area has a mess and a laundry room, similarly to the benchmark design (section 4.3.1 Figure 4). Differently than what happens on the benchmark, in the new design, the stores are placed on the lower deck close to the laundry room instead of being placed on main deck close to the galley (section 4.3.2 Figure 5).

Afterwards, the guest accommodation area starts. Since the real estate area is a performance parameter, the guest accommodation area was kept as comparable to the benchmark as possible. In terms of cabins, it is possible to keep the reference layout, thus two VIP and two guest cabins. Nonetheless, it is possible to customize the area according to owner's wishes.

Aft of the guest accommodation area there is the engine room. As stated before (8.2.1), several changes in equipment occur in the engine room. Nonetheless, while some components are introduced and others up-sized, there are others that are down-sized allowing for some balance in terms of required space. Consequently, the engine room is increased in comparison to the one of the benchmark. However, the increase is not major accounting for the decrease in the chiller unit, the main engines and respective equipment.

Behind the engine room there is the tender garage. The tender garage is reduced in comparison to the benchmark design for two main reasons. Firstly, due to the increase in engine room area and secondly in order to have an extended swimming platform. It is still possible to fit all the required tender and Jet Ski's. However, it is possible to enlarge the tender garage reducing the swimming platform area, in this case a careful tonnage calculation is required to make sure the limit of 500 GT is not surpassed.

Lastly on this deck there is the beach club. As well as in the reference design, there is a steam room and a lounge area. In this case the beach club is directly connected to the swimming platform which is larger than the one on the reference vessel.

This enlargement of the swimming platform and connection with the lounge area of the beach club (lazarette) creates more space available for guests, promoting the connection between interior and exterior spaces much valued in yachts.

8.2.3 The Main Deck

On main deck no changes are made to the design, only a few small area variations due to the difference in hull shape. The main deck's layout of the new design can be seen in Figure 41.

Figure 41: Main Deck layout of new design

On the forward part of the main deck is the owner area, a full beam cabin with closet, a bathroom and an office.

Aft of the owners' cabin there is the galley, isolated according to fire protection regulations (7). The galley is connected to the main deck's pantry on portside that leads to the dinning salon. In the pantry a dumbwaiter going from main deck up to the sundeck is installed similarly to what happens in the benchmark design.

On the starboard side opposite to the pantry there is a stair atrium where the main deck is connected to the guest accommodation area on the lower deck. Moreover, the owner area entrance is also through this atrium area. The day toilet on main deck is located in this area as well. Furthermore, there is a side entrance from the exterior on starboard.

The main salon and dinning salon are an open space where the windows are full height, unlike in the benchmark to meet the new design trends. This contributes for better interior lighting and interior/exterior connection. In the main salon area it is possible to go to the upper deck guest area as it is going to be further elaborated on the next sub-section.

8.2.4 THE WHEELHOUSE DECK

The wheelhouse deck is where the most noticeable changes in arrangement can be found, as it can be seen from Figure 42 in comparison with Figure 6 from section 4.3.3.

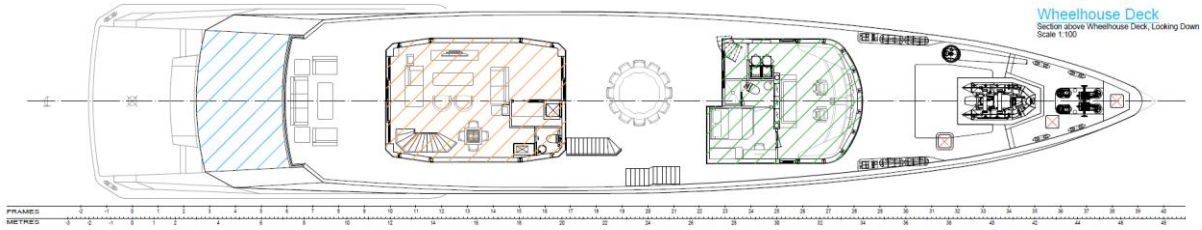


Figure 42: Wheelhouse Deck layout of new design

As a consequence of the roof area increase for the possible installation of solar panels there was the need to re-arrange de superstructure in a way that would not result in additional tonnage neither in an imbalanced superstructure design.

The roof is extended approximately 5.6 m in the forward direction, which results in extra area available for solar panels. However, this requires some structural support, thus requiring the structure to move forward.

If possible, the internal space would also be lengthened by some meters to offer a more stable and structurally feasible solution together with an increased internal area. Nonetheless, this would result in tonnage increase; since there is no margin to increase the internal volume and still be under 500GT this is not an option.

Alternatively, it is possible to move the whole block forward, but this leads to a rather odd design and instabilities at the aft end of the roof as well. Otherwise, the wheelhouse deck is divided in two blocks.

The first block is moved forward to support the extended roof area. In this block there is the wheelhouse and the captain’s en-suite cabin. This block is internally connected to the portside crew hallway on main deck.

The second block is left at the aft of the deck supporting the aft end of the roof. The aft block is dedicated to the guests, thus features a salon connected to the salon on main deck via stairs. Moreover, there is a day toilet and a pantry connected to the main deck’s pantry via the dumbwaiter.

In between the two blocks there is a semi-exterior area where it is possible to allocate a dining table and where the stairs to the sun deck are located. This way it is possible to separate the aft lounge area from the exterior dining area, creating a completely private lounge space for guests. Furthermore, it creates a completely shaded dining area that is still in the exterior. This way it is possible to extend the roof area without resulting in additional tonnage or imbalanced superstructure design.

In the end, solar panels are not fitted in this concept's first approach. Nevertheless, as stated in section 7.3 technology is evolving, thus there are high possibilities that solar panel installations become feasible in the near future. Furthermore, it can be an option from of the owner to equip the yacht with solar panels, this way the flexibility in the design is increased, as is the extent of environmental friendly strategies possible. Nevertheless, it is possible to eliminate the roof area increase, maintaining the wheelhouse deck united as it was before in case the owner is not satisfied with a two block wheelhouse deck.

8.2.5 THE SUN DECK

Finally the sun deck's layout is kept the same as in the benchmark's layout. As it can be seen from Figure 43.

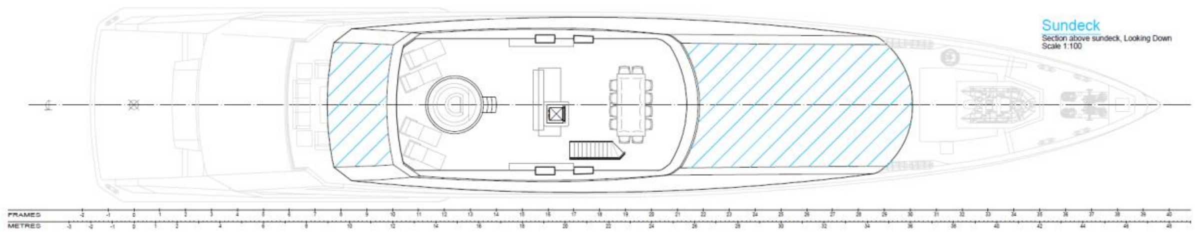


Figure 43: Sun Deck layout of new design

It features a Jacuzzi and a sunbathing area around it at the aft. In addition, there is a dining table, a bar and barbecue area with all the necessary appliances including the dumbwaiter connected to both wheelhouse and main deck's pantries.

Likewise in the wheelhouse deck, in the sundeck the roof area can be slightly increased in case solar panels need to be fitted, as displayed in

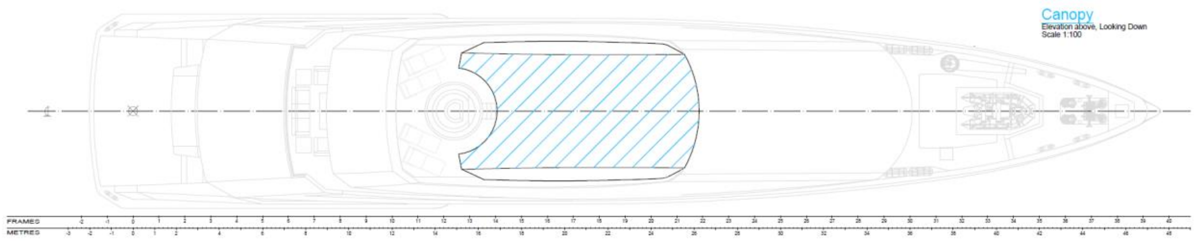


Figure 44: Sun deck roof for the placement of solar panels

8.3 GROSS TONNAGE CALCULATION

The gross tonnage is defined by the total volume of all enclosed spaces of the vessel, being the base to determine many factors such as manning regulations, safety requirements, etc, reason why the gross tonnage plays such a determinant role.

In this case, staying below 500GT offers some regulatory benefits, for instance not having to comply with SOLAS regulations or having benefits in the compliance of the Large Commercial Yacht Code (LY3), mainly related to manning requirements, crew area requirements and structural fire protection.

Many times when designing a yacht there are gross tonnage requirements that will affect the general arrangement as the gross tonnage is to a large extend limited by the interior areas.

The adopted gross tonnage calculation is based on the following formulations (Equation 14 & Equation 15) (61). Equation 15 shows the calculation of constant K in the gross tonnage calculation.

$$Gross\ Tonnage = K * Volume\ of\ encolsed\ spaces\ (V)$$

Equation 14

$$K = 0.2 + 0.02 * \log(V)$$

Equation 15

For simplicity purposes the calculation of the volume of internal spaces concerns only a first estimation. The internal volume calculation is then calculated separately for the hull and superstructure. The hull's volume up to main deck and the full beam part of the main deck (owner cabin) are calculated with Maxsurf and the remaining part of the superstructure volume is based on the deck area and height.

Table 36 displays an estimation on gross tonnage of the design, which is still below the requirement of 500GT even including a margin for the extended roof areas..

Table 36: Internal Volume and Tonnage Calculation

	Area [m²]	**Height [m]**	**Volume [m³]**
Hull up to main Deck			991.75
Transom Stairs	2.3	-0.7	-1.61
Aft Seating Area	10.6	0.4	4.24
Main Deck	103	2.55	262.65
Wide Body			385
Wheelhouse Deck	83.99	2.55	214.17
MOB tender bay	11.9	0.9	10.71
Foredeck recess	10	-0.4	-4
Bulwark	15.2	0.9	13.68
Bulwark margin (20%)			2.74
Total Volume			1879.33
K			0.265
Gross Tonnage			498.92

9. PERFORMANCE

9.1 INTRODUCTION

Once the concept is finished, there is the need to assess its performance according to the performance parameters defined in section 2.4, energy efficiency, luxury and costs.

In addition, the performance parameters will also be the basis for the user's evaluation. As defined under section 2.4.1, there are three different user profiles that value different aspects of the design, the economist, the family man and the environmentalist, prioritizing costs, luxury and energy efficiency, respectively.

After reducing the CO_2 emissions, having an attractive design for the market is an appreciated characteristic, thus it is important that the new concept performs well in all three parameters.

This chapter assesses the performance of three options, a diesel direct configuration and a hybrid configuration with and without Hull Vane®. The design is assessed in two ways, firstly according to the performance parameters and secondly according to the different user profiles and their preferences.

In addition, a sensitivity analysis on the operational profile is performed within this chapter.

9.2 ENERGY EFFICIENCY

The energy efficiency is a measure of the CO_2 emissions.

Firstly, the rate of CO_2 emissions per hour at each operational mode is calculated. Afterwards, the hourly rate of emissions per mode is combined with the operational profile, thus the yearly operating hours per mode. This way it is possible to quantify the overall yearly CO_2 emissions.

Table 37 displays the hourly CO_2 emissions rate and the yearly CO_2 emissions per operational mode for the case of the benchmark, as presented in section 4.4.

Table 38 displays the hourly CO_2 emissions rate and the yearly CO_2 emissions per operational mode for three configuration options of the new design, diesel direct, hybrid and hybrid with the Hull Vane®.

Table 37: Hourly rate of emissions per mode and annual CO_2 emissions of the benchmark design

Operational Mode	Hourly rate of emission [kg of CO_2/hour]	CO_2 emissions [ton CO_2/year]
Cruising	539	397
Max Speed	1516	58
Crossing	515	362
Anchor	101	346
Manoeuvring	213	24
Port	-	-
Total		1187

Table 38: Hourly rate of emissions per mode and annual CO_2 emissions for each operational mode for the three different options

		Diesel Direct		Hybrid Arrangement		Hybrid Arrangement with Hull Vane®
Operational Mode	**Hourly rate [kg/h]**	**CO_2 emissions [ton/year]**	**Hourly rate [kg/h]**	**CO_2 emissions [ton/year]**	**Hourly rate [kg/h]**	**CO_2 emissions [ton/year]**
Cruising	371	273	340	250	297	219
Max Speed	717	27	781	30	511	19
Crossing	387	273	302	213	259	182
Anchor	79	270	77	264	77	264
Manoeuvring	147	17	151	17	153	17
Port	-	-	-	-	-	-
Total		860		774		701

Comparing Table 37 and Table 38, it is possible to conclude that in all operational modes emissions are reduced in comparison with the benchmark design. In the case of the diesel direct arrangement, the emissions reduction mainly results from the power demand reduction in terms of both propulsion and auxiliary power.

Table 39 displays the percentage of reduction attained at each operational mode for all the options considered. The highest savings are indeed achieved by combining the hybrid power plant with the Hull Vane®. Savings of 45% at cruising speed are possible with this configuration, while at maximum speed savings can reach the 66%.

Table 39: Reduction of CO_2 emissions in comparison with the benchmark design

Operational Mode	Diesel Direct	Hybrid Arrangement	Hybrid Arrangement with Hull Vane®
Cruising	31%	37%	45%
Max Speed	53%	48%	66%
Crossing	25%	41%	50%
Anchor	22%	24%	24%
Manoeuvring	31%	29%	28%
Port	-	-	-
Total	28%	35%	41%

On a yearly basis, the diesel direct configuration emitting approximately 860 ton of CO_2 emissions per year translates into 28% savings. By introducing a hybrid configuration it is possible to save 86 ton of CO_2 which translates into extra 7% savings. Finally, extra 6% savings can be achieved by introducing the Hull Vane®.

On a yearly basis, the highest possible savings are attained with hybrid arrangement together with the application of the Hull Vane® which is capable of reducing the CO_2 emissions by 486 ton per year, which translates into 41%.

For low speed modes and anchorage modes the attained savings are not as significant which indicates that indeed the reduction of propulsion power demand plays a decisive role concerning the emissions. Nevertheless, considering overall savings of 24% while at anchorage based only on the auxiliary power demand reduction and better operating conditions of the generator sets is a remarkable result.

The fact that the operational profile plays a decisive role in determining the yearly emissions as it determines the operational hours per mode. Therefore, this requires a sensitivity analysis on the operational profile. The next section elaborates on the analysis of the operational profile based on the hybrid configuration. Since the relation between the operational profile and the hourly emission of every mode is the same it is feasible to evaluate its impact on the yearly emissions in only one configuration.

9.2.1 Sensitivity Analysis on the Operational Profile

As previously stated the operational profile is volatile. Moreover, it has a great influence on the yearly emissions as it defines how many hours the yacht spends at each operational mode. Varying the operational profile might lead to a different outcome in terms of yearly emissions. Therefore, there is the need to assess the sensitivity of the results in relation to the operational profile.

The sensitivity analysis on the operational profile is based on a scenario analysis. Ten different scenarios are elaborated based on beta distributions of the operational hours of each mode. A beta distribution is a continuous probability distribution parametrized by two shape parameters, α and β as defined in Equation 16 and Equation 17. The shape parameters are defined based on the maximum (*b*), minimum (*a*) and most average (*m*) values for operational times defined by the analysis on the Marine Traffic data (11) as displayed in Figure 1 and Figure 2, chapter 3.

$$\alpha = \frac{\mu - a}{b - a} * \left(\frac{(\mu - a) * (b - \mu)}{\sigma^2} - 1 \right)$$

Equation 16

$$\beta = \frac{b - \mu}{b - a} * \left(\frac{(\mu - a) * (b - \mu)}{\sigma^2} - 1 \right)$$

Equation 17

$$\mu = \frac{1}{6} * (a + 4 * m + b)$$

Equation 18

$$\sigma^2 = \frac{(b - a)^2}{36}$$

Equation 19

Each operational mode has its own beta distribution, as the shape parameters vary from mode to mode. Table 40 displays the shape parameters α and β of the operational modes' distributions. Furthermore, it displays the standard deviation of each distribution. The standard deviation is a measure of uncertainty, thus higher standard values result in higher uncertainties. In order to assess the magnitude of the uncertainty, the percentage of the standard deviation in relation to the average duration of the mode is also calculated. From Table 40 it is possible to identify the sailing operating modes as the ones having higher uncertainties, having a variability of approximately 40% in relation to the average duration.

Table 40: Beta Distribution parameters for each operational mode

	α	β	Standard deviation	% σ / average duration
Cruising	2.858	4.636	299.2	41%
Crossing	3.605	4.322	271.3	39%
Max Speed	2.669	4.665	14.3	38%
Manoeuvring	2.711	4.660	43.1	38%
Anchorage	4.035	3.964	829.1	24%
In Port	4.053	3.945	1048.4	28%

Ten different scenarios are generated based on random probabilities for each distribution. Nonetheless, one constraint has to be implemented so that the total operational hours estimated do not exceed the yearly available hours (365*24=8760 hours).

Once the ten different scenarios are created, the yearly emissions of each scenario are calculated based on the hourly emissions per mode. The hourly emissions per mode are calculated in chapter 7, based on the power demand investigated in chapters 5 and 6 and the power supply configuration chosen. Table 41 displays the data on the different scenarios in terms of hours per operational mode and the CO_2 emissions per scenario, while Figure 45 plots the emission data per scenario.

Table 41: Operational Profile Scenarios

Hours/year	Current Scenario	Scn. 1	Scn. 2	Scn. 3	Scn. 4	Scn. 5	Scn 6	Scn. 7	Scn. 8	Scn. 9	Scn. 10
Cruising	735.84	717.84	631.60	1098.71	616.42	503.73	1143.96	446.80	406.70	814.67	1160.07
Crossing	703.43	1371.74	807.49	1104.18	265.22	1040.46	704.46	744.00	283.99	594.39	888.12
Max Speed	37.67	41.61	51.49	30.28	20.26	42.30	33.56	48.48	41.30	59.53	24.29
Manoeuvring	113.88	158.69	190.10	73.74	140.84	198.37	69.82	116.33	50.72	154.94	184.10
Anchorage	3414.65	4944.69	3489.74	4783.45	3523.85	3238.08	3446.85	3652.13	2876.34	3026.48	3809.01
In Port	3754.54	1525.43	3589.58	1669.65	4193.41	3737.07	3361.34	3752.24	5100.96	4109.99	2694.40
Yearly Emissions	774.07	1100.32	795.12	1117.40	602.38	797.15	907.01	714.40	486.65	756.45	1006.11

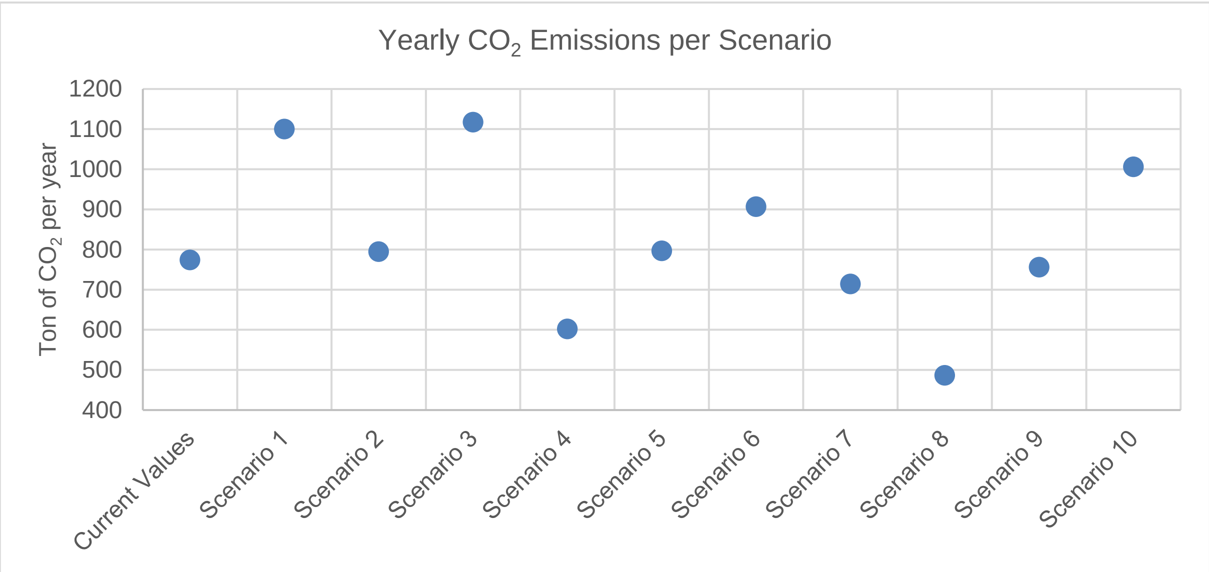


Figure 45: Yearly CO_2 emissions per operational profile scenario

Different operational profiles most likely lead to different yearly CO_2 emissions as it can be seen from the sample data plotted in Figure 45. Therefore, the volatility of the yearly emissions is a consequence of the volatility of the operational profile as this is the only parameter changed among scenarios.

Again, in order to assess the uncertainty associated with the yearly CO_2 emissions due to the variation of the operational profile, the standard deviation is calculated and its relation with the average scenario calculated in order to assess its magnitude. Based on the values present on Table 41, a standard deviation of 196.5 ton of CO_2 per year which represents 25.38% of the missions of the average scenario used as a reference.

The dependency of the yearly emissions on the operational profile and the uncertainty on the determination of the operational are such that it leads to approximately 25% uncertainty on the results. As a consequence of the fact that the time spent at each mode is not independent, i.e. the total of yearly operated hours cannot exceed the total amount of hours in a year, the increase in the operating time of some modes results in the decrease of operating time of another modes.

By increasing the duration of operational modes that have a high hourly emission rate results in the increase of annual emissions. Hence, the increase in modes such as cruising, crossing or manoeuvring results in the increase of emissions, while the increase of the operational time spent in port translates into a reduction of CO_2 emissions from the yacht. It is important to notice that even though the emissions while in port are not quantified in this analysis due to the assumption that the yacht will be on shore power, in reality CO_2 is emitted.

The fact that the manoeuvring operating time has an uncertainty around 38% has a big impact on the contribution of this mode to the total yearly emissions. Therefore, it impacts the decision of implementing or not the use of batteries. In other words, by increasing the time of manoeuvring, in the case of having batteries, translates in increasing the time at which the yacht operates in zero emission conditions. Table 42 presents the yearly emissions per scenario of both cases, with and without batteries. The fact that, scenario 2, 5, 7 and 10 have lower yearly emissions when operating with batteries would lead in those cases to a different decision than taken considering the current scenario.

Table 42: Yearly CO_2 emissions per scenario with and without batteries comparison

Ton CO_2/year	Current Scenario	Scn. 1	Scn. 2	Scn. 3	Scn. 4	Scn. 5	Scn 6	Scn. 7	Scn. 8	Scn. 9	Scn. 10
No Batteries	774.1	1100.3	795.1	1117.4	602.4	797.1	907.0	714.4	486.6	756.4	1006.1
With Batteries	788.5	1107.5	793.0	1154.9	609.8	789.1	946.8	493.9	766.5	1032.5	713.9

9.3 LUXURY

In this case, luxury is a measure of the space available for guests, thus real estate area. Furthermore, as a pleasure craft is also about enjoying the exterior and nature, a comparison of external areas is likewise made.

The areas are estimated from 2D layout drawings as presented in chapter 8 (Appendix G). An overview areas available in the new design can be found in Appendix H. The following paragraphs will compare the main areas of both designs.

By comparing the areas available for guests, such as salons and accommodation areas it is possible to state that while in some compartments area is added, in others it is reduced. Nevertheless, the sum of all the main internal areas available for guests is approximately the same in both designs, as it can be seen from Table 43.

Table 43: Comparison between main internal areas available for guests

	Benchmark	New Design	Variation
Salon main deck	68 m^2	60 m^2	-8 m^2
Salon wheelhouse	30 m^2	41 m^2	11 m^2
Owner State room	55 m^2	56 m^2	1 m^2
Guest Accommodation	95 m^2	93 m^2	-2 m^2
Beach club/Lazarette	18 m^2	16 m^2	-2 m^2
Total	266 m^2	266 m^2	0 m^2

In addition, the exterior areas are also part of the space available for guests, thus they should also be included in the comparison. Table 44 displays a comparison between the main external areas.

While in terms of interior some compartments where reduced, in terms of exterior the new design offers more area, mainly due to the extended length in combination with a reduction of main and wheelhouse deck's area.

Table 44: Comparison of exterior Areas

	Benchmark	New Design	Variation
Main deck	54 m^2	58 m^2	4 m^2
Wheelhouse deck	126 m^2	137 m^2	17 m^2
Sundeck	81 m^2	90 m^2	9 m^2
Swimming platform	6 m^2	25 m^2	19 m^2
Total	267 m^2	310 m^2	43 m^2

It is worth noticing that even though the lazarette area is now reduced the fact that it is now connected to the swimming platform, which is larger than in the reference case creates and overall all larger area available for guests. Furthermore, it enhances the connection interior/exterior so much appreciated by owners.

In terms of Crew Area on the lower deck, the new design has a larger available space due to two reasons. Firstly, the benchmark design was not compliant with the regulations from the Large Yacht Commercial Code (62) regarding the crew area requirements since it was designed before these regulations came to force. Secondly, in the benchmark design, the stores and walk-in fridge are placed on main deck next to the galley, while on the new design these are integrated in the crew area.

In addition, the engine room is increased by approximately 4 m^2 in order to provide more space to fit the new components of the power plant and to allow for the placement of larger generator sets.

As a consequence of the increased crew area and increased engine room are, the tender garage area is slightly reduced, about 5.5m^2, which is not very significant due to the fact that the length of the hull is increased as elaborated on chapter 6. Despite having its area reduced, the tender garage is still able to accommodate the same items as the benchmark tender garage.

All in all, the total internal area available is increased by 3 m^2 as displayed on Table 45. The increase in total area follows mainly due to the increase in lower deck area so that the yacht could comply with the new regulations in term of available crew area. On the contrary, the areas on main deck and wheelhouse deck are reduced as an attempt to maintain the gross tonnage below 500 GT.

Table 45: Total Area Comparison

	Benchmark	New Design	Variation
Lower Accommodation Deck	251 m^2	266 m^2	15 m^2
Main Deck	173 m^2	164 m^2	-9 m^2
Wheelhouse deck	77 m^2	74 m^2	-3 m^2
Total	501 m^2	504 m^2	3 m^2

9.4 Costs

As stated before, the costs are divided in two categories, investment IC and running costs RC.

In order to calculate the total costs, the lifespan *n* of the yacht is assumed to be 20 years. Moreover, the value of money in time is accounted by considering the interest rate *i* and the inflation rate *g*, both set up at 1.5%.

The total costs comparison is based on the future value of both the investment and running costs. The future value of investment and running costs are calculated according to Equation 20 and Equation 21 based on a growing annuity formulation, accounting for the interest rate *i*, the inflation rate *g* and the lifespan of the yacht *n*, 20 years.

$$FV_{IC} = IC * (1+i)^n$$

Equation 20

$$FV_{RC} = \frac{RC_{t=0}((1+i)^n - (1+g)^n)}{i-g}$$

Equation 21

The following sub-sections elaborate on the calculation of the investment and running costs for the new design with the three possible configurations, diesel electric, hybrid and hybrid with a Hull Vane®.

9.4.1 Investment Costs

The investment costs for a vessel are assumed to be the combination of the yacht's acquisition AC_Y and its berth acquisition AC_B, as presented in Equation 3.

$$IC = AC_Y + AC_B$$

Equation 22

The estimation of the yacht's acquisition price is based on a market research together with the extra cost due to the introduction of new components described throughout the chapters.

Despite having approximately the same tonnage, the designs are different in length and in material, which leads to a different base price. The benchmark' base price is estimated to be 30 million euros. Accounting for the extra length and change in hull material the base price of the new design is estimated to be 1.6 million euros higher than the one of the benchmark. (63)

In addition, there are other components that contribute to the variation of the acquisition price of the new design, depending on the configurations chosen. Table 46 displays the variation in costs of each contributing system.

Table 46: Acquisition Cost variation for the three different configurations considered

Systems	Diesel Direct	Hybrid Arrangement	Hybrid Arrangement with Hull Vane®
Lengthening & Material	€1,600,000.00	€1,600,000.00	€1,600,000.00
Windows	€40,000.00	€40,000.00	€40,000.00
HVAC	€0.00	€0.00	€0.00
Lights	€6,888.00	€6,888.00	€6,888.00
Boilers	-€6,800.00	-€6,800.00	-€6,800.00
Engines	-€187,745.20	-€265,972.37	-€265,972.37
Generator Sets	€0.00	€96,013.65	€96,013.65
E-machine	€0.00	€140,000.00	€140,000.00
Gearbox	€0.00	€20,000.00	€20,000.00
Hull Vane	€0.00	€0.00	€200,000.00
Total	**€1,452,342.80**	**€1,630,129.28**	**€1,830,129.28**

The berth acquisition price is assumed to be the same for both cases since the 5m difference in overall length does not result in the need of increasing the berth size, as both are within the same category (40-50m). According to (10), the berth costs for a 50m yacht are approximately 2.02 million euros.

Table 47 presents the investment costs for all the considered options. Undoubtedly, the new designs have higher investment costs when compared to the benchmark. However, this increase in investment is only between 4-5.5% compared to the investment cost of the benchmark design

Table 47: Investment Costs of benchmark and new design in the three different configurations

Benchmark Design	Diesel Direct	Hybrid Arrangement	Hybrid Arrangement with Hull Vane®
€32,020,000.00	€33,472,342.80	€33,659,065.45	€33,859,065.45

9.4.2 Running Costs

Alike the benchmark design, the running costs of the new design encompass categories such as crew salaries, berthing fees, fuel consumption and outgoings.

The outgoings category includes a large variety of items such as, uniforms, food, drinks, toiletries, gadgets, electronics and AV equipment, Sports equipment, garage equipment, bridge equipment, paint, deck equipment, insurance and engine room & technical equipment.

Taking into consideration that both designs the have similar characteristics, from the outgoings point of view the only varying item is the engine room & technical equipment due to the changes in auxiliary systems and power plant arrangement.

As elaborated throughout the report, the changes in auxiliary systems do not lead to significant changes in terms of running costs, thus the variation in engine room and technical equipment maintenance costs is caused by the implementation of a hybrid power plant arrangement.

The introduction of new components increases maintenance costs, however, since no batteries are introduced in the hybrid arrangement the increase in maintenance costs is not critical. It is considered that the maintenance costs of e-machines and gearboxes will follow the same trend of engines and generators, thus approximately 4% of investment cost. Extra 3% are added to account for frequency converters and other components which complexity is increased.

Nonetheless, as a consequence of operating a hybrid power plant, the operating hours of engines and generators are reduced. Moreover, the reduction in size of engine also leads to a reduction in terms of maintenance costs.

Table 48 presents the estimated changes in terms of maintenance costs for each possible configuration. On a diesel direct configuration higher savings are possible since the no equipment is introduced, the generator is kept the same and the engine size is reduced.

Table 48: Estimate of the increase in maintenance costs of engine room and equipment

	Diesel Direct	Hybrid Arrangement	Hybrid Arrangement with Hull Vane®
Engines	-€6,812.83	-€7,930.88	-€7,930.88
Generator	€0.00	-€7,098.80	-€7,098.80
E-machine	€0.00	€10,425.53	€10,425.53
Gearbox	€0.00	€800.00	€800.00
Total	**-€6,812.83**	**-€3,804.15**	**-€3,804.15**

When changing to a hybrid power plant, the fact that new components are introduced is mitigated by the reduction of operating hours of the engines and generators. This is only possible once battery packs are not introduced, thus maintenance costs for introduced equipment are not significant.

The salary of the crew is the same as for the benchmark design since the number of crew members is kept constant and the variation in yacht length is not enough to increase the monthly salary of a crew member. Therefore, each crew member earns 4,703.17 € per month, assuming 8 crew members plus captain the total annual crew salary costs are 507,942.43 €.

Likewise, the berthing costs are the same as for the benchmark design, thus 90,606.25 € per year.

Finally, the last item of the running costs if the fuel consumption, the item that has the biggest impact on overall running costs. Once the fuel consumption of the new configurations is reduced, this translates in to significant savings in terms of annual fuel consumption costs. Table 49 presents the fuel consumption costs for each configuration.

Table 49: Annual Fuel Consumption and costs for the benchmark and three configurations of the new design

	Benchmark Design	Diesel Direct	Hybrid Arrangement	Hybrid Arrangement with Hull Vane®
Fuel Consumption [l/year]	445027	322308	290090	263217
Cost of Fuel [€/year]	€467,278.71	€338,423.43	€304,594.59	€276,377.50

Table 50 displays the running costs of the benchmark design and the new design in three different configurations. As it can be seen, the fuel costs are the ones most expressively affected by the changes in the design. Nevertheless, the reduction in running costs varies between 5.4%, 6.6% and 7.8% for the different configurations of the new design, diesel direct, hybrid arrangement and hybrid arrangement with Hull Vane®, respectively.

Table 50: Running Costs of Benchmark and new design possible configurations

	Benchmark Design	Diesel Direct	Hybrid Arrangement	Hybrid Arrangement with Hull Vane®
Crew Salaries	42,328.54 €	42,328.54 €	€42,328.54	€42,328.54
Outgoings	1,519,689.79 €	1,519,689.79 €	€1,519,689.79	€1,519,689.79
Maintenance Engine Room	386,176.62 €	379,363.78 €	382,372.47 €	382,372.47 €
Berthing Fees	90,606.25 €	90,606.25 €	€90,606.25	€90,606.25
Fuel Consumption	467,278.71 €	338,423.43 €	€304,594.59	€276,377.50
Total	**€2,506,079.90**	**€2,370,411.78**	**€2,339,591.64**	**€2,311,374.55**

Combining the investment and running costs in terms of future value over the yacht's lifespan of 20 years shows that all the configurations have a lower future value than the benchmark, as it can be seen in Table 51. In addition, the payback period of the Hybrid Arrangement with Hull Vane® is only 3.7 years which compared to the lifespan of the yacht is acceptable.

Table 51: Future Value of Costs after lifespan of 20 years

	Benchmark Design	**Diesel Direct**	**Hybrid Arrangement**	**Hybrid Arrangement with Hull Vane®**
Future Value of Costs over the lifespan	€178,502,872.26	€177,292,295.17	€176,637,304.25	€176,114,706.33

9.5 The Users' Performance Assessment

Likewise the strategies regarding the auxiliary systems (chapter 5), the final concepts are ranked according to the user's preferences and the performance parameters elaborated throughout this chapter, sections 9.2, 9.3 and 9.4, by a multi-objective comparison function.

The multi objective comparison is as elaborated on section 2.4. Firstly, the objective values are normalized according to Equation 23 and the parameter for each design calculated for each user according to Equation 24. However in this case, instead of strategies there are different design options, and the criteria are the performance parameters, energy efficiency, luxury and costs.

$$(O_{i,s}) = \begin{cases} 1, & O_{i,s} = O_{i,max} \\ \dfrac{O_{i,s}}{O_{i,max}}, & O_{i,s} \neq O_{i,max} \end{cases}$$

Equation 23

$$P_{d,u} = \sum_{i=1}^{5} w_{u,i} * f(O_{i,d})$$

Equation 24

Firstly, the weight factors are defined according to the user preferences as defined on section 2.4.1:

- The Economist, that looks for a good value for his money
- The Family man, that looks for luxury and space for the comfort of his family
- The Environmentalist, that looks for the better solution environmentally

According to these preferences, weights are assigned for each user. An overview of the weight factors for the criteria *i* are displayed on Table 52.

Table 52: Weight Factors for each performance parameter

	Energy Efficiency	**Luxury**	**Costs**
The Economist	0.3	0.2	0.5
The Family Man	0.2	0.5	0.3
The Environmentalist	0.5	0.2	0.3

Having this in consideration Table 53 displays the scores for each of the options considered from benchmark design to a design featuring a hybrid power plant and Hull Vane®.

Table 53: Performance Parameter P calculated according to Equation 28

	Benchmark	Diesel Direct	Hybrid Arrangement	Hybrid Arrangement with Hull Vane®
The Economist	0.88	0.91	0.94	0.96
The Family Man	0.82	0.82	0.84	0.85
The Environmentalist	0.80	0.88	0.93	0.97

The new concept design with a hybrid arrangement and a Hull Vane® is unanimously the one with an overall better performance. Despite having a larger investment costs, it has a lower future value due to running cost reduction. Furthermore, it has a better energy efficiency performance.

In addition, the difference in terms of investment costs is small, thus not severely impacting the decision of the economist user. The reason for this lays on the fact that the increased investment costs are mitigated by the reduced running costs due to the reduction in fuel consumption and maintenance.

Consequently, it is possible to confirm the attractiveness of such a design to the market taking into consideration different types of users. This is only possible since the design features mature technology in the market. Technology that is already developed up to a point that the added costs do not severely hindrance the overall costs of the yacht.

Also contributing to this, is the fact that it was possible to lengthen the yacht for 5m without resulting in a rise of gross tonnage, advantage of the Fast Displacement Hull Form, which allowed for a minimal increase in internal area, quality valued by the family man type of user.

All in all, besides the larger investment costs the new design featuring a hybrid power plant and a Hull Vane® is able to be the best performing considering all the parameters. In addition, the payback period of this design is about 3.7 years which compared to the life time of the yacht is acceptable.

10. Conclusions

10.1 Introduction

Attentively keeping track of the new IMO regulations concerning the reduction of greenhouse gas emissions for the years to come motivated van Oossanen to move towards innovation and look for energy efficient solutions besides the hull form design. This research focused on the combination of a multitude of readily available strategies that could be implemented in a design today and result in a reduction of CO_2 emissions.

This chapter revisits the research question, elaborating an answer for it and for its associated sub-questions based on the findings described throughout this report. Conclusions and recommendations for future work are presented in the end.

10.2 The research questions

Taking into consideration the growing awareness for environmental issues from society and the pressing regulations from IMO there is the need to look for cleaner alternatives. This is the main reason why several fields have been working together to achieve better performing and alternative systems to move towards zero emissions operations.

Today it is common to discuss zero emission vehicles as the future however how far this future is, is still unknown to most of us, which leads to the research question of this project:

> *"How much of the CO_2 emissions can already be reduced by combining the state of the art technology in various areas and still have an attractive under 500 GT design for the market?"*

The answer to this main research question is achieved by answering the three sub-questions.

1. How much of the auxiliary load demand is it possible to reduce?

The answer to the first question follows from the analysis of the electric loads of the yacht. The reduction of auxiliary power demand is achieved by implementing strategies that reduce the electric demand either by reducing the loads on the equipment or by improving the efficiency of the systems.

The reduction is different for each operational mode since the load factors on equipment also differ from mode to mode. On average it is possible to reduce the auxiliary power demand around 24% by reducing consumption on air conditioning, water and lighting systems and by introducing basic functionalities of a power management system at maximum speed and manoeuvring.

2. How much of the propulsion power demand is it possible to reduce?

The answer to the second sub-question is obtained by improving the efficiency of the hull form. This question is answered making use of van Oossanen's previous research and development work on the patented Fast Displacement Hull Form, that attempts to improve the performance of the yacht over the whole speed range rather than only focusing on maximum speed performance. Moreover, the material of the hull is changed from steel to aluminium in an attempt to reduce displacement, thus resistance.

In addition to the changing the hull form, the application of the Hull Vane®, an energy saving device invented by van Oossanen, is considered to further improve performance.

All in all, with the new hull it is possible to reduce power demand by 39% at cruising speed of 12 knots and 57% at the top speed of 16 knots. Furthermore, by featuring a Hull Vane further power demand reductions of 12% at cruising and 16% at maximum speed are attained.

3. How much of the CO_2 emissions is it possible to reduce by considering power supply alternatives?

The answer to the third sub-question is based on the assessment of several possibilities in terms of power supply, from renewable energies, alternative fuels and different power plant arrangements.

In the end, the new concept design has a hybrid power plant arrangement without batteries, which allowed the reduction of the size of main engines despite the increase in generator size. In comparison with the conventional diesel electric arrangement, the hybrid power plant arrangement results in approximately 10% reduction in the yearly CO_2 emissions reductions without significant drawbacks in terms of volume, weight and cost.

Finally, by combining the findings of all three sub-questions it is possible to answer the main research question. The reduction of power demand in propulsion and auxiliary systems combined with a hybrid power plant arrangement results in a CO_2 emissions reduction of approximately 41%.

10.3 Conclusion

In a time where reducing ecological footprints is becoming a priority not only owing to social awareness but also to comply with stricter regulations, it is critical to uncover to what extent it is possible to reduce emissions with the already available technology.

In ship design the feasibility and benefits of energy saving measures are highly dependent on the vessel type; its function, size and operational profile. Even in this case of a super yacht, a different operational profile or size may lead to a different outcome.

The singularity of this project lays on the fact that it acknowledges the transitional moment the industry is facing, thus that there is the need to reduce emissions by combining the strategies available in the market so that it is possible to meet the double goal of reducing emissions and obtaining a design attractive to be commercially marketed.

The new directions from the International Maritime Organisation, IMO, aim at a 50% reduction of the EEDI by the year of 2050. In spite of the fact that at the moment this directory is drawn only for the shipping sector, thus only taking into consideration the impact of transit speed operational modes, the yachting sector wishes to be on the forefront in reducing emissions.

In this case, if one only considers the cruising mode (transit speed operations) the combination of all the strategies results in a 45% CO_2 emissions' reduction, especially remarkable since only readily available and mature technology is considered. When the whole range of operational profile is considered, which is more realistic, the reduction of emissions during the other operational modes lead to a reduction of 41% in relation to the benchmark design.

To have a 41% CO_2 emissions reduction already today just by combining several strategies regarding power demand reduction in both propulsion and auxiliary with hybrid power plant indicates that it is highly possible to achieve the 50% goal in the coming years, thus before 2050.

The majority of the savings are a result of the improvements in hull performance by the implementation of the Fast Displacement Hull Form as a replacement of the full displacement hull and the introduction of the Hull Vane®. Reason why the emission's reduction at sailing operational modes is larger in comparison to the reduction at anchorage mode. However, the significant yearly savings of 41% in CO_2 emissions are only possible with the combination of propulsion and auxiliary power demand reduction.

Furthermore, the change in power plant configuration results in approximately 10% of savings. The fact that there is still a great margin for improvement in relation to power supply indicates that there is a great potential still to be gained from power supply alternatives concerning emission reduction.

In comparison with the benchmark design, the new design not only outperforms in terms of energy efficiency but also in terms of available interior area, which means that it is possible to reduce the ecological footprint of a super yacht without losing significant floor area.

One of the main findings of this research is that it is possible to achieve significant CO_2 emission reduction with available and mature technology in the market, which results in an investment cost increase of approximately 6% only. Furthermore, the fact that running costs are reduced by approximately 8% reduces the payback period. In this case, it is possible to have a payback period of about 3.7 years which compared to the lifetime to the yacht is acceptable.

This research confirms that there are many advantages on integrated designs. Potential savings are hidden in the synergy between propulsion and auxiliary systems in terms of both demand and supply. Moreover, a well-defined operational profile together with the combination of various energy saving strategies may result in low cost CO_2 emission reduction.

10.4 For the future

After this research it is possible to provide some recommendations for future work.

Firstly, the approximate 25% uncertainty found on the yearly CO_2 emissions results due to the operational profile indicates that more accurate predictions of the operational profile distribution can be advantageous not only to the results but also to better choose the strategies to be applied. Furthermore, accurate operational profiles can point out which operational modes have greater influences on yearly emissions. Hence, the operational profile, as in this case is capable of ruling out strategies if the yearly impact versus drawbacks are not advantageous.

Likewise, having a more accurate prediction of the load factors on auxiliary equipment contributes to a better prediction of heavier consumers, pointing out a more accurate research direction. In addition, a better prediction of the actual demand contributes to a better sizing of equipment as generally the over estimations result in oversized equipment.

In addition, combining more accurate operational profiles, simultaneity and service timing of systems will improve the capabilities of power management systems. Power management has a great potential in improving the operation of the yacht in terms of energy consumption, thus emissions as they allow for the stabilizing of power demand, allowing for continuous optimal operation of power supply systems.

Research and develop of power management systems together with more accurate predictions of operational profiles may enhance further savings in what concerns the auxiliary systems, as power management is the connection to find the synergy between power demand and supply.

In terms of hull form design, the industry is continuously evolving in an attempt to achieve better performing vessels. Once again, a more accurate prediction of the operational profile of each vessel points out the speed range that should be the focus of the design since this will be the mode with higher impact on energy efficiency. However, not always the designs are focused on energy efficiency.

Nevertheless, it is in the power supply that most energy saving potential is still to be found. In terms of power supply there are multiple options that in different ways can improve energy efficiency.

As it is elaborated in chapter 7, finding the synergy between power supply components has a great potential regarding energy efficiency. Future research should focus on the introduction and correct sizing of more components to the power supply arrangement, such as renewables and alternative fuels or equipment such as batteries or fuel cells. As the maturity of technology evolves the feasibility of applications increases, and this is happening at a growing pace.

It is fundamental to optimize the sizing of components in a combined and integrated way, since is in the interaction of operations that the energy efficiency benefits lay. In addition, the individual progress of components is critical to improve the feasibility of combined systems. Reason why research and development of systems such as engines, generators, fuel cells, batteries, renewable energy production systems, etc has such a significant impact on the develop of widely available zero emission vessels.

Zero emission or nearly zero emission vessel concepts are already possible however the challenge is to make them widely available in the market and not only in concept or prototype projects. Market attractiveness of solutions is fundamental for the introduction of energy saving yachts.

In this case of the luxury market, owners' environmental concerns propel research and develop in more energy efficient yachts. Nonetheless, this always depends on the design requirements and investment capital availability.

The boundaries of this design and the lack of available data were the main challenges in improving energy efficiency. In terms of design boundaries, allowing for larger gross tonnage and dimensions of the yacht may contribute for the increased feasibility of introducing more energy efficient strategies.

Finally, in the pursuit of energy efficiency there are two main research paths. On the one hand, the research in improving efficiency and characteristics of isolated equipment and systems. On the other hand, research on integrating the available systems and strategies in the market, matching demand and supply of power in order to find the better combined efficiencies. Especially during breakthrough moments as the one we are living today, focus in combining energy saving strategies in the most efficient way should be continuously done as a way of attaining the highest possible savings.

References

1. **International Maritime Organization.** Greenhouse Gas Emissions. *IMO.* [Online] [Cited: June 01, 2018.] http://www.imo.org/en/OurWork/environment/pollutionprevention/airpollution/pages/ghg-emissions.aspx.
2. **IMO.** Brief History of IMO. *IMO.* [Online] [Cited: June 01, 2018.] http://www.imo.org/en/About/HistoryOfIMO/Pages/Default.aspx.
3. **International MAritime Organization.** Energy Efficiency Measures. *IMO.* [Online] [Cited: June 1, 2018.] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx.
4. **European Commission.** *MEMO: 72nd session of the Marine Environment Protection Committee (MEPC 70) at the International Maritime Organization (IMO).* Brussels : s.n., 2018.
5. **Greenhouse Gas Emissions. *IMO- International Maritime Organization.* [Online] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/GHG-Emissions.aspx.**
6. Air Polution, Energy and Greenhouse Gas Emissions. *IMO- International Maritime Organization.* [Online] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Default.aspx.
7. Maritime and Coastguard Agency. *LY3 - The Large Commercial Yacht Code.* Southampton : Crown, August 2012.
8. *From operational profile to hybrid propulsion.* van Loon, P. T. and van Zon, P. Amsterdam : HISWA, 2016. 978-94-6186-749-0.
9. de Almeida, Adiel Teixeira, et al. *Multicriteria and Multiobjective Models for Risk, Reliability and Maintenance Decision Analysis.* s.l. : Springer, Cham, 2015. Vol. 231. 2214-7934.
10. Uithof, Kasper. *The feasibility and Performance of a trimaran yacht concept equipped with a Hull Vane®.* 2012.
11. Marine Traffic. Itineraries History. *Marine Traffic.* [Online] https://www.marinetraffic.com.
12. *Reducing the Environmental Impact of Large Yachts.* Roy, James, et al. Genoa, Italy : The Royal Institution of Naval Architechts, 5-6 May, 2011. Design Conference: Design, Construction & Operation of Super & Mega Yachts.
13. Brade, Ellie, Cheney, Thea and Muller, Pedro. *Economic analysis of the superyacht industry.* London : TRP Magazines, 2012.
14. *Energy Efficient Maritime Accommodations.* Taen, Jeroen, Otheguy, Mariano and Hekkenberg, Robert. Cortona : HIPER, September 2016.
15. Feist, Wolfgang. *Passive House.* s.l. : Passive House Institute.
16. American Society of Heating, Refrigeration and Air-Conditioning Enigineers. *ASHRAE Handbook - Fundamentals.* Atlanta, USA : AnonAtlanta, 2009.
17. Alwan, Sabah, et al. *Energy Efficiency Design Index (EEDI) Impact on Super Yacht Design.*
18. Calleya, John, et al. *Designing Future Ships for Significantly Lower Energy Consumption.* London, UK : University College London.
19. Dykins, Rose. *Shaping the Future of Luxury Travel, Future Traveller Tribes 2030.* s.l. : Amadeus & Tourism Economics, 2016.
20. Isoclima. Cromalite. *Isoclima.* [Online] [Cited: December 13, 2017.] http://www.isoclima.net/cromalite_spd_glass.html.
21. van Oossanen, Perry. *Interview on different subjects related to yacht design.* Wageningen, 2018.
22. *Next Generation ultra-luxury cruise ship: A passive Design eco-luxury cruise ship for the mediterranean.* McCartan, S. and Kvilums, C. London, UK : Design & Operation of passenger ships, November 2013.
23. Aste, Niccolo, Adhikari, Rajendra Singh and Del Pero, Claudio. *An algorithm for designing dynamic solar shading systems.* Nilan, Italy : ELSEVIER, 2010.
24. Hopman, Heinen &. *Estimations of Air Conditioning Loads and dimensioning of systems.* Wageningen, March 2018.

25. ASHRAE. Panel Heating and Cooling. *Handbook - HVAC systems and equipment Radiant systems.* s.l. : ASHRAE, 2000.
26. *Ceiling Radiant Cooling Panels as Viable Distributed Parallel Sensible Cooling Technology Integrated with Dedicated Outdoor Air Systems.* Conroy, Christopher L. and Mumma, Stanley A. s.l. : ASHRAE , 2001.
27. Rhee, Kyu-Nam, Olesen, Bjarne W. and Kim, Kwang Woo. *Ten questions about radiant heating and cooling systems.* s.l. : ELSEVIER, 2016.
28. Feustel, H.E. and Stetiu, C. *Hydronic radiant cooling - preliminary assessment.* s.l. : Energy Build, 1995.
29. Heinen & Hopman. Absortion Chiller. *Heinen & Hopman.* [Online] Heinen & Hopman. [Cited: December 14, 2017.] https://heinenhopman.com/en/yachting/motor-yachts/motor-yacht-air-conditioning/absorption-chiller/.
30. Kuczynska, Agnieszka and Szaflik, Wladyslaw. Absorption and adsorption chillers applied to air conditioning systems. *Archives of thermodynamics.* 2010, Vol. 31, 2.
31. Heinen & Hopman. Turbocor chiller. *Heinen & Hopman.* [Online] [Cited: January 18, 2018.] https://heinenhopman.com/heinen-and-hopman/pdfs-gecomprimeerd/hh-turbocor-compressor.pdf.
32. *Efficient Lighting Strategies.* U.S. Department of Energy. 2002.
33. Dilouie, Craig. Estimating Energy Savings with Lighting Controls. *LCA - Lighting Controls Association.* [Online] The Lighting controls Authority, September 16, 2013. [Cited: January 25, 2018.] http://lightingcontrolsassociation.org/2013/09/16/estimating-energy-savings-with-lighting-controls/.
34. de Bakker, Christel, et al. *Occupancy-based lighting control in open-plan office-spaces: A state-of-the-art review.* s.l. : Elsevier, 2016.
35. ACV. Tank-in-Tank Technology. *ACV.* [Online] ACV. [Cited: January 19, 2018.] https://www.acv.com/gb/customer/faq/VlH7dx4AALwf6Qpz/tank-in-tank-technology.
36. Cathelco Hem. *Hot Water Systems.* s.l. : Cathelco Hem, 2018.
37. Barnes, Vanessa, Collins, Thomas K. and Mills, Godfrey A. *Design and Implementation of Home Energy and Power Management and Control System.* s.l. : IEEE, 2017.
38. Morgan, Jacob. A simple Explanation Of 'The Internet Of Things'. *Forbes Magazine.* [Online] May 13, 2014. [Cited: December 15, 2017.] https://www.forbes.com/sites/jacobmorgan/2014/05/13/simple-explanation-internet-things-that-anyone-can-understand/#1f6c27d91d09.
39. Rouse, Margaret. Internet of Things. *TechTarget.* [Online] [Cited: December 18, 2017.] http://internetofthingsagenda.techtarget.com/definition/Internet-of-Things-IoT.
40. van Ooossanen, Perry, et al. *Motor yacht hull form design for the displacement to semi-displacement speed range.* Athens : s.n., 2009.
41. *Resistance Characteristics of Semi-Displacement Hull Forms.* Blount, D.L. and McGrath, J. Genoa, Italy : Royal Institution of Naval Architects, 2009. Symposium on the Design, Construction and Operation of Super and Mega Yachts.
42. Keuning, J.A. *Comparison of the Resistance and Motions in Waves of a Round bilge and Hard Chine Model of a high Speed Displacement Ship.* Hydromechanics Laboratory, Delft University of technology. Delft : Delft University of technology, 1984. 612.
43. Bailey, D. *The NPL High Speed Round Bilge Displacement Hull Series.* s.l. : Maritime Technology, 1976. 4.
44. Uithof, K., et al. *An update on the development of the Hull Vane®.*
45. Moerke, N. and Zaaijer, K.S. *Systematic study into the performance of the Hull Vane®.* 2009.
46. Eyres, David J. Aluminium Alloy. *Ship Construction.* s.l. : Elsevier, 2007.
47. DNV-GL. *Energy Transition Outlook - Renewables, Power and Energy Use - Forecast to 2050.* 2017.
48. Lloyd's Register & UMAS. *Zero-Emission Vessels 2030. How do we get there?*
49. Dobson, Jim. *The Best Eco-Friendly Superyachts, Toys and Tenders to help save the planet.* s.l. : Forbes, 2016.
50. Energy Observer. The Vessel. *Energy Observer.* [Online] [Cited: MAy 15, 2018.] http://www.energy-observer.org/en/.
51. Wijtzes, S. *Fuel Cell electric vehicles & hydrogen balancing national 100% renewable integrated transport & energy systems.* s.l. : Delft University of Technology, 2017.
52. Veldhuis, Ivo. *Application of hydrogen marine systems in high-speed sea container transport.* School of Engineering, IUniversity of Southampton. 2007. Doctoral Thesis.

53. *Analysing the possibilities of using fuel cells in ships.* de-Troya, Jose J., Alvarez, Carlos and Fernandez-Garrido, Carlos. 48, s.l. : Elsevier, 2015, Vol. 40. 0360-3199.
54. Sanford, Kelley. Rolls-Royce's Tech-Forward Yacht Concept. *Yachting magazine.* [Online] November 30, 2017. [Cited: May 12, 2018.] https://www.yachtingmagazine.com/rolls-royces-tech-forward-yacht-concept..
55. IRENA. *Renewable Power Generation Costs in 2017.* Abu Dhabi : International Renewable Energy Agency, 2018. 978-92-9260-040-2.
56. HelioClim -3 Archives. [Online] SODA - Soalr Radiation Data, 2006. [Cited: February 22, 2018.] http://www.soda-pro.com/web-services/radiation/helioclim-3-archives-for-free.
57. Solbian. *Flexible Solar Panels.* s.l. : Solbian, 2017.
58. Woud, Hans Klein and Stapersma, Douwe. *Design of Propulsion and Electric Power Generation Systems.* London : IMarEST, 2015.
59. Kwasieckyj, Bas. *Hybrid Propulsion systems - Efficiency analysis and design methodology of hybrid propulsion systems.* Augsburg : Delft University of Technology, 2013.
60. John Deere Generators. *Zenoro.* [Online] [Cited: May 2018, 29.] https://static.zenoro.com/default/files/documents/zenoro_specs_6068AFM85_109ekW_IMOexempt_1512.pdf.
61. *International Convention on tonnage measurement of ships.* IMO. London : International Maritime Organization, 1969.
62. MCA. *The Large Commercial Yacht Code.* 2012.
63. Oossanen, Perry van. *The price of yachts.* Wageningen, The Netherlands, May 2018.
64. Zhu, Yuanqing, et al. *Influences of solar energy on the energy efficiency design index for new building ships.* China : Elsevier, 2017.
65. *Preparation of carbon based getter for glass fiber core vacuum insulation panels (VIPs) used on marine reefer containers.* Zheng, Q.R., et al. s.l. : Vacuum, December 20017, Vol. 146.
66. Tronstad, Tomas, et al. *Study on the use of fuel cells in shipping.* s.l. : ESMA European Maritime Safety Agency & DNV-GL, 2017.
67. *Large-scale photovoltaic system on green ship and its MPPT controlling.* Tang, Ruoli. China : Solar Energy, 2017, Vol. 157.
68. Seddiek, Ibrahim S., Elgohary, M. Mohamed and Ammar, Nader R. *The Hydrogen-Fuelled Internal Combustion Engines for Marine Applications with a Case Study.* s.l. : Brodogradnja/Shipbuilding, 2015. 0007-215X.
69. Rosa, Aldo Vieira da. Solar Radiation. *Fundamentals of Renewable Energy.* Stanford : Elsevier, 2013, 12.
70. Raucci, C., et al. *Hydrogen on Board Ship: A first analysis of key parameters and implications.* London : s.n.
71. Pearson, G., et al. *Performance Comparison of Hydrogen Fuel Cell and Hydrogen Internal Combustion Engine Racing Cars.* 978-3-642-19052-0.
72. Oossanen, Perry van. *The current state of the market and other items related with yacht design.* Wageningen, 2018.
73. Mittler, Anna. Travel Trends for 2017. *BoatBookings.* [Online] May 23, 2017. [Cited: September 21, 2017.] https://www.boatbookings.com/blog/2017/05/23/travel-trends-for-2017/.
74. *Development of an eco-catamaran for the charter market through the implementation of "Passive Design" Technology.* McCartan, S. and Kvilums, C. Genoa, Italy : Super & Mega Yachts, May 2013.
75. *Design-Driven Innovation Avant Garde 50M superyacht under 500GT.* McCartan, S, et al. Genova : s.n., 2015. Design&Construction of Super & Mega Yachts.
76. Lasselle, Sarah and Abusdal, Havard. *Methanol as marine fuel: Environmental benefits, technology readiness, and economic feasibility.* s.l. : DNV-GL, 2016. 2015-1197.
77. *Optimal sizing of hybrid PV/diesel/battery in ship power system.* Lan , Hai, et al. Taiwan : Elsevier, 2015, Applied Energy, Vol. 158.
78. Lacey, Matthew, et al. Shipping Smarter: IoT opportunities in transport and logistics, The Internet of Things in shipping. *Deloitte insights.* [Online] Deloitte Consulting, September 15, 2015. [Cited: December 18, 2017.] https://www2.deloitte.com/insights/us/en/focus/internet-of-things/iot-in-shipping-industry.html.
79. Kalnaes, Simen Edsjo and Jelle, Bjorn Petter. *Vacuum insulation panel products: A state-of-art review and future research pathways.* Trondheim, Norway : ELSEVIER, 2013.
80. *Design and control of hybrid power and propulsion systems for smart ships: A review of developments.* Geertsma, R. D., et al. 2007, Applied Energy, pp. 30-54.

81. Cain, M., et al. The (super) yachting index. *Camper & Nickolsons International Fifth Edition.* Geneva, Switzerland : Camper & Nickolsons International, 2013.
82. Brade, E., Muller, P. and MHR. *Economic Analysis of the super yacht industry.* London, United Kingdom : The Super Yacht Intelligence, 2012.
83. Bauer, Lorenz. Ocean Going Vessels Going Green. [Online] Lee Enterprises Consulting, November 22, 2016. [Cited: September 19, 2017.] http://www.biofuelsdigest.com/bdigest/2016/11/22/ocean-going-vessels-going-green/.
84. Andersson, Karin. *Methanol as a Marine Fuel Report.* Chalmers : Methanol Institute, 2015.
85. What is a superyacht. *Warsash Super Yacht Academy.* [Online] http://www.warsashsuperyachtacademy.com/about/superyacht-industry/what-is-a-superyacht.aspx.
86. The Passive House. Thermal Insulation. *Passipedia - The Passive House Resource.* [Online] Passive House. [Cited: November 22, 2017.] https://passipedia.org/planning/thermal_protection/integrated_thermal_protection.
87. Camper & Nicholsons & Wealth - X. *The State of Wealth, Luxury and Yachting.* s.l. : Camper & Nicholsons & Wealth - X.
88. Auto Desk. Stack Ventilation and Bernoulli's Principle. *Auto Desk Sustainability Workshop.* [Online] Auto Desk. [Cited: November 5, 2017.] https://sustainabilityworkshop.autodesk.com/buildings/stack-ventilation-and-bernoullis-principle.
89. Boat International & Burgess. Industry Data. *Boat International.* [Online] [Cited: September 21, 2017.] https://www.boatinternational.com/yacht-market-intelligence/superyacht-industry-data.
90. CAMS Radiation Service. *Atmosphere Monitoring Service.* [Online] Copernicus, 2006. [Cited: February 22, 2018.] http://www.soda-pro.com/web-services/radiation/cams-radiation-service.
91. AMAP. *Artic Climate Issues 2011: Changes in Artic Snow,water, Ice and Permafrost.* Oslo : AMAP, 2012. 978-82-7971-073-8.

Appendix A. THE OPERATIONAL PROFILE

A.1 THE MARINE TRAFFIC DATA

	In Port		Crossing		Cruising		Max Speed		Manoeuvring		At Anchor		Total [min]
	[min]	%	[min]	%	[min]	%	[min]	%	[min]	%	[min]	%	
1	109934	74.84%	4968	3.38%	10871	7.40%	200	0.14%	600	0.41%	20310	13.83%	146883
2	104971	78.04%	9712	7.22%	5053	3.76%	260	0.19%	780	0.58%	13739	10.21%	134515
3	41116	31.94%	0	0.00%	16264	12.64%	460	0.36%	1380	1.07%	69496	53.99%	128716
4	30926	23.25%	23265	17.49%	2394	1.80%	200	0.15%	600	0.45%	75608	56.85%	132993
5	76823	52.22%	25356	17.24%	7933	5.39%	600	0.41%	1800	1.22%	34598	23.52%	147110
6	1556	6.23%	0	0.00%	5569	22.29%	280	1.12%	840	3.36%	16737	67.00%	24982
7	76748	55.08%	490	0.35%	11000	7.90%	1020	0.73%	3060	2.20%	47010	33.74%	139328
8	10263	21.23%	8980	18.58%	2927	6.05%	180	0.37%	540	1.12%	25452	52.65%	48342
Maximum		78.04%		18.58%		22.29%		1.12%		3.36%		67.00%	
Minimum		6.23%		0.00%		1.80%		0.14%		0.41%		10.21%	
Average		42.86%		8.03%		8.40%		0.43%		1.30%		38.97%	

Appendix B. THE ELECTRIC LOAD BALANCE OF REFERENCE DESIGN

B.1 CONSUMER GROUPS: MAIN MACHINERY, STEERING & MANOEUVRING, STABILIZING, FUEL & OIL SYSTEMS

				Cruising			Crossing			Manoeuvring			At Anchor					
													Day Duty			Night Duty		
spec.	Consumer	Qty.	Actual Load kW	Load Factor	kW	%	Load Factor	kW	%	Load Factor	kW	%	Load Factor	kW	%	Load Factor	kW	%
1	**Main Machinery**				14.60	7.70%		14.60	9.42%		14.22	7.22%		0.82	0.55%		0.82	0.52%
1.1	Pre-heating circulation pump	2	6.00	100%	12.00		100%	12.00		100%	12.00		0%	0.00		0%	0.00	
1.2	Propulsion Plant Automation	1	0.50	100%	0.50		100%	0.50		100%	0.50		0%	0.00		0%	0.00	
1.4	Water lubrication	2	0.75	90%	1.34		90%	1.34		90%	1.34		5%	0.07		5%	0.07	
1.6	Battery chargers service batteries	1	1.89	20%	0.38		20%	0.38		10%	0.19		20%	0.38		20%	0.38	
1.7	Battery chargers start batteries	1	1.89	20%	0.38		20%	0.38		10%	0.19		20%	0.38		20%	0.38	
2	**Steering & Manoeuvring**				8.11	4.28%		8.11	5.24%		50.59	25.67%		0.00	0.00%		0.00	0.00%
2.1	Hydraulic steering system	2	5.28	70%	7.39		70%	7.39		70%	7.39		0%	0.00		0%	0.00	
2.2	Bow thruster	1	72	1%	0.72		1%	0.72		60%	43.20		0%	0.00		0%	0.00	
3	**Stabilizing**				21.12	11.14%		21.12	13.63%		17.60	8.93%		21.12	14.00%		21.12	13.31%
3.1	Hydraulic Stabilizing fins	2	17.6	60%	21.12		60%	21.12		50%	17.60		60%	21.12		60%	21.12	
4	**Fuel & Oil Systems**				3.53	1.86%		3.43	2.21%		2.71	1.38%		2.63	1.74%		1.19	0.75%
4.1	Tranfer pump	1	2.4	90%	2.16		90%	2.16		70%	1.68		60%	1.44		30%	0.72	
4.2	fuel separator	1	0.88	90%	0.79		90%	0.79		70%	0.62		60%	0.53		30%	0.26	
4.3	Raco filters type 1000	6	0	90%	0.00		90%	0.00		70%	0.00		60%	0.00		30%	0.00	
4.4	pump for tender's fueling station	1	0.51	20%	0.10		0%	0.00		0%	0.00		60%	0.31		5%	0.03	
4.5	Lube Oil pumps	2	0.296	80%	0.47		80%	0.47		70%	0.41		60%	0.36		30%	0.18	

B.2 CONSUMER GROUPS: WATER SYSTEMS, FIRE & BILGE SYSTEMS

				Cruising			Crossing			Manoeuvring			At Anchor					
													Day Duty			Night Duty		
spec.	Consumer	Qty.	Actual Load kW	Load Factor	kW	%	Load Factor	kW	%	Load Factor	kW	%	Load Factor	kW	%	Load Factor	kW	%
5	**Water Systems**				25.95	13.69%		17.29	11.16%		11.21	5.69%		20.61	13.66%		27.30	17.20%
5.1	Fresh Water treatment	1	0.4	40%	0.16		40%	0.16		10%	0.04		70%	0.28		80%	0.32	
5.2	Hydrophore	2	4	21%	1.68		30%	2.40		10%	0.80		60%	4.80		50%	4.00	
5.3	Boilers	3	10.4	36%	11.23		12%	3.74		3%	0.94		24%	7.49		50%	15.60	
5.4	Circulation pums for hot water	3	0.0368	80%	0.09		40%	0.04		5%	0.01		24%	0.03		60%	0.07	
5.5	water maker	2	5.28	24%	2.53		10%	1.06		5%	0.53		30%	3.17		40%	4.22	
5.6	feed water pumps for water maker	2	0.296	24%	0.14		10%	0.06		3%	0.02		30%	0.18		40%	0.24	
5.7	EVAC/JETS Vacuum system	2	1.76	40%	1.41		32%	1.13		5%	0.18		40%	1.41		50%	1.76	
5.8	Cooling water systems (engine+ generators)	1	10.88	80%	8.70		80%	8.70		80%	8.70		30%	3.26	%	10%	1.09	
6	**Firefighting & Bilge Systems**				5.36	2.83%		5.15	3.32%		5.36	2.72%		5.36	3.55%		5.36	3.38%
6.1	bilge/firefight pumps	2	8.8	6%	1.06		6%	1.06		6%	1.06		6%	1.06		6%	1.06	
6.2	Oil/Water Separator	1	2.16	10%	0.22		10%	0.22		10%	0.22		10%	0.22		10%	0.22	
6.3	High Fog firefighting system (half is for redundancy)	1	27	10%	2.70		10%	2.70		10%	2.70		10%	2.70		10%	2.70	
6.4	CO_2 firefight Galley	1	1.156	10%	0.12		10%	0.12		10%	0.12		10%	0.12		10%	0.12	
6.5	Hamann Treatment system	1	2.125	60%	1.28		50%	1.06		60%	1.28		60%	1.28		60%	1.28	

B.3 CONSUMER GROUP: AIR SYSTEMS (HVAC)

				Cruising			Crossing			Manoeuvring			At Anchor					
													Day Duty			Night Duty		
			Actual Load	Load Factor		%	Load Factor		%	Load Factor		%	Load Factor		%	Load Factor		%
spec.	Consumer	Qty.	kW		kW			kW			kW			kW			kW	
7	**Air Systems (HVAC)**				66.47	35.06%		48.81	31.50%		57.98	29.42%		59.69	39.56%		54.37	34.26%
7.1	Compressed air system	1	1.2	20%	0.24		20%	0.24		5%	0.06		20%	0.24		5%	0.06	
7.2	Dive Compressor system	1	3.2	10%	0.32		10%	0.32		0%	0.00		10%	0.32		0%	0.00	
7.3	Forced Ventilation Engine Room	2	6	100%	12.00		100%	12.00		100%	12.00		60%	7.20		30%	3.60	
7.4	Mechanical Ventilation Exhaust		0		0.00			0.00			0.00			0.00			0.00	
7.5	Fresh Air Supply	1	20.24	100%	20.24		100%	20.24		100%	20.24		100%	20.24		100%	20.24	
7.6	Window defogging pilot house	5	1.2	30%	1.80		60%	3.60		20%	1.20		0%	0.00		0%	0.00	
7.7	*Air Conditioning*				0.00			0.00			0.00			0.00			0.00	
7.7.1	Chilled water pumps	2	2.4	40%	1.92		30%	1.44		40%	1.92		40%	1.92		40%	1.92	
7.7.2	Seawaterpumps	2	1.2	40%	0.96		30%	0.72		40%	0.96		40%	0.96		40%	0.96	
7.7.3	Chilled unit	1	29.75	80%	23.80		30%	8.93		60%	17.85		80%	23.80		80%	23.80	
7.7.4	***Fancoil Units***				5.19			1.33			3.75			5.01			3.79	

B.4 CONSUMER GROUP: LIGHTING

				Cruising			Crossing			Manoeuvring			At Anchor – Day Duty			At Anchor – Night Duty		
spec.	Consumer	Qty.	Actual Load kW	Load Factor	kW	%	Load Factor	kW	%	Load Factor	kW	%	Load Factor	kW	%	Load Factor	kW	%
8	**Lighting**				14.12	7.45%		14.35	9.26%		14.31	7.26%		13.26	8.79%		25.16	15.85%
8.1	One way Switches	25	0.051	10%	0.13		10%	0.13		10%	0.13		10%	0.13		10%	0.13	
8.2	pulse switch	70	0.051	10%	0.36		10%	0.36		10%	0.36		10%	0.36		10%	0.36	
8.3	socket outlets Europe	75	0.2805	8%	1.58		8%	1.58		8%	1.58		8%	1.58		8%	1.58	
8.4	socket outlets for equipment	30	0.2805	20%	1.68		20%	1.68		20%	1.68		20%	1.68		20%	1.68	
8.5	telephone/ISDN/ LAN outlet	26	0.068	10%	0.18		10%	0.18		10%	0.18		10%	0.18		10%	0.18	
8.6	switch waterproofhouse	10	0.0425	10%	0.04		10%	0.04		10%	0.04		10%	0.04		10%	0.04	
8.7	socket oulet waterproof house	11	0.2805	8%	0.23		8%	0.23		8%	0.23		8%	0.23		8%	0.23	
8.8	*Interior Lighting*		0.13		6.88			4.42			6.88			5.56			12.64	
8.9	*Exterior lighting*	350	0.035	48%	5.88		32%	3.92		48%	5.88		40%	4.90		81%	9.92	
8.10	technical area lights	22	0.05	42%	0.46		21%	0.23		42%	0.46		35%	0.39		81%	0.89	
8.11	underwater lights	50	0.045	24%	0.54		12%	0.27		24%	0.54		12%	0.27		81%	1.82	
8.12	Floodlights	95	0.05	14%	0.67		21%	1.00		14%	0.67		35%	1.66		81%	3.85	
8.13	PS AS55	100	0.05	24%	1.20		72%	3.60		24%	1.20		30%	1.50		50%	2.50	
8.14	SB AS55	6	0.32	20%	0.38		0%	0.00		20%	0.38		0%	0.00		80%	1.54	
8.15	Stern AS55	2	0.25	40%	0.20		60%	0.30		40%	0.20		60%	0.30		70%	0.35	
8.16	Head AS55																	
8.17	Anchor AS55	2	0.025	24%	0.01		60%	0.03		32%	0.02		0%	0.00		0%	0.00	
8.18	nuc AS55	2	0.025	24%	0.01		60%	0.03		32%	0.02		0%	0.00		0%	0.00	
8.19	bow light AS40	2	0.025	24%	0.01		60%	0.03		32%	0.02		0%	0.00		0%	0.00	
8.20	Search Light	2	0.025	24%	0.01		60%	0.03		32%	0.02		0%	0.00		0%	0.00	
8.21	Vessel'sName	2	0.025	0%	0.00		0%	0.00		0%	0.00		100%	0.05		100%	0.05	

B.5 CONSUMER GROUP: DOMESTIC APPLIANCES (GALLEY & LAUNDRY)

			Cruising			Crossing			Manoeuvring			At Anchor					
												Day Duty			Night Duty		
spec.	Consumer	Actual Load kW	Load Factor	kW	%	Load Factor	kW	%	Load Factor	kW	%	Load Factor	kW	%	Load Factor	kW	%
9	**Domestic [Galley & Laundry]**			12.20	6.44%		9.87	6.37%		8.63	4.38%		12.20	8.09%		10.83	6.82%
9.1	Main Galley	33.70	26%	8.77		26%	8.77		21%	7.24		26%	8.77		26%	8.77	
9.2	Pantry on Main Deck	3.9	29%	1.134		2%	0.076		20%	0.7728		29%	1.134		21%	0.7998	
9.3	Crew mess	8.3	7%	0.606		5%	0.44		1%	0.064		7%	0.606		6%	0.48	
9.4	Crew Laundry	12.69	5%	0.63		1%	0.13		0%	0.00		5%	0.63		1%	0.11	
9.5	Owner's Stateroom	2.78	4%	0.118		2%	0.06		2%	0.064		4%	0.118		3%	0.091	
9.6	Guest Area	2.78	7%	0.20		2%	0.06		4%	0.11		7%	0.20		3%	0.09	
9.7	Bar on Main Deck	0.32	28%	0.088		24%	0.08		21%	0.06784		28%	0.088		22%	0.0688	
9.8	Sky Lounge	0.4	22%	0.09		0%	0.00		17%	0.07		22%	0.09		17%	0.07	
9.9	Flying bridge exterior	0.32	28%	0.088		0%	0		21%	0.0678		28%	0.088		22%	0.0688	
9.10	Lazarette	0.32	21.5%	0.068		0.0%	0.00		21.2%	0.0678		21.5%	0.068		21.5%	0.0688	
9.11	Cooled garbage storage (450L)	0.32	50%	0.16		80%	0.26		16%	0.05		50%	0.16		50%	0.16	
9.12	Flying bridge exterior	6.8	1%	0.07		0%	0.00		0%	0.00		1%	0.07		0%	0.00	
9.13	Dumbwaiter	1.2	10%	0.12		0%	0.00		0%	0.00		10%	0.12		0%	0.00	

B.6 CONSUMER GROUP: NAVIGATION & COMMUNICATION, ENTERTAINMENT SYSTEMS, MOORING & BOARDING & OTHERS

				Cruising			Crossing			Manoeuvring			At Anchor					
													Day Duty			Night Duty		
			Actual Load	Load Factor		%	Load Factor		%	Load Factor		%	Load Factor		%	Load Factor		%
spec.	Consumer	Qty.	kW		kW			kW			kW			kW			kW	
10	**Navigation & Communication**				8.00	4.22%		8.00	5.16%		8.00	4.06%		0.80	0.53%		0.80	0.50%
10.1	**Navigation**			100%	4.00		100%	4.00		100%	4.00		0%	0.00		0%	0.00	
10.2	**Communication**			100%	4.00		100%	4.00		100%	4.00		20%	0.00		20%	0.00	
11	**Entertainment**		10.62	61%	6.51	3.43%	12%	1.27	0.82%	32%	3.39	1.72%	62%	6.62	4.39%	62%	6.63	4.18%
12	**Mooring & Boarding & Others**				3.60	1.90%		2.96	1.91%		3.06	1.55%		7.75	5.14%		5.11	3.22%
12.1	Anchor Winches	2	7.2	0%	0.00		0%	0.00		5%	0.36		0%	0.00		0%	0.00	
12.2	Mooring Capstans	2	4.4	0%	0.00		0%	0.00		2%	0.09		0%	0.00		0%	0.00	
12.3	Anchor Wash system	2	0.8	0%	0.00		0%	0.00		0%	0.00		0%	0.00		0%	0.00	
12.4	Boat Crane	1	7.2	0%	0.00		0%	0.00		0%	0.00		0%	0.00		0%	0.00	
12.5	Hydraulic Power plant	1	3.2	80%	2.56		80%	2.56		80%	2.56		50%	1.60		70%	2.24	
12.6	Steam Room	1	15	0%	0.00		0%	0.00		0%	0.00		30%	4.50		10%	1.50	
12.7	Window Wipers	5	1	20%	1.00		40%	0.40		5%	0.05		0%	0.00		0%	0.00	
12.8	Jaccuzzi	1	6.66	0%	0.00		0%	0.00		0%	0.00		20%	1.33		20%	1.33	
12.9	Sun Awnings	2	0.4	5%	0.04		0%	0.00		0%	0.00		40%	0.32		5%	0.04	

Appendix C. SOLAR ENERGY

The solar irradiation varies with position of the ship, date and time. Therefore, the solar irradiation that reaches the vessel can be estimated on an hourly basis, considering the following parameters:

- Direct Normal Radiation
- Diffuse Horizontal Radiation
- Ambient Temperature
- Local Latitude and Longitude
- Date and Local Time
- Time Zone
- Surface Albedo
- Surface Characteristics
    - Tilt Angle
    - Azimuth Angle

From the Atmosphere Monitoring Service of Cams radiation service from Copernicus (50), data was collected for the year of 2006 for a specified point on the Mediterranean (37º 57' N 12º 11' E). Data was collected on an hourly basis for a whole year.
Solar irradiation plays a determinant role, as proposed by (53)(52) the hourly total solar radiance on board is as follows:

$$G = G_{direct} + G_{diffuse} + G_{ground\ reflected}$$
$$= G_{direct\ normal}\left[\cos(\theta) + \cos^2\left(\frac{\phi}{2}\right)\sin(\chi) + \rho(\cos\chi + C\ )\sin^2\left(\frac{\phi}{2}\right)\right]$$

Equation 25

Where $\rho(\cos\chi + C\ )$ represents the Surface Albedo, the reflectance capacity of the surface. The Albedo varies with direction of sun incidence and type of surface, on average for the Ocean this value is rather low, around 7 % (54).
X is the zenith angle and φ the tilt angle of the panel. The variable θ is the represents the angle between the panels and the solar rays, calculated using Equation 26.

$$\cos\theta = [\cos\phi\cos\chi + \sin\phi\sin\chi\cos(\xi - \zeta)]$$

Equation 26

The variables ξ and ζ are the sun and plate azimuths respectively. Equation 27 and Equation 28 are used to calculate the sun zenith and azimuth angles according to (book of fundamentals).

$$\cos\chi = \sin\delta\sin\lambda + \cos\delta\cos\lambda\cos\alpha$$

Equation 27

$$\tan\xi = \frac{\sin\alpha}{\sin\lambda\cos\alpha - \cos\lambda\tan\delta}$$

Equation 28

The variables δ, α and λ represent the solar declination angle (Equation 29), the solar angle (Equation 30) and the latitude in degrees, respectively. The variable *d* represents the day number, for example 1st January corresponds to *d*=1 and so on until the 31st of December that corresponds to **d**=365.

$$\delta = 23.44\sin\left[360\left(\frac{d - 80}{365.25}\right)\right]$$

Equation 29

$$\alpha = \frac{360}{24}(LST - 12)$$

Equation 30

$$LST = \left(T_{local} + \frac{1}{60}[4(L_{local} - LSTM) + EOT]\right)$$

Equation 31

$$LSTM = 15^o t_{zone}$$

Equation 32

$$EOT = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B)$$

Equation 33

$$B = \frac{360(d - 81)}{364}$$

Equation 34

LST is the Local standard time, representing the synchronization of the times within a time standard region. LSTM is the Local Standard time Meridian, is the translation for the reference meridian for the time region. Finally, the EOT, the equation of time that accounts for the discrepancies in time caused by the earth's speed around the sun. The equation of time can be estimated based on the number of the day *d* as in Equation 33 and Equation 34 or by data bases where the equation of time values are registered for the past years.
The above-mentioned formulation contributes for the calculation of both the heat absorbed by the glazing surfaces and for the solar power generation calculation. The main difference between the two cases lays on the surface characteristics; tilt angle ϕ and azimuth angle ζ.
Despite not being very realistic, for simplicity purposes the vessel's position is unchanged throughout the analysis.

C.1 ABSORBED HEAT BY WINDOWS

In the first case, the orientation of the yacht has to be considered since not all the windows are facing the same direction. Therefore, Figure 46 shows the considered orientation that is the base for the azimuth angles definition.
Regarding the tilt angle, windows are considered in a vertical position, thus with a 90º tilt angle.
From this, it is possible to uncover for every hour the angle between the solar rays and the window surface, θ, and the modified incident radiation, G in [W/m^2] for every hour of everyday of the year.
Taking into consideration the exposed area *A* and the solar coefficient *G-value*, a characteristic of the glass type, the absorbed heat calculation follows from Equation 35.

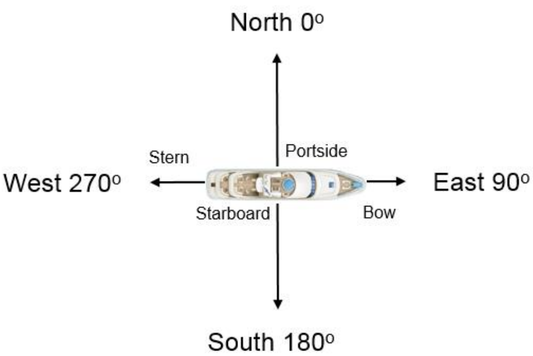


Figure 46: Yacht Orientation for Azimuth angle calculation

$$Absorbed\ Heat = A_{window} \times G - value \times G_{modified}\ [W\ per\ hour\ per\ day]$$

Equation 35

Giving the fact that in the Mediterranean the seasons are well defined it is possible to make a seasonal analysis by grouping data according to the seasons. (Table 54)

Table 54: Seasons' definition

Season	First Day	Last Day	d
Winter	21st of December	20st of March	255-79
Spring	21st of March	20st of June	80-171
Summer	21st of June	20th of September	172-263
Autumn	21st of September	20th of December	264-354

Therefore, a typical day of each season, based on the average of all the days in that particular season is defined.
For example, given a dark window (G-value=0.2) of 1 m^2, facing south (ζ=180º), the absorbed heat per hour in each different season is as presented on Table 55, all the hours not presented have absorbed heat values of zero.

Table 55: Absorbed heat per hour on a typical day for each season [W] for 1 m^2 of dark window facing south

	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
Winter	1.87	29.92	66.13	85.52	90.34	96.04	96.64	97.06	58.71	19.84	1.93	0.00	0.00
Spring	37.88	51.88	64.98	80.16	94.65	103.08	100.26	92.27	81.81	61.64	34.82	9.43	0.45
Summer	40.46	55.15	65.68	86.56	103.04	111.77	113.05	107.34	94.67	75.19	45.68	13.36	0.35
Autumn	13.91	54.07	88.63	110.14	125.00	131.61	125.85	107.14	84.22	35.20	3.59	0.00	0.00

Similarly, Table 56, Table 57 and Table 58 are built for the other azimuth angles, north, east and west.

Table 56: Absorbed heat per hour on a typical day for each season [W] for 1m^2 of dark window facing north

	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
Winter	1.70	18.35	34.28	39.44	38.21	38.68	37.83	38.27	24.32	9.24	1.10	0.00	0.00
Spring	55.17	60.08	58.51	59.31	61.99	62.57	58.99	55.28	51.97	43.91	30.02	11.15	0.69
Summer	59.54	64.61	59.84	64.44	67.68	67.84	66.34	63.52	59.41	52.71	38.39	15.01	0.51
Autumn	11.24	33.18	46.31	51.39	53.95	54.22	51.12	44.32	36.76	17.18	2.15	0.00	0.00

Table 57: Absorbed heat per hour on a typical day for each season [W] for 1 m^2 of dark window facing east

	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
Winter	4.73	50.29	88.69	92.11	76.12	61.45	42.93	38.27	24.32	9.24	1.10	0.00	0.00
Spring	105.35	139.37	147.50	137.98	121.98	96.71	64.14	55.28	51.97	43.91	29.91	9.31	0.45
Summer	112.57	147.91	150.49	150.95	134.69	106.54	73.74	63.52	59.41	52.71	38.36	13.17	0.35
Autumn	31.88	90.96	118.20	116.33	101.96	78.83	51.47	44.32	36.76	17.18	2.15	0.00	0.00

Table 58: Absorbed heat per hour on a typical day for each season [W] for 1m^2 of dark window facing west

	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
Winter	1.67	18.35	34.28	39.44	38.21	38.68	37.83	50.61	42.66	19.90	2.78	0.01	0.00
Spring	37.88	50.74	56.92	59.31	61.99	62.57	58.99	76.21	94.44	96.63	74.67	24.87	1.24
Summer	40.46	53.71	57.81	64.44	67.68	67.84	66.34	86.09	106.74	115.04	95.24	35.14	0.95
Autumn	11.24	33.18	46.31	51.39	53.95	54.22	52.03	65.45	70.31	39.49	5.60	0.00	0.00

Based on the previous tables it is possible to calculate the absorbed heat from solar radiation once the exposed window area is defined. It is important to consider that in line with the operational profile, the most important season regarding the heat load is summer.

Appendix D. Overhang Design

D.1 Introduction

As stated before, the careful design of the overhang plays a decisive role in the benefits and drawbacks it may have.

Excessively wide overhangs are many times unnecessary since the heat absorption reduction does not have a significant impact on the electric consumption of the air conditioning systems. Furthermore, excessively wide overhangs may have a severe impact on the interior area available, which translates into a reduction of luxury and comfort on board.

The study on the overhang width and shape took into consideration the average overhang size on the benchmark design as the start point. In addition, the study from McCartan & Kvilums (22) considers that overhang sizes below 1.5m are optimal.

Nevertheless, McCartan & Kvilums' study is on a cruise ship, which varies not only in terms of styling and function but also in terms of vessel shape. This means that interior area reduction in that case is not as expressive as it is in the super yacht case.

The effect of the overhang in terms of heat gains is translated in the height of the shadow it produces on the windows, thus it also depends on the window's height. As a result, the different locations and heights of windows translate into different optimal widths.

Two different shapes for the overhang have been considered, horizontal and L-shaped (Figure 47 & Figure 48, respectively)

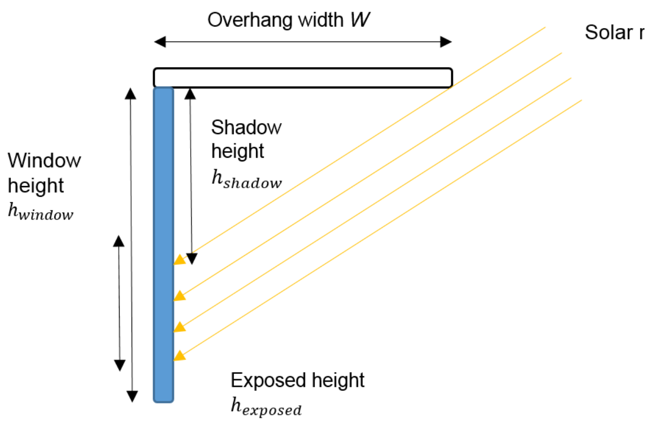


Figure 47: Horizontal Overhang

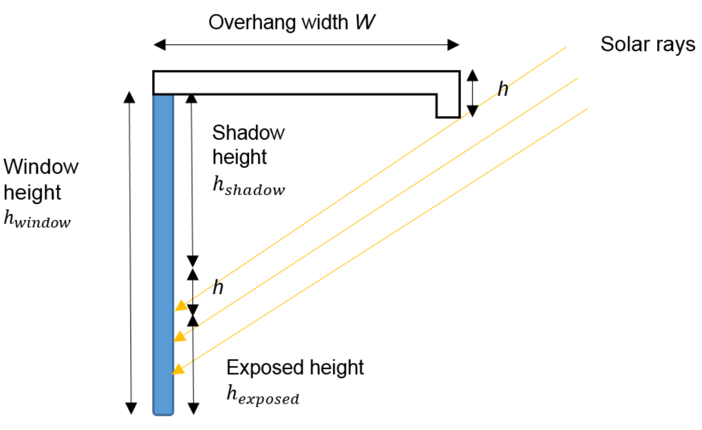


Figure 48: L-shaped Overhang

The L-shaped overhang's main advantage is the increase in shadow height without an increase in overhang width, thus without any interior area reduction. This feature is mainly applied in full height window salon area case since the need for shadow heights is greater and the impact on views shorter.

On the other hand, the L-shaped overhang causes an increase in the construction weight, even though the increase is marginal it has to be bounded. Moreover, too large L-shaped overhangs may have an impact on natural light and exterior views. Therefore, h is bounded to a maximum of 0.1m.

The height exposed to the sun light, thus to solar radiation is defined by Equation 36. The larger the exposed height, the larger the radiation absorbed by the spaces.

$$h_{exposed} = h_{window} - (h_{shadow} + h)$$

Equation 36

Due to the curved non-linear shapes of yacht's superstructures the overhang width is not continuous over the length of the yacht. In order to allow some flexibility in to the design, for each case an interval of overhang width is defined instead of a single width.

In addition, for the same reason, different areas are assigned with different overhang width intervals. On the main deck two areas are distinguished, the saloon area and the owner's area. The wheelhouse deck is considered as a whole even though it can be divided in two areas, the saloon and pilot house area, the overhang width lays within the same interval.

The impact of overhang is calculated based on the formulation described in Appendix A, considering a tilt angle of 0^{o} for the overhang and 90^{o} for the considered window.

Since the goal of the project is not to deeply study the matter of heat absorption, only a primary study is made considering the worst case scenario of a south facing window. It is worth noticing that in the future, deeper studies on the matter may lead to further improvements.

D.2 MAIN DECK OVERHANG

D.2.1 SALON AREA

The salon area on main deck is characterized by long full height windows, thus more glazing area is exposed to solar radiation, increasing the importance of maximizing the shadow height.

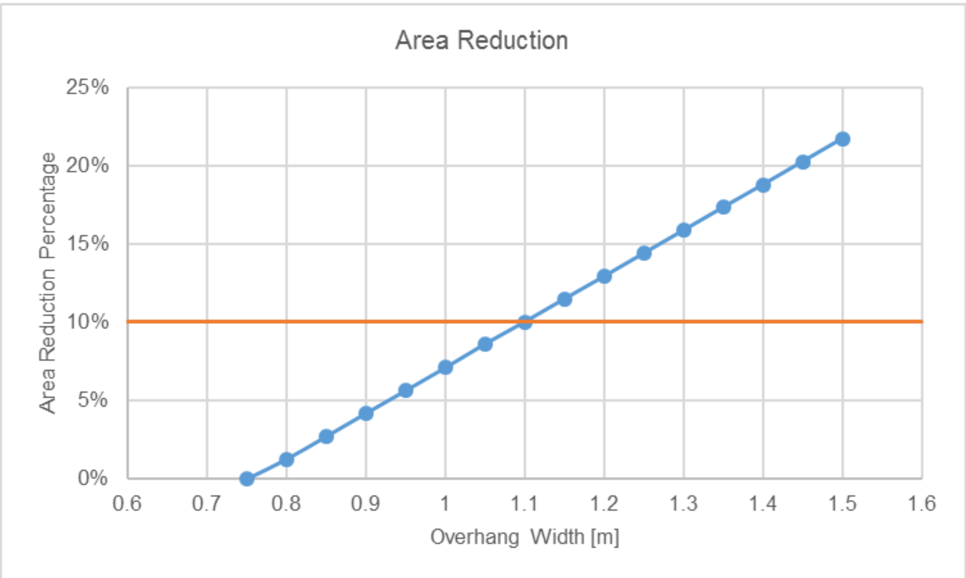


Figure 49: Area reduction percentage due to overhang width

As stated before, the maximum allowable area reduction is 10% in relation to the area corresponding to the original overhang width. For this reason, the area reduction percentage due to an increased overhang width is presented on Figure 49.

As it can be seen, for overhang widths higher than 1.1 m the area reduction from the reference area is approximately 10%.

The impact of the overhang varies with the orientation and location of the vessel, as stated before, for this primary study the worst case scenario of south facing windows. Moreover, it also varies with the time of the day.

Figure 50 shows the variation of heat absorbed throughout the day depending on the overhang width.

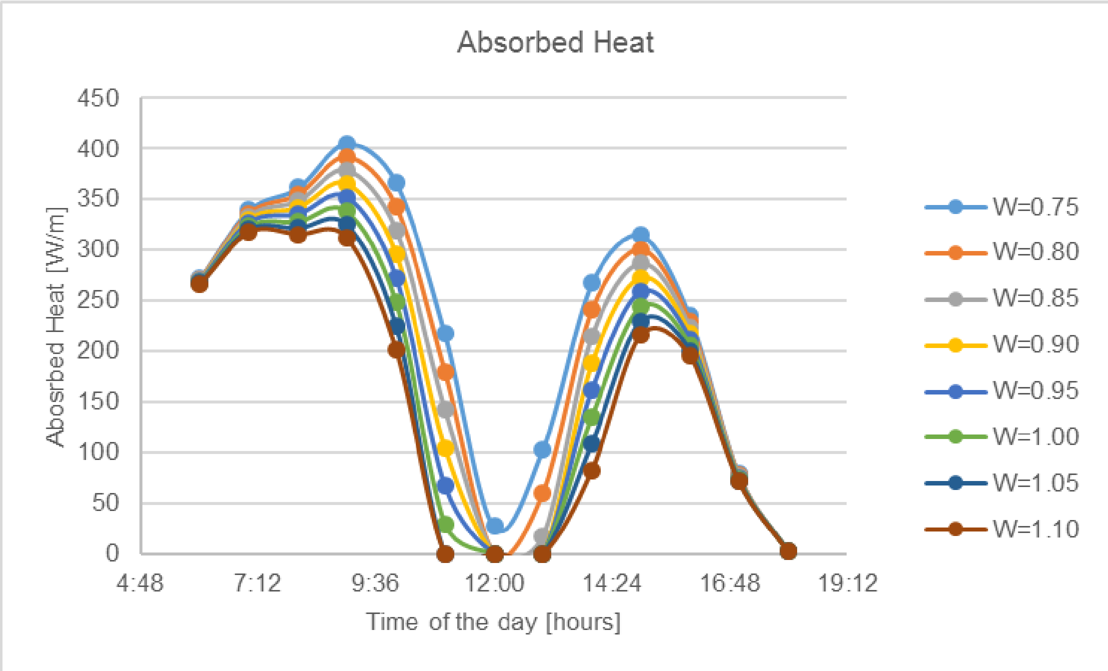


Figure 50: Absorbed Heat [W/m] variation throughout the day

From Figure 50 it is possible conclude that the effect of the overhang is more significant during the moments it is able to provide a shaded environment for the whole window, thus avoiding radiation to penetrate the space.

In addition, the impact of an increase of 0.05m is lower after 0.9m, therefore the optimal interval for the salon area on main deck is between 0.9m and 1.1m, the maximum allowable in terms of area reduction.

On a daily basis, by changing the overhang shape from horizontal to L-shaped it is possible to achieve extra savings in the heat absorbed between 7% and 8%. Overall, on a daily basis it is possible to save between 17% and 40% in comparison with the original overhang width.

D.2.2 Owner Area

Due to the form of the hull and superstructure, the interior area problem becomes more critical as approaching the owner area. Moreover, reducing the area available for the owner can became rather a delicate issue when going to the market.

While in the salon area a “balcony” area already exists, in the owner area this is not the case. Consequently, there are two options, either a marginal increase or a large increase to overhang that would allow the creation of a balcony area.

As stated before, interior area in this case is critical, thus a balcony space creation is not an option. It is worth mentioning that for alternative general arrangements, where more freedom is allowed, this might be an interesting option to consider.

Contrarily to what happens in the salon area, on the owner area the windows are not full height. The fact that shorter windows are considered contributes to mitigate the effect of shorter overhang widths by reducing the area exposed to solar radiation.

The choice of not creating a balcony area leaves a small room for an increase in overhang width, thus it is only possible to increase from 0.1m to 0.2m due to construction issues. Nonetheless, this marginal increase to overhang width translates in an approximate reduction of 8% in the absorbed heat on a daily basis during summer.

D.3 WHEELHOUSE DECK OVERHANG

The wheelhouse deck has a combination of full and half height windows, on the salon and pilot house area respectively. However, for symmetry and building purposes the overhang width is the same range in both areas.

Once more, the overhang width cannot implicate an area reduction higher than 10% in relation to area considering the reference overhang width.

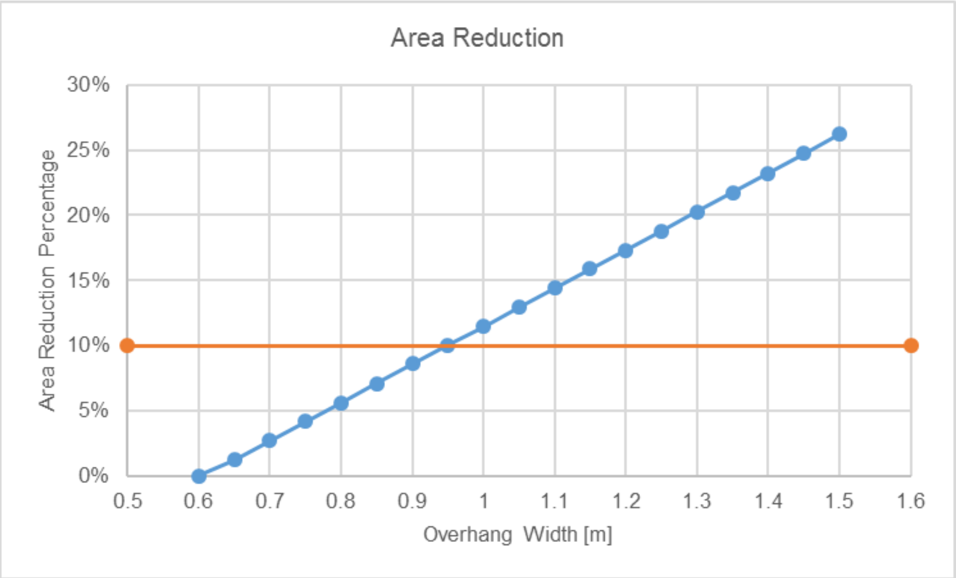


Figure 51: Area reduction percentage due to overhang width on wheelhouse deck

From Figure 51 it is possible to see that the 10% area reduction is achieved when the overhang width is 0.95m. Therefore, the range for the overhang width will be limited to 0.95m.

Once more, higher overhang widths result in less absorbed heat. From Figure 52, it can be seen that higher benefits can be achieved when the overhang is wider than 0.9m since the windows are full shaded for a longer period.

Consequently, for the wheelhouse deck the optimal interval considered is shorter when compared to the one on the main deck, ranging from 0.9m to 0.95m.

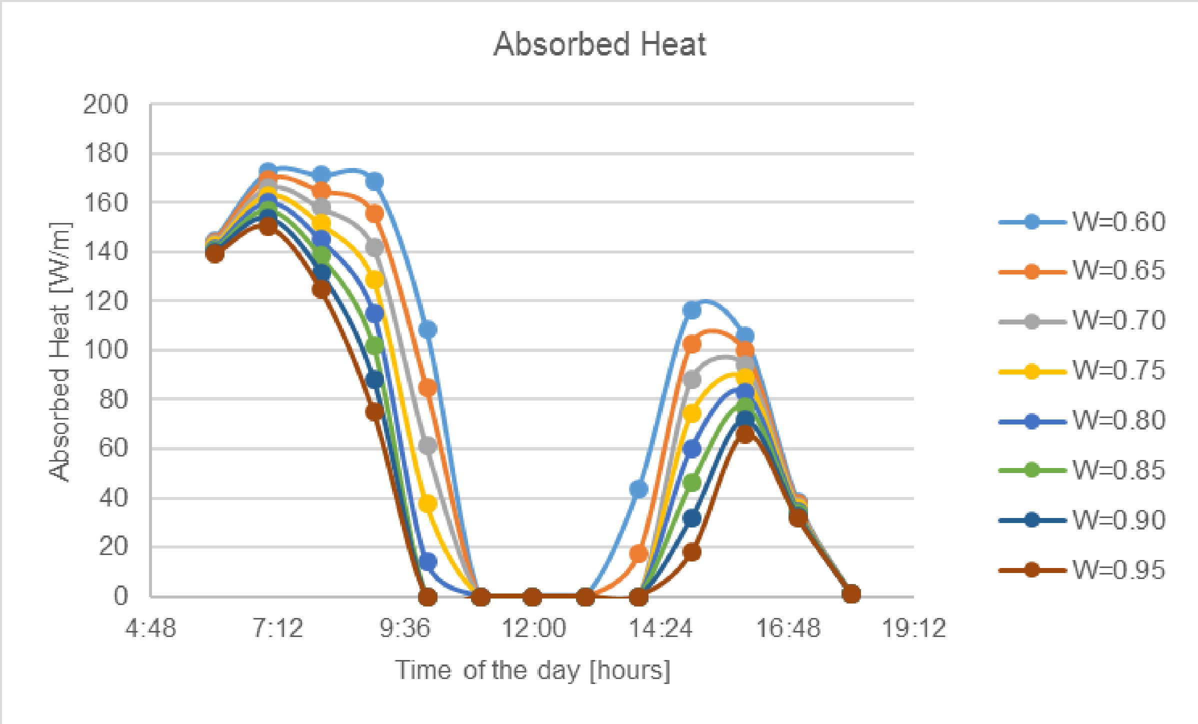


Figure 52: Absorbed Heat [W/m] variation throughout the day

For this reason, and for the fact that on the wheelhouse deck, especially on the pilot house area, it is possible to increase overhang without reducing the interior area, the overhang width may be increased when no area reduction follows.

On a daily basis, the increase in overhang to the specified range resulted in savings between 33% and 46%. Furthermore, the L-shaped overhang led to extra savings of about 6%.

Appendix E. STABILIZERS COMPARISON

E.1 POWER REQUIREMENT VARIATIONS DUE TO STABILIZERS

By estimating the resistance of the yacht for the four different scenarios it is possible to predict the power requirements, thus fuel consumption. The following tables present the resistance data and resultant power requirements for the three gyroscope options and for the stabilizing fins option.

Table 59: Resistance Components

Speed [knots]	Integrated Appendage factor	Appendage Resistance [kN]	Fin Resistance [kN]	Still Air Resistance [kN]
6	1.08	0.38	0.46	0.32
8	1.08	0.72	0.78	0.57
10	1.08	1.58	1.17	0.89
12	1.08	1.73	1.64	1.26
13	1.08	2.10	1.91	1.50
14	1.08	2.46	2.19	1.74
16	1.08	3.28	2.80	2.27

Table 60: Gyroscope Option 1

Speed	Bare Hull Resistance [kN]	Total Resistance [kN]	RPM engine	P_B [kW]
6	6.43	7.65	581.49	35.26
8	13.07	15.40	795.33	95.10
10	21.73	25.94	1009.65	200.30
12	31.69	37.22	1206.15	342.33
13	38.19	44.84	1319.12	450.15
14	44.93	52.72	1424.72	570.32
16	60.99	71.42	1641.76	885.34

Table 61: Gyroscope option 2

Speed	Bare Hull Resistance [kN]	Total Resistance [kN]	RPM engine	P_B [kW]
6	6.39	7.60	582.04	35.07
8	12.98	15.31	795.99	94.57
10	21.55	25.75	1010.12	198.87
12	31.43	36.94	1206.66	339.82
13	37.87	44.49	1319.62	446.75
14	44.55	52.31	1425.23	565.99
16	60.47	70.85	1642.20	878.35

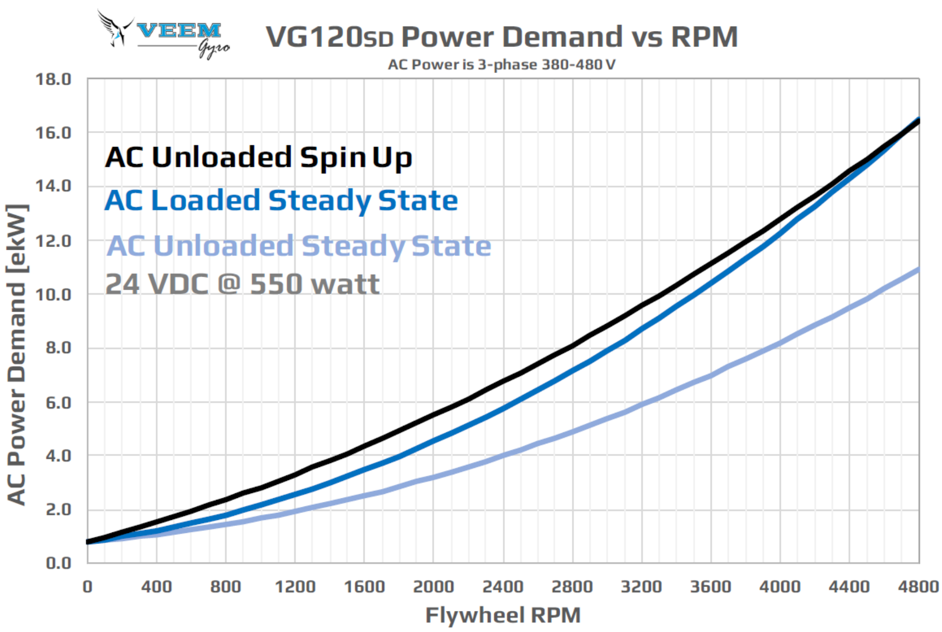
Table 62: Gyroscope option 3

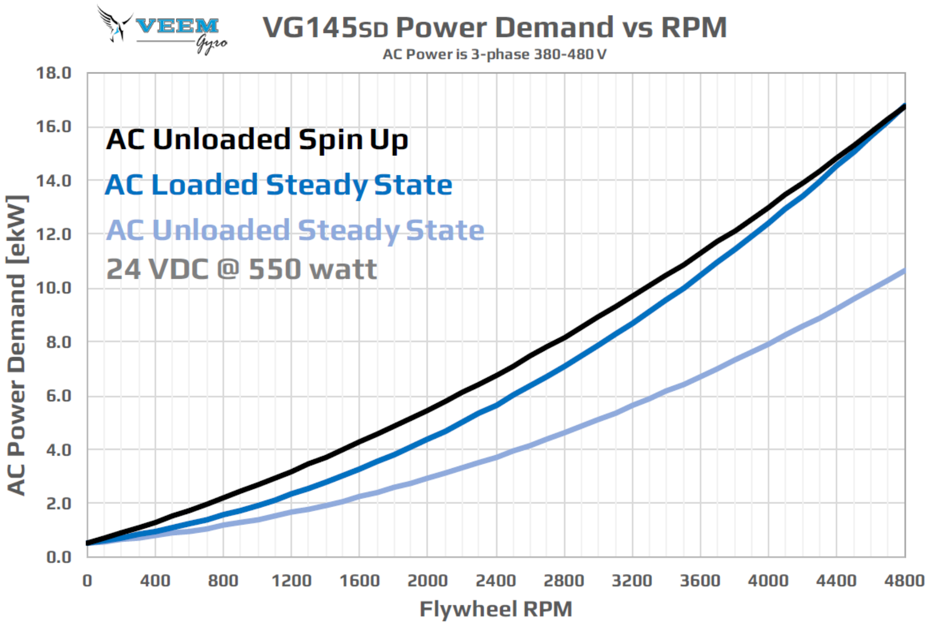
Speed	Bare Hull Resistance [kN]	Total Resistance [kN]	RPM engine	P_B [kW]
6	6.42	7.63	581.70	35.19
8	13.04	15.37	795.59	94.89
10	21.66	25.86	1009.84	199.74
12	31.59	37.11	1206.35	341.34
13	38.06	44.71	1319.32	448.82
14	44.78	52.56	1424.92	568.62
16	60.79	71.20	1641.93	882.60

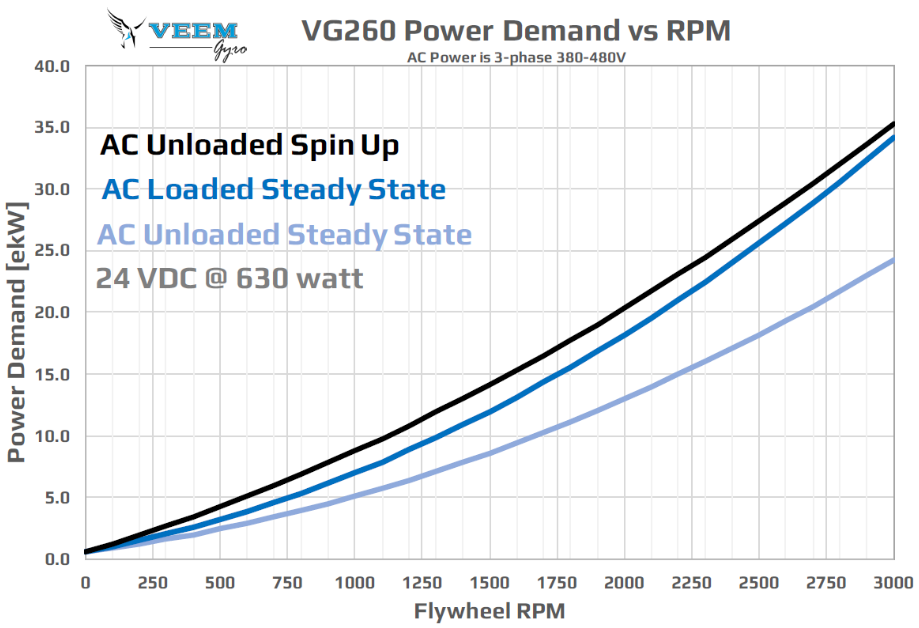
Table 63: Stabilizing Fins option

Speed	Bare Hull Resistance [kN]	Total Resistance [kN]	RPM engine	P_B [kW]
6	6.26	7.92	584.79	36.51
8	12.72	15.80	798.70	97.64
10	21.02	26.34	1011.86	203.47
12	30.65	37.73	1208.40	347.22
13	36.91	45.37	1321.03	455.61
14	43.42	53.28	1426.47	576.61
16	58.91	71.97	1642.76	892.34

E.2 LOADING CONDITION OF GYROSCOPES




VEEM Gyro
VG145SD Power Demand vs RPM
AC Power is 3-phase 380-480 V
AC Unloaded Spin Up
AC Loaded Steady State
AC Unloaded Steady State
24 VDC @ 550 watt
AC Power Demand [ekW]
Flywheel RPM
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
0
400
800
1200
1600
2000
2400
2800
3200
3600
4000
4400
4800

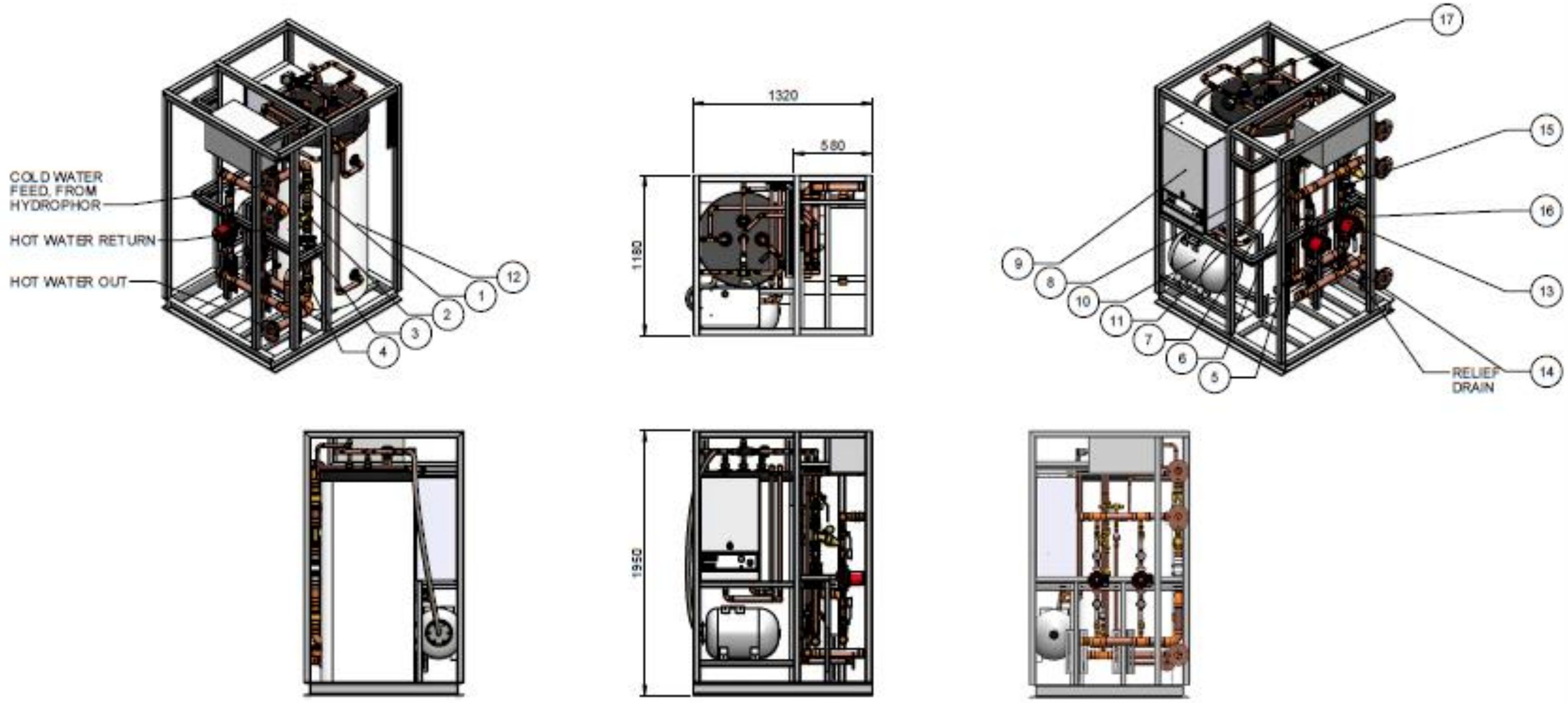

VEEM Gyro
VG260 Power Demand vs RPM
AC Power is 3-phase 380-480V
AC Unloaded Spin Up
AC Loaded Steady State
AC Unloaded Steady State
24 VDC @ 630 watt
Power Demand [ekW]
Flywheel RPM
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000

Appendix F. WATER SYSTEMS

F.1 CONSUMPTION DATA (36)

Power Consumption/ Cylinder configuration	9kW	15kW	22kW	28kW	36kW
1 boiler + 1 x 320 ltr	513 (194)	615 (301)	778 (473)	901 (602)	1064 (774)
2 boiler + 2 x 320 ltr	1026 (388)	1230 (602)	1556 (946)	1802 (1204)	2128 (1548)
3 boiler + 3 x 320 ltr	1539 (582)	1845 (903)	2334 (141)	2703 (1806)	3192 (2322)
1 boiler + 1 x 600 ltr	740 (194)	842 (301)	1006 (473)	1128 (602)	1292 (774)
2 boiler + 2 x 600 ltr	1480 (388)	1684 (602)	2012 (946)	2256 (1204)	2684 (1548)

F.2 DIMENSIONS OF BOILER SETS



NOTE

FLOW METERS AND COMBINED PRESSURE / TEMPERATURE GAUGES FITTED FOR PERFORMANCE ANALYSIS. ALL DHW RELIEF LINES COMBINE INTO ONE COMMON OULET AT SAME LOCATION AS HOT/COLD MAINFOLDS. EXPANSION TANKS CAN BE RELOCATED USING SUITABLE FLEXIBLE HOSE.

ITEM NO	DESCRIPTION
1	COLD FEED, DN50 BALL VALVE
2	COLD FEED, DN50 PRESSURE REDUCTION VALVE WITH TEMP+PRES GAUGE
3	COLD FEED, DN50 NON RETURN VALVE
4	COLD AND HOT WATER RETURN, DN50 BALL VALVE
5	HOT WATER OUT, DN25 BALL VALVE
6	DN25 FLOW REGULATOR AND FLOW METER GAUGE
7	MULTIPORT VALVE, INC EXPANSION TANK CONN, NON RETURN
8	PRESSURE RELIEF VALVE WITH PRESSURE GAUGE
9	ACV E-TECH W 36 KW PRIMARY FLOW HEATER, WITH PRIMARY EXPANSION

ITEM NO	DESCRIPTION
10	DHW EXPANSION TANK, 50 LITRE
11	VENTED SIGHTGLASS / TUNDISH
12	ACV HRS321 HOT WATER CYLINDER
13	GRUNDFOS RECIRCULATION PUMPS
14	DN25 RECIRCULATION NON RETURN VALVE
15	DN25 RECIRCULATION BALL VALVE
16	COLD AND HOT WATER RETURN, DN25 BALL VALVE
17	TEMPERATURE / PRESSURE SAFETY VALVE

TRIPLE BOILER (FLOW HEATER, DHW CYLINDER) ASSEMBLY PERFORMANCE CHARACTERISTICS:

POWER:	36KW TOTAL
NOMINAL SUPPLY:	3 PHASE X 400 VOLT + N (42 PER PHASE)
TOTAL CAPACITY:	318 LITRES TOTAL
40°C LITRES IN FIRST 10 MINS:	707 LITRES TOTAL
40°C LITRES IN FIRST HOUR:	1506 LITRES TOTAL
40°C CONTINUOUS FLOW:	1032 LITRES TOTAL
ESTIMATED DRY WEIGHT:	500 KG
ESTIMATED WET WEIGHT:	871 KG

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WEB: www.cathelco.com

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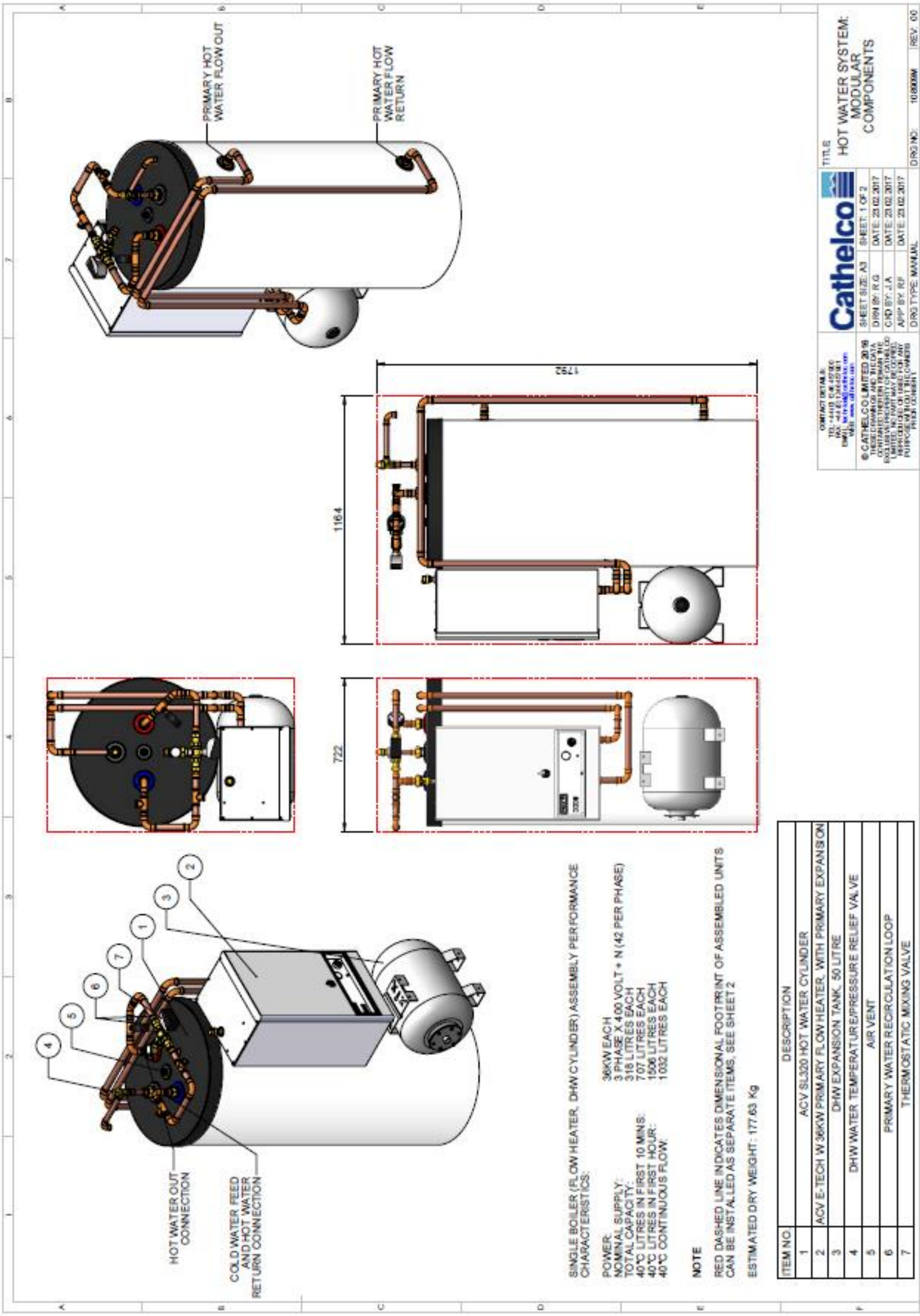
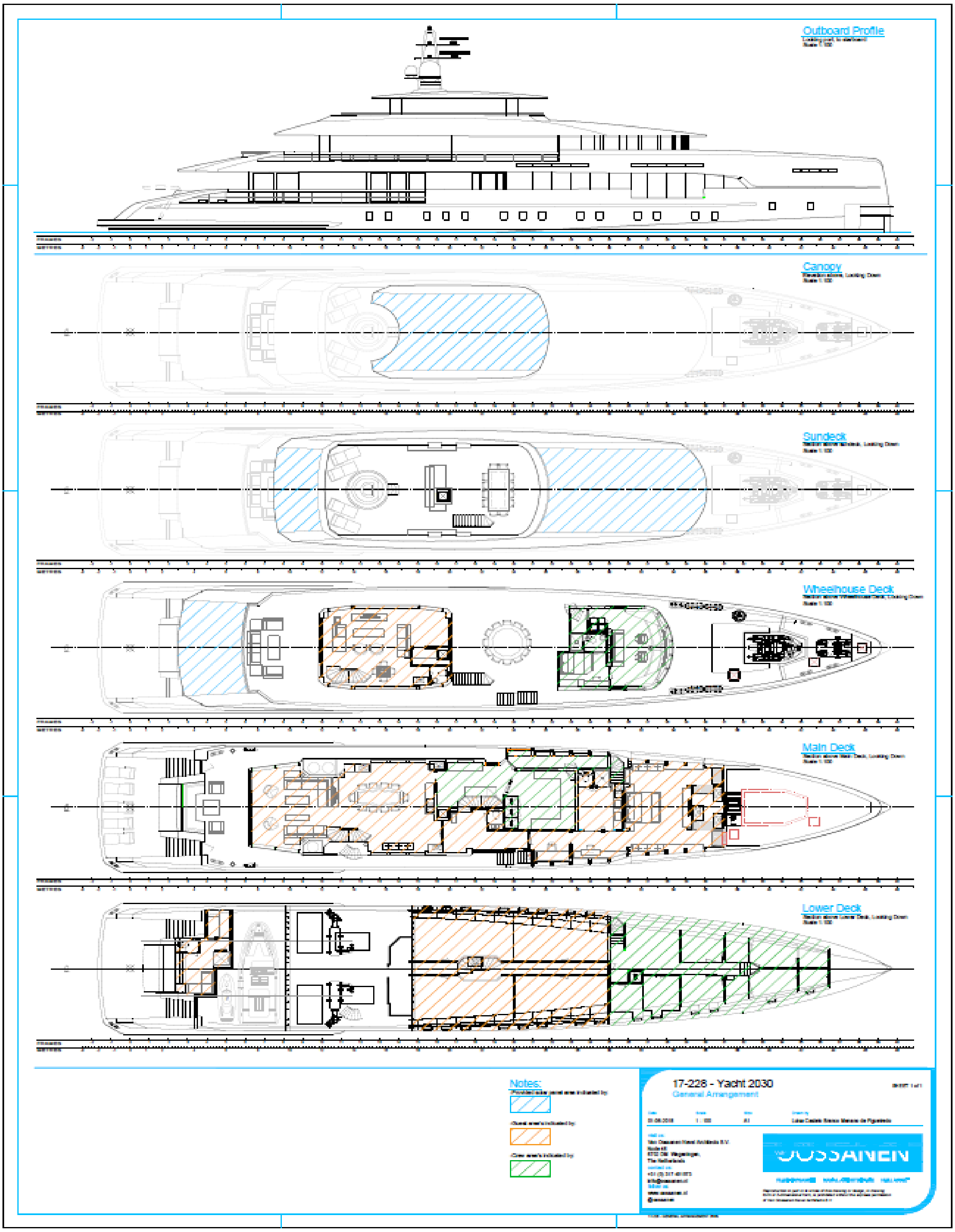
Cathelco

SHEET SIZE: A3	SHEET: 1 OF 3	TITLE: HOT WATER SYSTEM: 1 CYLINDER SKID MOUNTED
DRN BY: R.G	DATE: 02.02.2017	
CKD BY: J.A	DATE: 02.02.2017	
APP BY: RF	DATE: 02.02.2017	
DRG TYPE: MANUAL	DRG NO: 10888IM	REV: 01

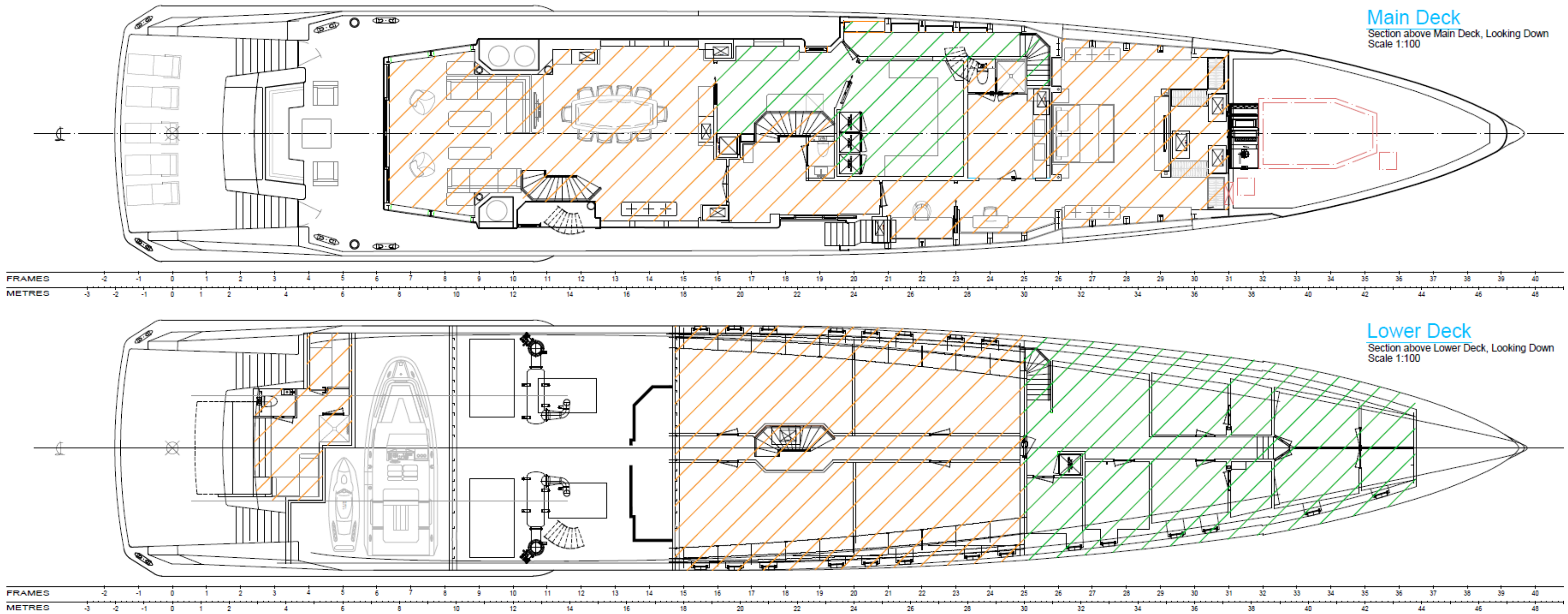

HOT WATER OUT CONNECTION
COLD WATER FEED AND HOT WATER RETURN CONNECTION
PRIMARY HOT WATER FLOW OUT
PRIMARY HOT WATER FLOW RETURN
722
1164
1792
SINGLE BOILER (FLOW HEATER, DHW CYLINDER) ASSEMBLY PERFORMANCE CHARACTERISTICS:
POWER: 36KW EACH
NOMINAL SUPPLY: 3 PHASE X 400 VOLT + N (42 PER PHASE)
TOTAL CAPACITY: 318 LITRES EACH
40°C LITRES IN FIRST 10 MINS: 707 LITRES EACH
40°C LITRES IN FIRST HOUR: 1506 LITRES EACH
40°C CONTINUOUS FLOW: 1032 LITRES EACH
NOTE
RED DASHED LINE INDICATES DIMENSIONAL FOOTPRINT OF ASSEMBLED UNITS CAN BE INSTALLED AS SEPARATE ITEMS, SEE SHEET 2
ESTIMATED DRY WEIGHT: 177.63 Kg
ITEM NO / DESCRIPTION
1 ACV SL320 HOT WATER CYLINDER
2 ACV E-TECH W 36KW PRIMARY FLOW HEATER, WITH PRIMARY EXPANSION
3 DHW EXPANSION TANK, 50 LITRE
4 DHW WATER TEMPERATURE/PRESSURE RELIEF VALVE
5 AIR VENT
6 PRIMARY WATER RECIRCULATION LOOP
7 THERMOSTATIC MIXING VALVE
Cathelco
TITLE
HOT WATER SYSTEM: MODULAR COMPONENTS
SHEET SIZE: A3 SHEET: 1 OF 2
DRN BY: R.G DATE: 23.02.2017
CKD BY: J.A DATE: 23.02.2017
APP BY: R.F DATE: 23.02.2017
DRG TYPE: MANUAL
DRG NO: 108099M REV: 00

Appendix G. General Arrangement

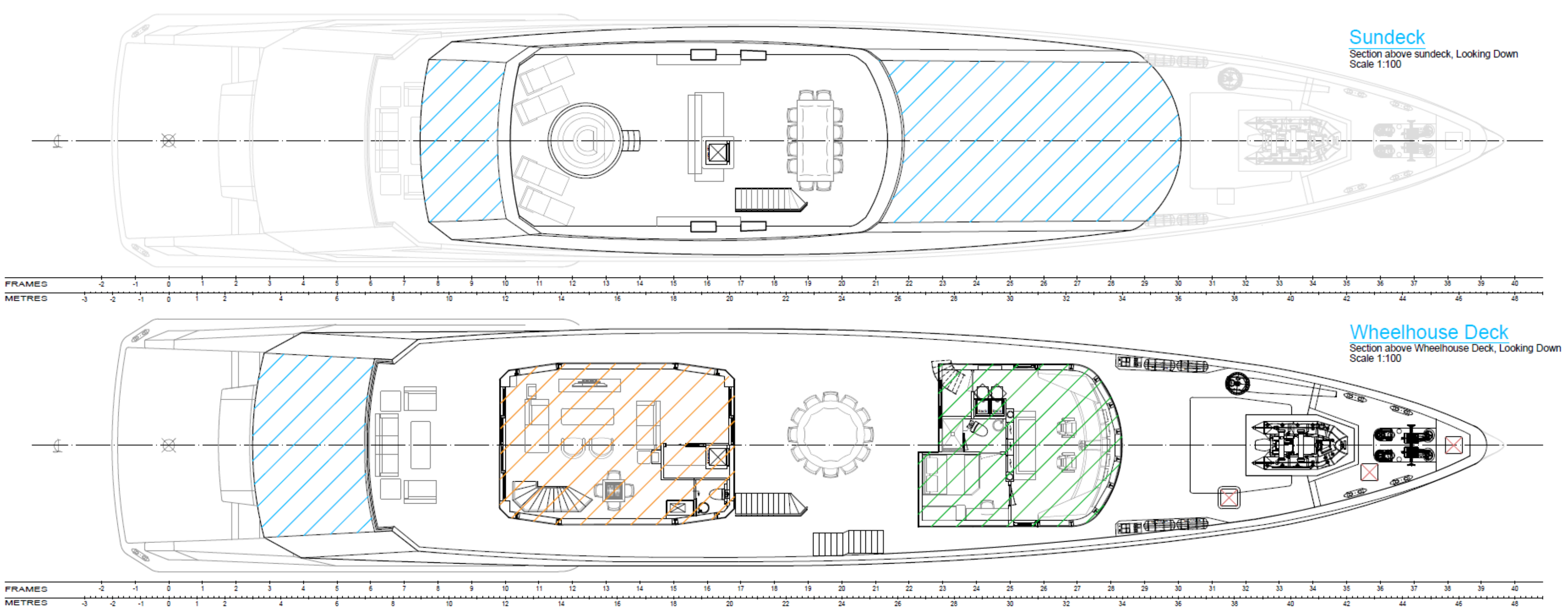
G.1 Overview



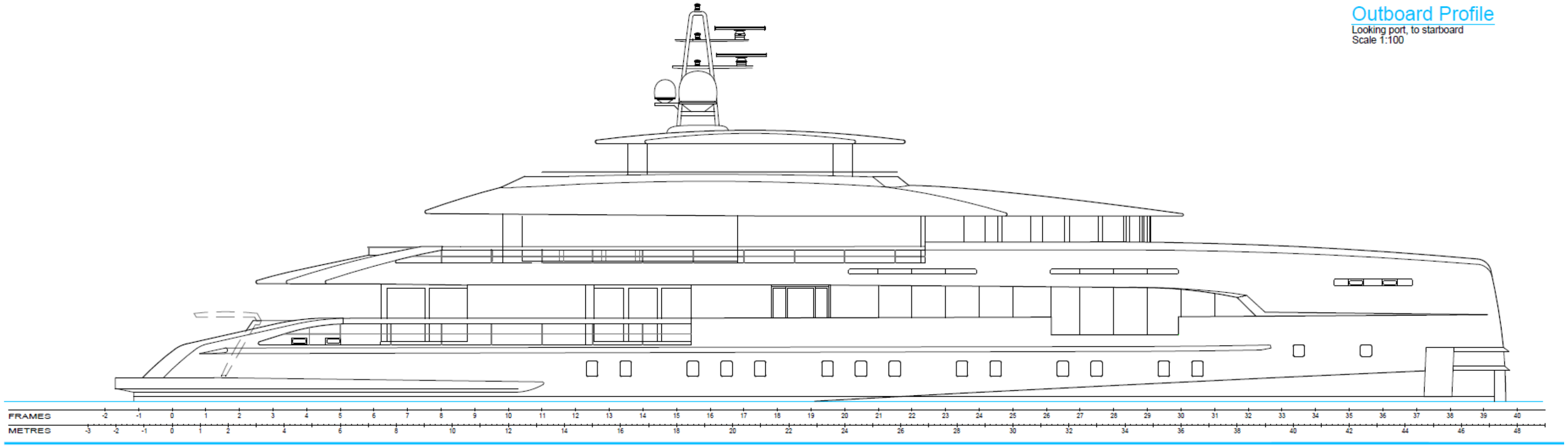
G.2 Lower and Main Deck

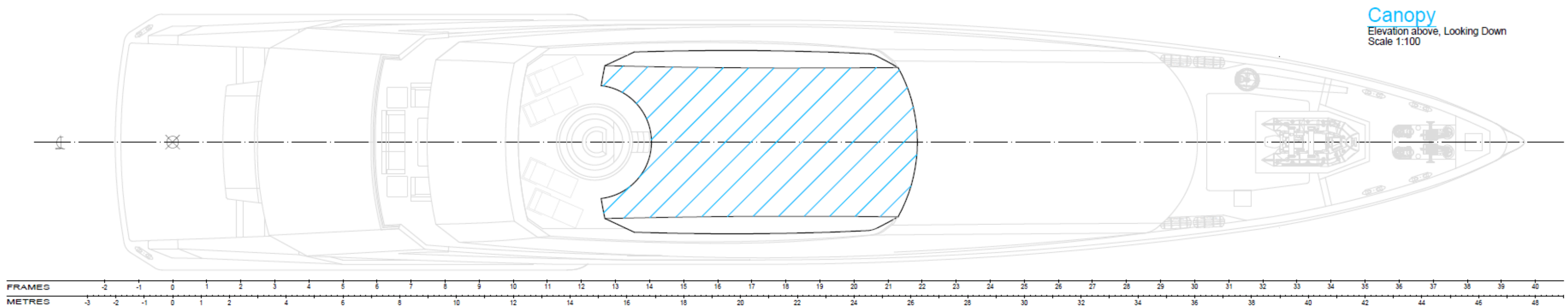


G.3 WHEELHOUSE AND SUNDECK



G.4 CANOPY AND OUTBOARD PROFILE





Appendix H. DECK AREA'S DATA

H.1 REFERENCE

	Area [m²]
Accommodation Lower Deck	**252**
Lazarette / Beach Club	18
Guest Accommodation	95
Crew Area	42
Tender garage	39
Engine Room	58
Main Deck	**172**
Owner's Stateroom and Bathroom	55
Galley	12
Pantry	6
Corridor & Stores	17
Day Toilet & Hallway	14
Salon & Dinning	68
Wheelhouse Deck	**77**
Wheelhouse, emergency generator & switchboard	28
Hallway & Day toilet	9
Captain's cabin	10
Salon	30
Exterior area on wheelhouse deck	126
Sun Deck	**81**
Swimming Platform	**6**

H.2 New Design

	Area [m²]
Accommodation Lower Deck	**266**
Lazarette / Beach Club	16
Guest Accommodation	93
Crew Area	62
Tender garage	34
Engine Room	61
Main Deck	**164**
Owner's Stateroom and Bathroom	56
Galley	17
Pantry	12
Corridor	7
Day Toilet & Hallway	12
Salon & Dinning	60
Wheelhouse Deck	**74**
Wheelhouse, emergency generator & switchboard	21
Hallway on wheelhouse	2
Captain's cabin	10
Salon	41
Exterior area on wheelhouse deck	**137**
Sun Deck	**90**
Swimming Platform	**25**

Appendix I. SCIENTIFIC PAPER

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