THE YACHT OF 2030:

HOW MUCH CO_2 EMISSION REDUCTION IS POSSIBLE TODAY?

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ABSTRACT

Nowadays, greenhouse gas emissions' reduction is on the agenda in all sectors of economy and the Marine industry is no different. Reason why the IMO outlined a strategy aiming for a 50% reduction by 2050.

In line with that, this project pretends to uncover how large can the CO_2 emission reduction be by combining today's available strategies in terms of power demand reduction and cleaner power supply alternatives. All this in a 50m super yacht with a gross tonnage below 500GT, so that it is eligible for the reduced regulatory framework.

The combination of a 33% reduction in auxiliary power demand, a reduction in propulsion power demand between 50-70% and the savings achieved by implementing a hybrid power plant arrangement resulted in a reduction of annual CO_2 emissions by 41%.

1. INTRODUCTION

The growing awareness for environmental issues together with the 2.2% share of CO_2 emissions accountable to the shipping sector led the IMO to draw a set of strategies aiming to reduce the sector's emissions in phases. (1) The end goal of the program is to have a reduction of 50% by 2050 in relation to the global levels measured in 2008.

In spite of the fact that the yachting sector is not yet included in the emission regulations is not inhibiting the sector to search for alternatives to achieve CO_2 emissions reduction. Actually, the yachting industry has been characterised over the years as being in the forefront of technological development, thus regarding environmental issues this is no different.

In line with this, the research question pretends to uncover how much of the CO_2 emissions of a 50m yacht under 500GT is it possible to reduce today by applying readily available state of the art technology and still have a commercially attractive super yacht.

The gross tonnage requirements play a decisive role in this research due to the reduced regulatory framework for under 500GT super yachts in terms of fire protection, crew area requirements, crewmember requirements (2).

The reduction of CO_2 emissions was performed in two phases. Firstly, in terms of power demand reduction. On the one hand, looking into the auxiliary systems, reducing their power demand. On the other hand, reducing the propulsion power demand improving the performance of the yacht. Secondly, by looking in terms of alternative power supply sources or configurations, enhancing fuel savings or introducing alternative cleaner power sources to achieve the end goal of CO_2 emissions reduction.

The performance of the end design is compared to the one of a chosen benchmark and is done in terms of three performance parameters. Primarily, in terms of energy efficiency measured by the annual CO_2 emissions. Secondly, in terms of luxury, measured by the available interior area. Finally, in terms of costs, both investment and running costs.

The first step is to define the operational profile of the super yacht. The reason for this lays on the fact that contrarily to what happens in the shipping sector, a super yacht has a variable operational profile, varying from being cruising at transit speed to sailing at maximum speeds or spending long periods in port or at anchorage. (3)

2. The Operational Profile

The definition of the operational profile was performed based on data collected from the Marine Traffic (4) for ten different yacht within the length range of the benchmark design, thus 40 to 60 meters. Six operational modes were considered:

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

The operational profile of a super yacht can be very challenging since it is dependent on a number of factors that are mostly unpredictable such as owner wishes. However, one of its most important characteristics is that the time spent at anchorage covers a significant percentage of the operational time. (5)

The variability of the operational profile led to a large amplitude in terms of maximum and minimum percentages of time spent at each mode as it can be seen from Figure 2. For this reason, the average points at each mode were taken, Figure 1. Nevertheless, the sensitivity of the results in relation to the operational profile were analysed through a scenario analysis in a later stage.

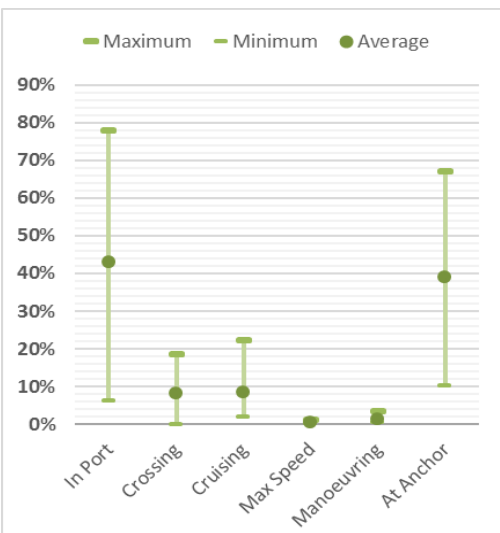

Figure 2: Operational Profile range per Operating mode

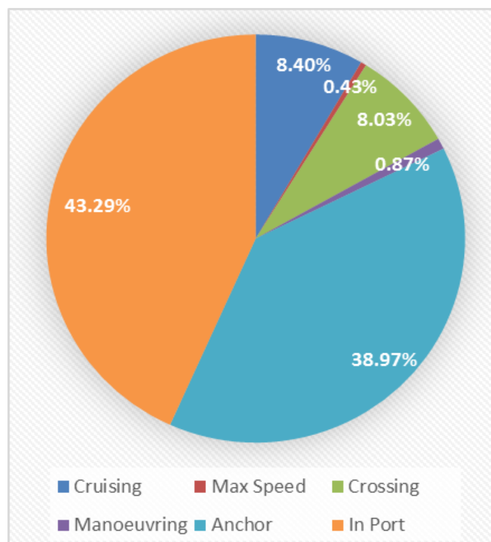

Figure 1: Operational Profile

In line with literature, the most significant part of the operational time is spent either in port or at anchorage. The CO_2 emitted while in port is left out of scope since it is assumed that the yacht is on shore power and no emissions rate data is available. Nevertheless, the reduction of auxiliary power demand will ultimately lead to a reduction of emissions from the port side as well.

Regarding the sailing modes, even though trends point to higher maximum speed requirements, these are sailed only for a short period as it can be seen from Figure 1. 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.

3. Answering the Research Question

Once defined the operational profile it was possible to start answering the research question by identifying the operational modes that have a more significant impact into the yearly emissions. This way it was possible to focus on reducing the emissions of the operational modes that would translate in larger reduction of CO_2 emissions. This is based on the specifications and CO_2 emissions of a benchmark design.

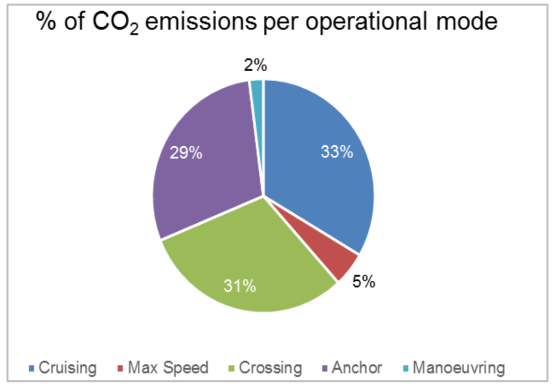

Figure 3: Percentage of Co_2 emitted per Operational Mode

From Figure 3, cruising, crossing and anchorage modes were identified as the modes at which the CO_2 emissions have a larger impact on the yearly emissions. The fact that at anchorage only auxiliary power is consumed together with impact the mode has on yearly emissions pointed at the direction that reducing the power demand of the auxiliary systems could bring significant gains when reducing the CO_2 emissions. Reason why this was the first question to be answered.

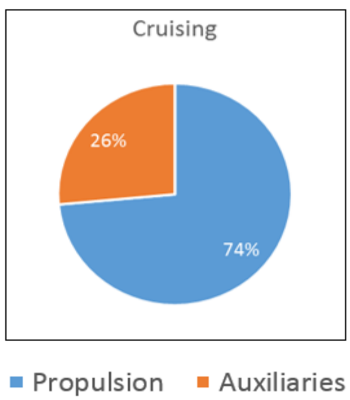

Figure 4: Percentage of auxiliary and propulsion power demand while at cruising

Nevertheless, when considering operational modes at which the yacht is sailing such as cruising, the percentage of power consumed by the yacht is significantly higher than the one consumed by the auxiliary systems (Figure 4). Therefore, reduction of propulsion power demand plays a significant role in emissions reduction and it was the second question to be answered.

After reducing the power demand, the power supply was analysed. In this analysis alternative fuels, renewable energies and different power plant configurations were taken into consideration in order to achieve the better performing design in all three parameters.

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

The analysis of the auxiliary power demand started with the analysis of the electric load balance of the benchmark design. Figure 5 show the power demand of each consumer group per operational mode, this way it was possible to identify the heavy consumers.

The first consumer to be indentified was the air systems group since it is the heaviest consumer at all operational modes. To reduce the consumption of the air systems two different approaches were taken. Firstly, reducing the heat absorbed by the yacht was possible to reduce the load on the air conditioning systems and this way reduce its consumption. After that, more efficient equipment was introduced to further reduce the power demand of the air systems.

The heat absorbed was reduced by improving the type of glass and increasing the overhang widths, thus increasing the shaded areas on the sides of the superstructure. This way the incident solar radiation was reduced, hence reducing the absorbed heat by the spaces and consequently reducing the demand on the air conditioning systems.

In terms of equipment, an absorption heat wheel exchanger was introduced in the fresh air unit for the pre-conditiong of the incoming air through the out-going air. The change in the fresh air unit results in a larger and heavier unit, however it reduces the cooling demand for the chiller from 120kW to 90kW. As a result, it was possible to reduce the size of the chiller unit, thus its electric consumption by 8 ekW.

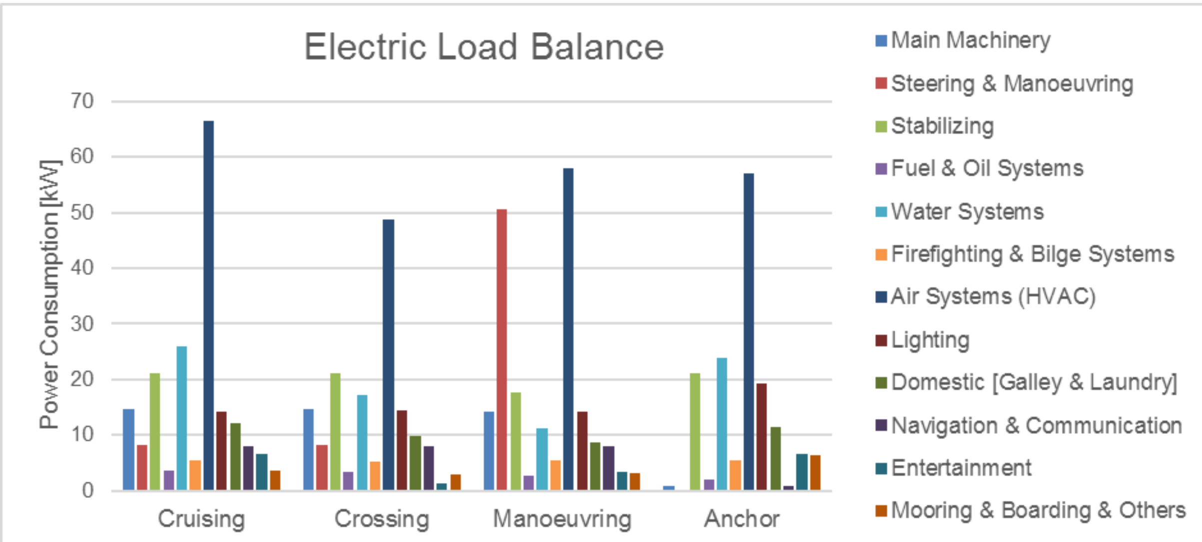

Figure 5: Electric Load Balance of the Benchmark design

All together the changes in the air systems resulted in 13% reduction in overall electric power demand from the auxiliary systems.

Afterwards, the steering and manoeuvring systems were identified as the second highest consumer group, however only during manoeuvring. Therefore, as the manouevring operational mode is only sailed for 1.3% of the time, the impact on yearly emissions of this consumer group is nearly insignificant, reason why they were not analysed.

Subsequently, the stabilizing systems were identified. In this case, the market is dominated with two types of stabilizing systems, gyroscopes and stabilizing fins. The fact that their performance goes hand in hand and the investment cost and the volume of gyroscopes is higher when compared to the stabilizing fins led to the decision of maintaing the stabilizing fins system as in the benchmark design.

Next, the lighting systems were identified. In the case of the lighting systems, LED lighting is already a mature and intensively applied startegy in both architecture and marine industries, thus the benefits of LED lighting were expected, especially considering the more than 300 light bulbs that the yacht is fitted with. Furthermore, occupancy sensors and dimming controls were applied according to (6). This resulted in savings between 5% and 10% in terms of overall auxiliary power demand.

Finally, the water systems were identified as a heavy consumer group, mainly due to the boiler's consumption. Similiarly to the air systems two different approaches were taken to reduce the power consumption from the water systems. On the one hand, the overall water consumption of the yacht was reduced by applying low flow fixtures, which were able to reduce the water flow and still maintain the comfort level. On the other hand, tank in tank technology (7) as an alternative to conventional storage systems was introduced, enabling the storage of hot water at higher temperatures. This together with mixing valves reduces the load on the boilers. Furthermore, by the combination of acumulator capacity and boiler power chosen (320L with 13 kW) resulted in the reduction of the number of boilers from three to two boiler units.

Individually, the impact of the power reduction of each consumer group is low. Nonetheless, when combined in the same design these changes are able to reduce the power consumption between 15% and 35% depending on the operational mode considered (Figure 6).

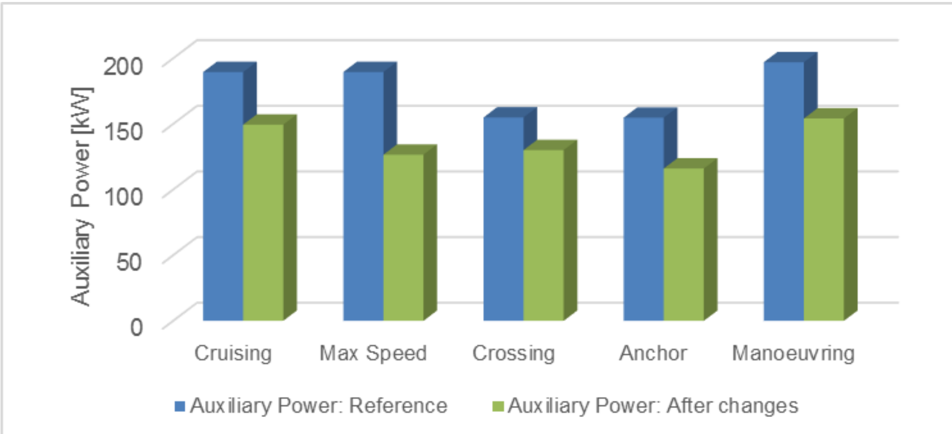

Figure 6: Auxiliary power before and after changes

3.2. HOW MUCH OF THE PROPULSION POWER DEMAND IS IT POSSIBLE TO REDUCE?

In terms of propulsion power the performance of the same benchmark is taken into consideration. The benchmark design was a full displacement 45m yacht.

The first step into improving the performance of the yacht was to look for a better hull shape. In this sense, van Oossanen Naval Architects Fast Displacement Hull Form (FDHF) proved to have a better performance (8). It was designed to be a semi-displacement form achieving a good overall performance, being able to achieve better results than conventional semi-displacement vessels. Furthermore, it is comparable to full displacement vessels at displacement speed (Froude number approximately 0.3).

The FDHF takes advantage of a combination of features from both displacement and semi-displacement form (9) in order to achieve a better performance at both speed ranges. The FDHF adopts a round bilge to achieve a better performance at lower speeds with the utilization of centreline skkeg, bilge keels and stabilizing fins to improve the performance at higher speeds.

In terms of immersed transom area it also aims at achieving a good combination between the ideal for displacement and semi-displacement speeds. At displacement speeds a small immersed transom is required to reduce frictional resistance, a consequence of immersed area, while at semi-displacement speeds the immersed transom area contributes to the generation of an upwards pressure that reduces the running trim. Since the impact of the immersed transom area is more signifficant at displacement speeds, the trends in the FDHF are to reduce the immersed transom. Therefore, having an immersed transom between 20% and 30% of the maximum sectional area. In order to reduce the running trim at semi-displacement speeds interceptors are applied.

In addition, one of the most signifficant differences between the FDHF and a conventional forms is the increased slenderness (Equation 1). The increased slenderness of the FDHF results in finer water line entries, which in turn results in a reduction of the available internal space, especially at the forward end of the hull.

$$Slenderness\ ratio = \frac{L}{D^{\frac{1}{3}}}$$

Equation 1

Figure 7: Resistance Comparison between benchmark and new design

Taking the luxury parameter into consideration an internal area reduction will reduce the attractiveness of the new design. For this reason, the hull was enlarged from 45m to 50m . Here lays another advantage of the FDHF, it allows the hull form to be enlarged without severe penalties in terms of performance.

In order to further reduce the hull's resistance, the steel hull was replaced by an aluminium hull. This change allowed for a severe reduction in terms of displacement, approximately 150 ton, which largely contributed to the resistance reduction as it can be seen in Figure 7. In this case, the environmental impact of aluminium construction is left out of scope.

Finally, the application of an energy saving device, the Hull Vane®, resulted in further resistance reduction at speeds higher than approximately 10 knots as displayed in Figure 8.

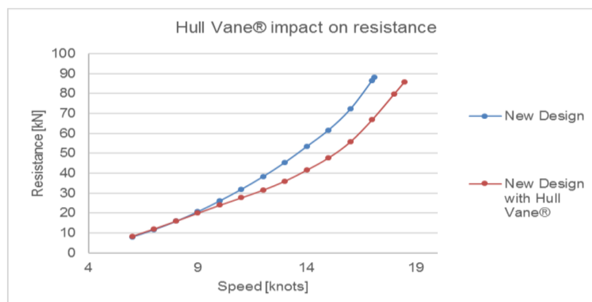

Figure 8: The impact of the Hull Vane® in resistance over the speed range

Likewise the reduction in propulsion power demand comes from a combination of factors, change in hull form, change in hull material and application of the Hull Vane®.

All together, resulted in savings of approximately 51.4% at cruising speed, which is the operational mode that has the larger impact on yearly emissions. The results for all the sailing operational modes are presented on Table 1.

Table 1: Propulsion power demand of the new design and respective reduction

	New Design with Hull Vane®	
	Brake power demand[kW]	**% reduction**
Manoeuvring	38.49	55.9%
Cruising	283.14	51.4%
Maximum Speed	665.27	67.6%

3.3. POWER SUPPLY ALTERNATIVES

Upon having uncovered the extent of the power demand, it was possible to investigate more efficient and cleaner ways of supplying this power. At first, the researched evaluated the feasibility of introducing alternative fuels and renewable energies. After that, it considered the power plant configuration.

Alternative fuels have a great potential in reducing the on board emitted CO_2. However, attention showed be given to the production process of these fuels, as in many cases changing the fuel type for on board energy production only means moving the source of CO_2 emissions a stage earlier. (10) A common issue related to alternative fuels is the on board storage systems due to their physical properties, such as density at ambient conditions. An added drawback is the poor bunkering options of such fuels, especially in the ports commonly visited by superyachts.

All in all, the application of alternative fuels was ruled out due to the lack of available feasible solutions in terms of equipment (engines, fuel cells, etc.), on board storage and bunkering options.

Similarly, the application of renewable energies on board a 50m yacht is not a mature solution if one considers it as the only power source. Nevertheless, it is becoming more common to combine renewable energy sources with the conventional systems (11). Both wind and solar energies are well known to the market.

In this case, a preliminary study on the impact of introducing solar energy on board resulted in the possibility of a daily production of 180.6 kWh/day not accounting for the instabilities in power production. This was possible by extending the available roof areas for the installation of high efficiency solar panels. Another downside of the lack of maturity of such solutions is the high cost associated with such installations, in this case approximately 170k€.

After ruling out alternative fuels and renewable energies as standalone strategies, it was still possible to reduce the CO_2 emissions by improving the efficiency of the power plant configuration, looking for the gains in finding the optimal synergies between components, thus in a well-designed hybrid configuration, fully taking advantage of all possible operating modes (12).

The potential of a hybrid configuration can be seen from Figure 9. The benefits are in the fact that the specific fuel consumption of a generator operating at a high load condition is lower than a larger engine operating at a low loading condition. In this way, at low speeds, thus low diesel engine loading conditions, instead of operating a low loaded diesel engine it is possible to have the diesel generator as the only prime mover. Nevertheless, this requires an increase in terms of generator size, so that it is able to operate during the poor operating conditions of the diesel engine. This operating mode is known as slow power take-in (PTI) mode.

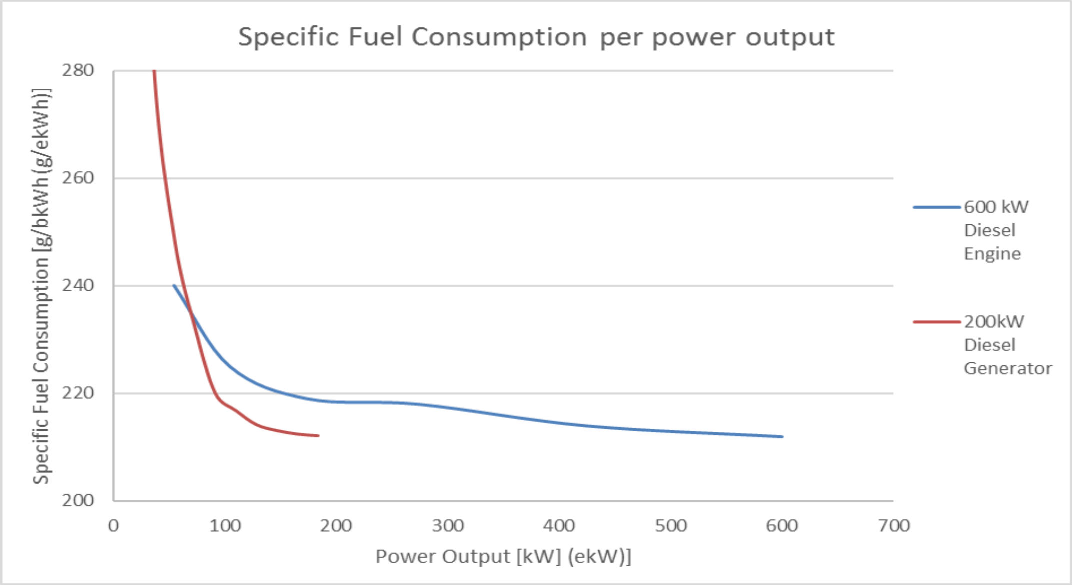

Figure 9: Specific Fuel Consumption curves of diesel engine and diesel generator in terms of output power

In the same way, the generator specific fuel consumption is higher when it is operating in low loading conditions. Therefore, in operational modes such as cruising, at which the auxiliary power demand is only a small fraction of the total power demand it is possible to have the diesel engine operating at higher loading conditions and supplying the total power demand by connecting a shaft generator at the gearbox. This is known as power take-off (PTO) mode.

In addition, a hybrid configuration enables the reduction of the diesel engine size due to the possibility of operating in boost PTI mode. In this case, the diesel engine is not required to supply the total power to achieve the maximum speed since the diesel generators are able to supply part of this power demand. As a result, the increase of generator size is partly compensated by the decrease in diesel engine size.

Figure 10**Error! Reference source not found.** displays the CO_2 emissions comparison between a diesel direct and a hybrid configuration taking advantage of the full capacities of a hybrid power plant arrangement. The main benefits are found during the PTO mode, thus during cruising, approximately 8.5% savings. The benefits at low speeds are negligible as they are mainly around 1%. At maximum speed (16 knots), thus boost PTI mode, the diesel direct configuration as a better performance. Nevertheless, this will have an insignificant impact in yearly emissions as this speed is only sailed over 0.43% of the operational time.

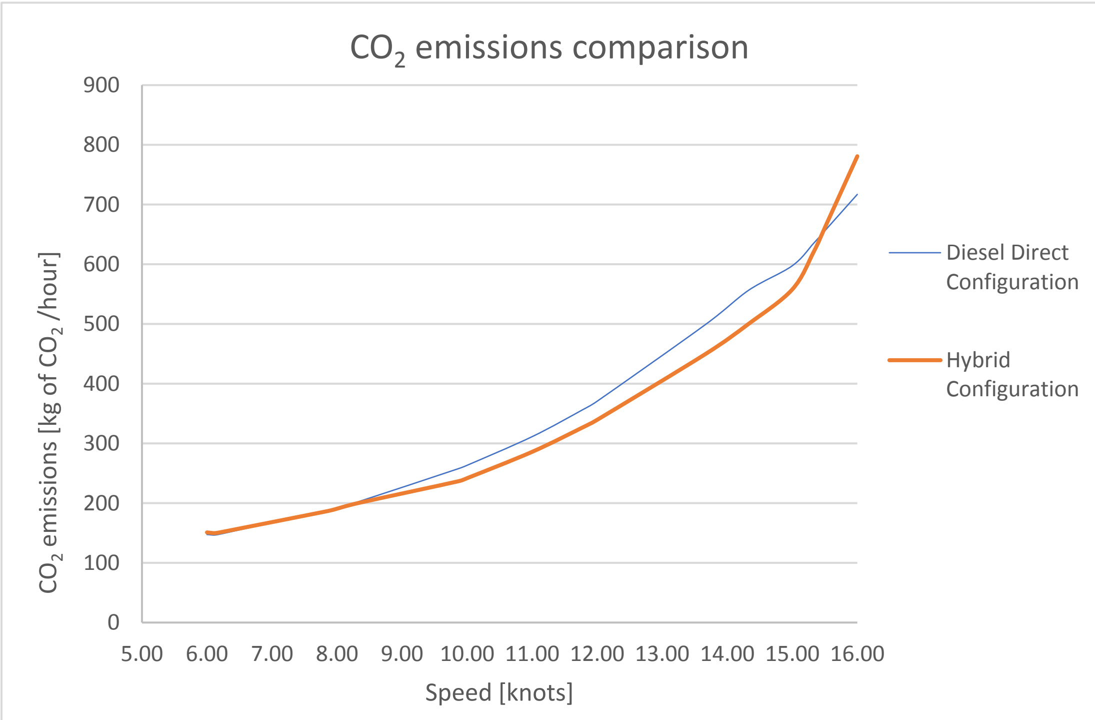

Figure 10: CO_2 emissions comparison between diesel direct an hybrid configuration over the speed range

4. Performance

All three questions have been answer; hence, the new design was evaluated based on three performance parameters: energy efficiency, luxury and costs.

4.1. Energy efficiency

The energy efficiency was a measure of the yearly CO_2 emissions. By combining the hourly rate of emissions with the operational profile, thus yearly hours of each mode it was possible to calculate the yearly emissions per operational mode.

Table 2 displays the results obtained after the study. It was uncovered that by combining power demand reduction in terms of auxiliary and propulsion systems with a more efficient power plant configuration it is possible to reduce the yearly CO_2 emissions by approximately 41%.

In comparison with the goals of the IMO these are very satisfactory results as this translates in the accomplishment of 82% of the goal already today only by combining readily available technology. Nevertheless, it is worth noticing that no emissions are accounted for when the yacht is in port.

Table 2: Yearly CO_2 emissions comparison between benchmark and new design

Operational Mode	**Benchmark**	**New Design**	**% of Reduction**
	[ton CO_2/year]	[ton CO_2/year]	
Cruising	397	219	45%
Max Speed	58	19	66%
Crossing	362	182	50%
Anchor	346	264	24%
Manoeuvring	24	17	28%
Port	-	-	-
Total	1187	701	41%

In addition, the impact of the operational profile on the final results was quite significant. For this reason, a sensitivity analysis based on different scenarios was needed to quantify the uncertainty associated with the operational profile determination. Figure 11 shows the disparity between the results obtained for each different results, confirming the uncertainty associated with the operational profile.

A standard deviation of almost 200 ton of CO_2 per year, which is approximately a deviation of 25% in relation to the actual outcome.

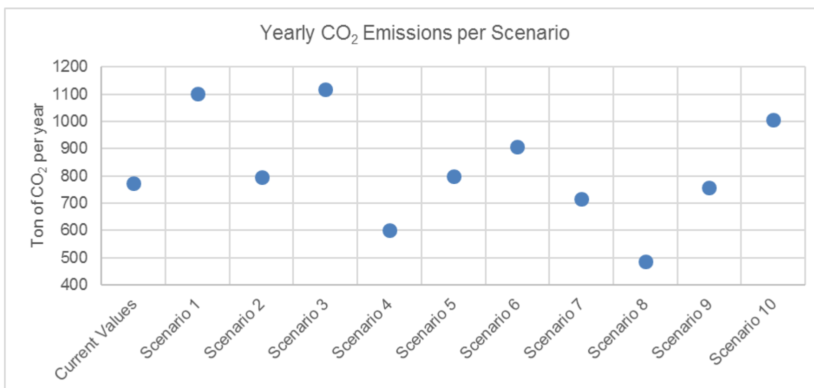

Figure 11: Scenario Analysis

4.2. LUXURY

Luxury was a measure of the internal deck area. One of the goals was to keep the internal space available for guests similar to the one of the benchmark even though changing the hull form and some of the equipment.

This was successfully achieved has it can be seen from Table 3, where despite deviations in terms of deck areas, the overall sum is the same in both cases.

Table 3: 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

4.3. COSTS

The Costs were divided in terms of Investment and running costs. The investment costs accounted for the acquisition of the yacht and berth. As both the benchmark and new design belong to the same overall length range, the same berth acquisition costs were assumed. The increase in terms of investment are due to the changes in the auxiliary systems, the introduction of the Hull Vane® and the introduction of the hybrid power plant that required not only larger generator sets but also e-machines and additional converters. (Table 4)

Table 4: Investment cost comparison

Benchmark Design	New Design
€32,020,000.00	€33,859,065.45

The running cost encompass categories such as crew salaries, berthing fees, fuel consumption and outgoings. Estimations of the running costs (Table 5) were based on Brade, E. et al. (12). The only significant difference in terms of fuel consumption, which was expected since all the savings made were in the direction of fuel economy as this also leads to a reduction of emissions.

Table 5: Running costs comparison

	Benchmark Design	Hybrid Arrangement with Hull Vane®
Crew Salaries	42,328.54 €	€42,328.54
Outgoings	1,519,689.79 €	€1,519,689.79
Maintenance Engine Room	386,176.62 €	382,372.47 €
Berthing Fees	90,606.25 €	€90,606.25
Fuel Consumption	467,278.71 €	€276,377.50
Total	**€2,506,079.90**	**€2,311,374.55**

The fact that the investment costs are only increased by 6% together with the fact that the running costs are reduced in about 8% resulted in a payback period of approximately 4 years which is relatively small compared to lifespan of the yacht.

5. Conclusions

The new directions from the IMO, aim at a 50% reduction of the CO_2 emissions by the year of 2050. In spite of the fact that at the moment this directory is drawn only for the shipping sector, the yachting sector wishes to be on the forefront in reducing emissions.

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 given the technological progress pace that we see today.

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, thus also playing an important role.

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 4 years which compared to the lifetime to the yacht is acceptable.

The uncertainty revealed in the operational profile indicates that for the future it is valuable to consider a more accurate prediction of the operational profile of the yacht, similarly to what happens with workboats or commercial shipping vessels. This will not only influence the results in terms of annual CO_2 emissions, but also influence the choices made along the process, especially regarding the power supply alternatives.

Finally, deeper investigation of hybrid power supplies is advised, as the savings are many times a result of the combination of strategies as it occurred in terms of auxiliary power demand reduction.

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