# Hybrid-electric solutions for the propulsion of a luxury sailing yacht

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***Abstract*—The application of hybrid-electric solutions for the propulsion of pleasure crafts is increasing in recent years. The more restrictive regulations on pollutants and the growing sensibility of the people on greenness make this solution even more attractive. In case the craft is stationing in a marine equipped with renewable energy sources, the attractiveness of such a solution increases even more. Besides, a hybrid-electric configuration can reduce the consumptions and, consequently, the operative costs against an initial higher investment. Therefore, hybrid-electric propulsion could give a benefit to raise a stationary market, as the pleasure craft one. This study compares in terms of consumptions three different solutions, besides conventional diesel one, for the propulsion of a sailing yacht.**

***Keywords— hybrid-electric propulsion; sailing yacht; Zero Emission Mode, Zero Emission Marina, Integrated Power System***

## I. INTRODUCTION

After the economic crisis in the past years, the market of luxury yachts is recovering [1]. At the same time, ship-owners are proving to be increasingly aware about the issues related to environmental protection. As regards large commercial ships, in recent years the International Maritime Organization (IMO) issued many compulsory Regulations [2] in order to reduce the environmental footprint of ships. In particular, air pollutant emissions (PM, $SO_x$, $NO_x$, GHG and VOC) have been restricted for ships operating in the so-called Emission Control Areas (ECAs). Moreover, other Regulations have imposed a continuous increase in the energy efficiency of ships. Nowadays, due to these actions technologies for reducing the ships' environmental footprint have achieved good reliability and diffusion.

Luxury yachts do not have to comply with the above Regulations. Nevertheless, the energy efficiency improvement, the fuel consumption reduction, and a low environmental footprint have a great commercial appeal in the sector. Furthermore, recent studies [3]-[4] have shown that electrification can be considered one of the most effective strategies to improve the environmental sustainability of small craft and pleasure vessel. Ship systems electrification provides extra flexibility to a luxury yacht, as well as fuel consumption and pollutant emissions reduction, low noise, integration of multiple sources of power, and energy storage systems integration. Additional operational flexibility is enabled by the installation of hybrid-electric powertrain [5]-[6], which allows supplying the propulsion system via other means, through the electrical system.

Regarding large sailing yachts, they still need an auxiliary propulsion system for low speed navigation, maneuvering, or to reach the bathing areas. Electric propulsion is a good option also in this case. However, being the navigation time very limited in the yacht overall life, it is essential to reduce the vessel environmental footprint also during berthing. To this end, the onboard power system should be designed to efficiently interact with onshore infrastructures, especially while stationing in a "Zero-Emission-Marina" (ZEMar) [7]. The latter is a marina able to exploit renewable energy sources, for carbon-free supplying the yacht and recharging its batteries during berthing periods, with high reliability and low costs.

In this paper, four different solutions for the auxiliary propulsion system of a luxury sailing superyacht are analyzed. The possibility of providing the ship with a shore connection is also considered, to supply the onboard loads and recharging the batteries. In the following, the traditional auxiliary propulsion system based on Diesel engines is compared in terms of fuel consumption with three new electrical/hybrid configurations (full electric and hybrid Diesel-electric propulsion), considering also the onboard integration of an energy storage system. Moreover, an estimation of the total weight of the four different machinery systems has been performed, to ensure the feasibility of the proposed solution for the considered yacht.

## II. THE VESSEL AND THE OPERATIVE PROFILES

### *A. The case study ship*

The case study vessel is a luxury sailing yacht (Fig.1), having the main dimensions as listed in Table I. As it can be observed, the ship presents two masts with a continuous deck. Being the sailing yacht devoted to a pleasure navigation, the sail management system is fully automated, allowing the skipper and the guest to sail without too much effort. However, the presence of the automated system increases the power demand during sail navigation, when compared to a standard sailing yacht. Thus, the implementation of green solutions for the power supply on board is of utmost importance. As in Fig.2, the

TABLE I. SAILING YACHT MAIN CHARACTERISTICS

| **Symbol** | **Characteristic** | **Value** | **Unit** |
|---|---|---|---|
| $L_{OA}$ | Length overall | 43.4 | m |
| $L_{WL}$ | Waterline length | 35.3 | m |
| $L_{PP}$ | Length between perpendiculars | 35.0 | m |
| $B$ | Breadth | 9.4 | m |
| $T$ | Draugh (keel up) | 3.9 | m |
| $T_{MAX}$ | Draught (keel down) | 6.8 | m |
| $\Delta$ | Displacement in weight | 300.0 | t |
| $V_C$ | Cruise speed | 10.0 | kn |
| $P_B$ | Installed propulsive power | 1000 | kW |

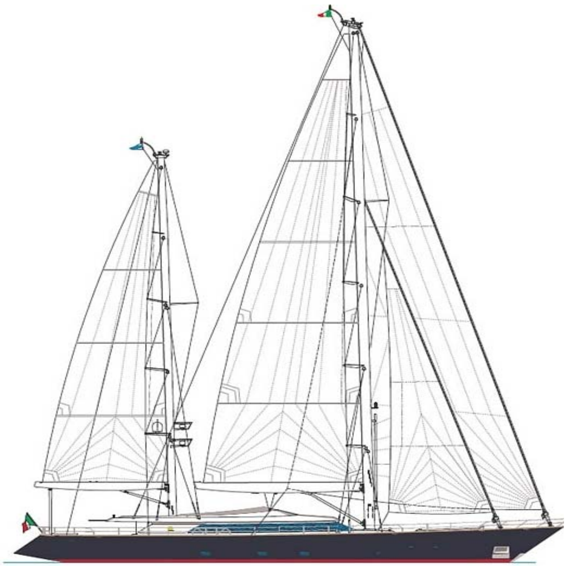

Fig. 1.   Profile view of the sailing yacht.

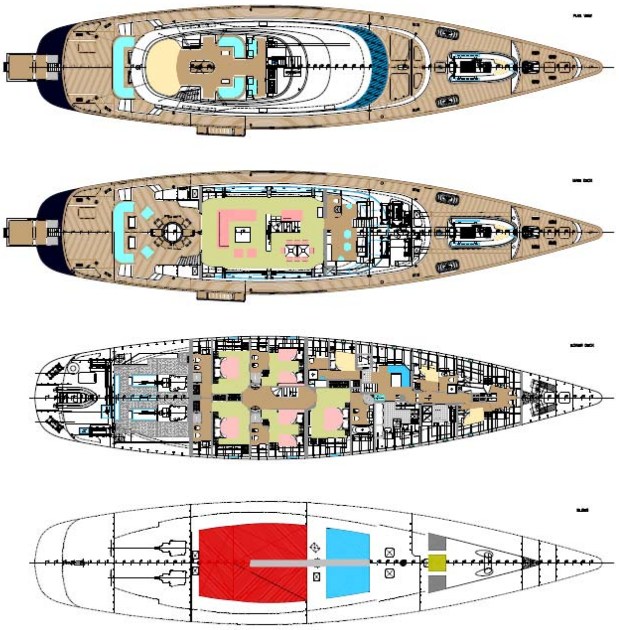

Fig. 2.   General arrangement plan of the sailing yacht

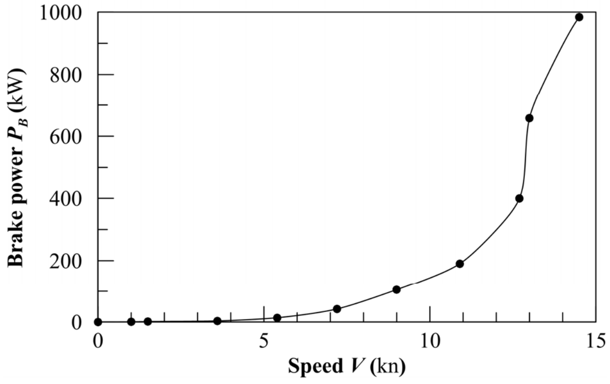

Fig. 3.   Fig. 3. Propulsive Brake power as a function of sailing yacht speed.

available technical spaces are limited, so electrification of sailing equipment (currently hydraulic) can certainly lighten the yacht to the benefit of sailing performance. Furthermore, the technical volumes released by the hydraulic pressure vessels and compressor units can be used more efficiently for accommodating the battery storage.

Even though the pleasure craft in study is a sailing yacht, the characteristics of such kind of yacht and the use that generally the owners do imply a strong use of the navigation with propellers. In fact, all the maneuvers and the long transfers are generally performed using on board Diesel engines as propulsive power. Therefore, the determination of the resistance of the unit have to be carried out as accurate as possible in order to establish the effective propulsive loads. Moreover, the analyzed sailing yacht is fitted with two main appendages: a rudder and a retractile keel. During navigation with propeller, half of the keel is in the water, which has a significant impact on the propulsion power calculations. The hull form parameters of the vessel are in line with the Delft Systematic Yacht Hull Series (DSYHS) [8]. However, to estimate the resistance of the hull, use has been made of a self-developed calculation method, specific for sailing yachts [9], and validated by computational fluid dynamics calculations.

### B. *Operative profiles*

The identification of a unique operative profile is almost impossible for a sailing yacht and in general for a pleasure craft. The effective use of the vessel depends upon the owner wishes and desires so that it is hard to define a universal operative profile during the yacht design stage. However, it is possible to identify some recursive operative modes and use them during the design for the sizing of the propulsion and energy system. For this sailing yacht, operative modes are as follows:

A. *Navigation with sails*: in this condition, wind-sails propel the yacht, thus the only power loads are the one given by hotel users and sail management.

B. *Navigation at full speed*: in this condition, the vessel is using propellers for the propulsion at the speed of 13 knots. This condition is usually adopted for less of the 10% of the operating time.

C. *Navigation at cruise speed*: in this condition, the vessel is using propellers for the propulsion at the speed of 10 knots. This is the typical condition for the transfer.

D. *Navigation at low speed*: in this case, the vessel is using propellers for the propulsion at 7 knots. This navigation type occurs when the vessel is approaching the coast.

E. *Maneuvering*: in this condition, the vessel is using propellers for the propulsion. This condition refers to the transitory actions between stationing and sailing.

F. *Stationing at anchor*: the vessel is not sailing but it is at anchor without connections with the shore.

G. *Stationing in harbor*: in this condition, the vessel is not sailing but is berthed with the possibility to have a connection with the shore.

These profiles can be combined together, generating possible daily configurations for determining the vessel performances in terms of consumptions. In case a hybrid-propulsion is fitted on the vessel, then, profiles D and E (and

TABLE II. REFERENCE DAILY OPERATIVE PROFILE

| Op. Mode | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| time | 3h 26m | 2h | 3h 45m | 2h 24m | 15m | 3h 36m | 8h 24m |

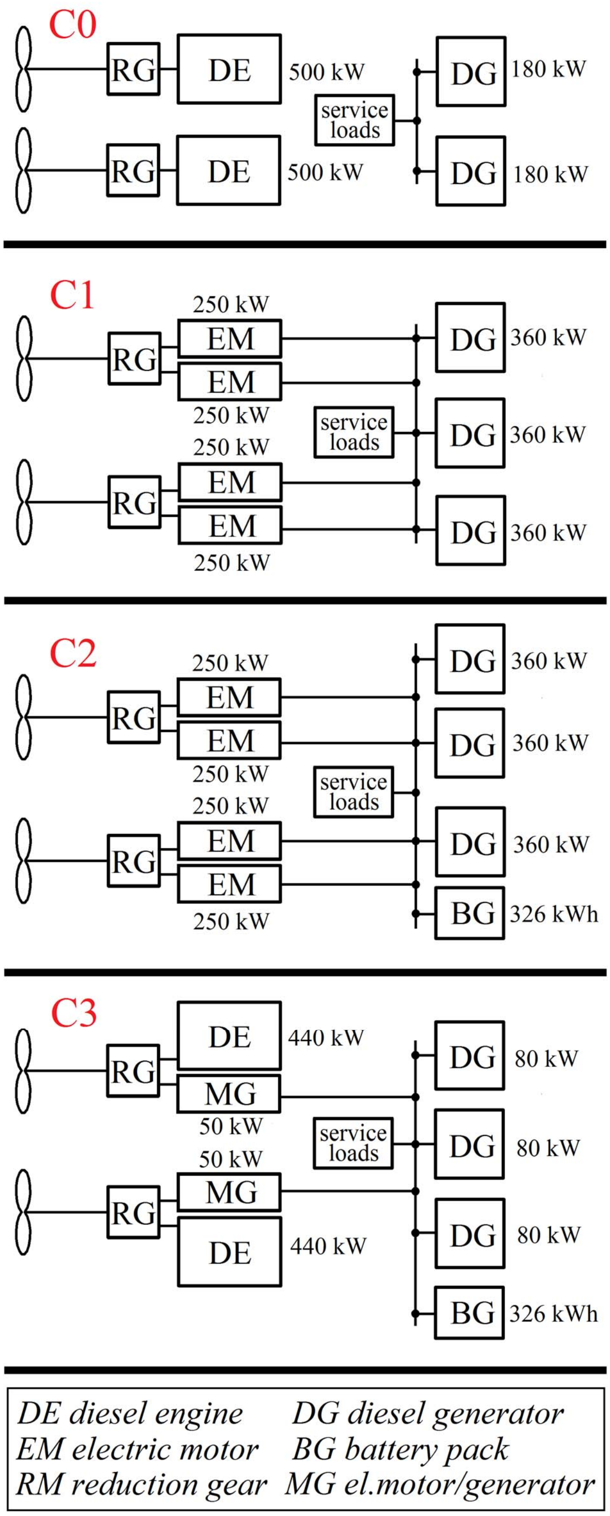

Fig. 4. Propulsive and power system configurations.

possibly F) can be performed in Zero Emission Mode, providing the required power by on-board storage systems. In case the energy system is provided of battery packs, the operative modes C, D, F and G may include also the battery recharge. In case of recharging, the operative mode will have a subscript *r*.

## III. PROPULSIVE CONFIGURATIONS

As previously mentioned, the yacht has been originally designed with a conventional Diesel mechanic propulsion, as well as Diesel generators for the supply of the other onboard loads. To evaluate the pros and cons of different propulsion systems, three additional configurations have been studied, along with the conventional one. These are a Diesel-electric solution, a series hybrid solution, and a parallel hybrid solution. As regards the sizing of the propulsion, since the power curve (Fig.3) is the same for each configuration, the maximum propulsive power is the same in all. The single exception is given by the last proposed configuration, which will be explained below. Concerning the onboard generators and the energy storage system, their sizing is made by taking into account the power required by onboard loads in the different operative modes, by the propulsion (when electric motors are used), as well as the reference daily operative profile (Tab. II). In this regard, the criteria used to design the electric power system are depicted in Section IV, by taking advantage of the C3 configuration as an example.

The main components are shown in Fig. 4, and listed below:

- *Configuration C0* is the original Diesel mechanic configuration of the vessel. Propulsion is performed with two diesel engines of 500 kW each. Electric generation for the onboard loads is performed by means of 2 Diesel generators of 180 kW power each.
- *Configuration C1* is a Diesel electric configuration. In this case, propulsion is performed by means of four electric engines of 250 kW each, while the power for them and the onboard loads is provided by 3 Diesel generators, with a rated power of 360 kW each.
- *Configuration C2* is the series hybrid configuration, i.e. the Diesel electric configuration C1 with the addition of an energy storage system. The latter is a battery pack of 326kWh Li-Ion (single module LIMP: 12.8V rated voltage, 138 Ah rated capacity @ C/5, 23°C).
- *Configuration C3* is the parallel hybrid configuration. Propulsion is performed with the coupling of two 440 kW Diesel engines and two 50kW electric Permanent Magnet (PM) machines. The total propulsion system is almost equal to the previous cases, when both machines are used for propulsion, making it possible to reach the full speed (operative mode B) with an adequate margin. The size of the electrical machine has been selected to provide the full electric propulsion up to 7 knots (operative modes D and E). Such a choice implies the use of electric propulsion for both maneuvering and low speed navigation, which can then be performed by using the onboard energy storage system to enable the emission free operation of the ship. Due to this choice, this configuration allows the ship both to lower the pollution in port, and to sail in marine protected areas in

absence of wind. To provide adequate electric power generation, three 80 kW Diesel generators are installed, together with the same battery pack of the configuration C2.

To establish the most convenient configuration among the four proposed, the fuel consumption (to be calculated according to the reference operative profile of Table II) is used as the main parameter. The results are discussed in Section V, where additional remarks will be offered also regarding the weight.

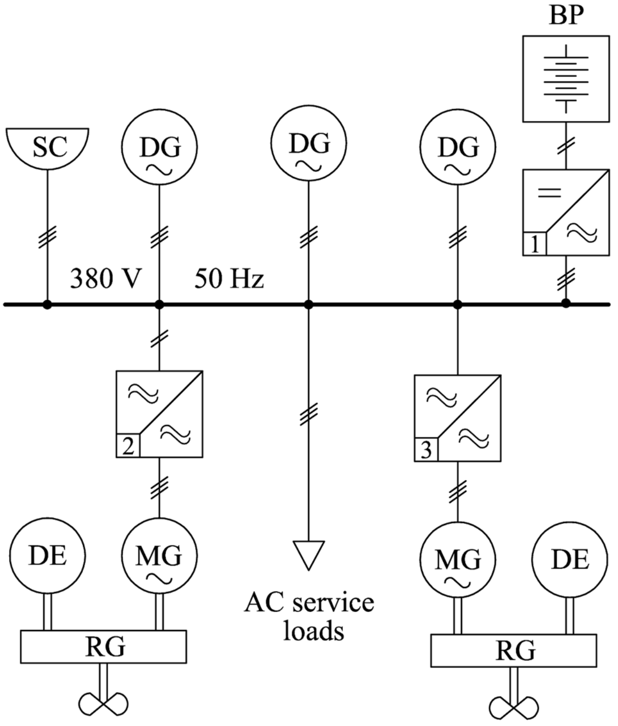

Fig. 5. LVAC power system for C3 parallel hybrid configuration.

TABLE III. POWER DEMAND IN THE DIFFERENT OPERATIVE MODES

| Operative Modes | Users | | | Total (kW) |
|---|---|---|---|---|
| | *Propulsion* | *Service loads* | *Battery charger* | |
| A. Navigation with sails | 0.0 | 148.0 | 0.0 | 148.0 |
| B. Full speed navigation | 956.8 [a. b.] | 112.8 | 0.0 | 1069.6 |
| C. Cruise speed navigation | 178.8 [a.] | 112.8 | 0.0 | 291.6 |
| $C_r$. Cruise speed with recharge | 178.8 [a.] | 112.8 | 50.1 [c.] | 341.7 |
| D. Low speed navigation | 50.2 [b.] | 112.8 | 0.0 | 163.0 |
| $D_r$. Low speed with recharge | 50.2 [b.] | 112.8 | 50.1 | 213.1 |
| E. Manoeuvring | 3.6 [b.] | 106.0 | 0.0 | 109.6 |
| F. Stationing at anchor | 0.0 | 112.3 | 0.0 | 112.3 |
| $F_r$. Stationing at anchor with recharge | 0.0 | 112.3 | 50.1 | 162.4 |
| G. Stationing in harbour | 0.0 | 95.9 | 0.0 | 95.9 |
| $G_r$. Stationing in harbour with recharge | 0.0 | 95.9 | 50.1 | 146.0 |

[a.] Diesel propulsion [b.] electrical propulsion [c.] power from shaft generators

## IV. SHIPBOARD POWER SYSTEM

### A. *Power loads balance*

Prior to perform the fuel consumption calculations, it is necessary to determine the power loads balance of the sailing yacht. Indeed, only by assessing the power and the time that has to be provided by each power source, in each operative mode, it is possible to correctly assess the ship's daily fuel consumption for each configuration. The ship has multiple electrical loads and different propulsion configurations, whose power requirements depend on the specific operative mode. To simplify the evaluation, the onboard users are divided in three groups, according to the following notation:

1. Propulsion
2. Service loads
3. Battery charger (if storage system is present)

For each operative mode, it is the possible to define the power of each users' group, as shown in Table III (i.e. the power load balance). It has to be noticed that Table III specifically addresses Configuration C3, which is the one used here as an example for the electrical power system detailed explanation. However, the same data can be used also for the other configurations. Indeed, for configuration C0 it is sufficient to consider only the operative modes without recharge, and suppose that all the propulsive power is achieved by Diesel engines. For configuration C1 it can be done the same, but considering all the propulsion being electrical. Finally, for configuration C2 it is possible to consider all the data in Table III, with electrical propulsion only.

### B. *Power system example: configuration C3*

The configuration C3 is used as an example, to provide a more detailed explanation of the ship's power system.

For what concerns the propulsive system sizing, the basic information has already been provided in Section III. In regards to the electric power generation system, its design has been made considering the following base concepts. First, the maximum electrical power required is given by considering full speed navigation operative mode, when the total 957 kW of propulsive power is delivered by the Diesel engines at maximum power (2 x 440 kW = 880 kW) and the electric motors providing the remaining 77 kW quota (957 kW - 880 kW = 77 kW). Then the service 113 kW service loads are added to this value, to obtain the total 190 kW of required electric power. Thus, the onboard generation system has to provide at least such power level. Then, another significant operating mode for the generators is the stationing at anchor with recharge one, where the generators have to supply both the onboard loads and the battery recharge. In this case the required power is up to 160 kW. Same power is required for the low speed navigation operative condition without battery recharging. Thus, the choice of three 80 kW generators allows to: provide the 160 kW power level required by several of the operative conditions with one generator stopped; achieve the maximum speed with all the generators online. Since most of the operative modes can be supplied by only two generators, it is possible to provide to the user most of the ship capabilities also in case of fault in one of the machines. Finally, the 326kWh battery pack is sized to allow for a 2 hours emission free navigating at low speed (operative mode D), given the 163 kW required in such operative mode. The choice among the different possible means of recharging the onboard energy storage system (electrical generators; shaft generators; shore connection) is left to the user, due to the extreme variability in the vessel's use (as mentioned in Section II.B).

Regarding the onboard power system for configuration C3, a Low-Voltage AC one has been selected (Fig.5), endowed with three DGs and several power electronics converters. The AC generators are used as the normal source of power for the onboard loads, being both DGs and loads directly connected to the main 380 V-50 Hz AC bus. Instead, the power electronics converters are used to interface the propulsion electric motor/generators to the main bus, as well as regulating the power flow in the batteries.

The power converter 1 enable the energy storage system's exploitation. In detail, it behaves as a DC-AC inverter, when energy flows from battery to then power system, thus allowing using the energy stored in the battery to supply the onboard loads. Moreover, as mentioned above in Section III, the battery pack has been sized to allow sailing in the *navigation at low speed* operating condition for up to 2 hours, thus making it possible to obtain the so-called Zero-Emission Mode. Conversely, the power electronics converter 1 behaves like a rectifier to recharge the batteries, during all the operative modes marked with the subscript *r* in Table II. Regarding converters 2 and 3, these are bidirectional AC-DC-AC ones. Thus, not only they allow the speed regulation of the electric motors, but also enable the shaft generation function at need.

The presence of several sources of power, as well as power electronics converters and energy storage systems, enable the smart operation of the onboard power system to achieve a high efficiency for the ship. As an example, in operative modes B and C the Diesel mechanical propulsion is used. In condition B, the total power of the Diesel engines is lower than the power needed to reach the required speed (it can be easily seen by comparing Fig.4 data with the propulsion power in Table III). This is because the missing power is to be delivered by the electric propulsion motors. Such a design allows installing engines with a lower size, thus reducing costs and increasing efficiency at low loads. Conversely, in condition C the propulsion Diesel Engines are lightly loaded, thus presenting a very low efficiency. To overcome such a disadvantage, it is possible to increase the load on them by operating the electric propulsion machines as shaft generators, thanks to the converters 2 and 3. Thus, the $C_r$ operative mode is achieved, allowing both to recharge the batteries during navigation and to increase the engines efficiency.

Moreover, other functions can be enabled by the coordinated operation of the MGs and BP converters. As an example, peak shaving for the propulsion engines can be achieved, by means of the electric motors (MG) operation and the use of the battery pack (to store excess energy or as a source of power during fast transients). Such a function is aimed at lowering the burden on the propulsion Diesel engines, by using the electrical machines to cope with the fast power variations (given either by hydrodynamic causes, or due to the pilot requests). At the same time, the energy storage system (BP) avoids overstressing the Diesel generators, coping with the fast power variations is spite of them.

Finally, the ship is endowed with a shore connection, to supply the onboard loads and to recharge the battery pack when berthed without relying on the onboard generators. Considering a common 380V 32A LV shore connection, which can be found in several marinas nowadays, it is possible to supply nearly 21 kW to the ship (although some marinas can limit such power to a lower level). The provided power is not sufficient for copying with both the Service Loads supply and the battery recharging at berth, which requires nearly 150 kW (Table III, operative condition $G_r$). Additionally, also if the battery recharge is not performed at berth (operative condition G), a reduced level of comfort can be achieved onboard, due to the power limitation (21 kW from shore in spite of the required 96 kW). However, if the ship is at berth and it is not used, the service loads will be greatly reduced. Then, such a small power shore connection is still able to recharge up to the 54% of the battery during the night (mode G in Table II: 8h 24min). Instead, if both the onboard loads and the energy storage recharge is required, a shore connection of more than 100 kW is needed. Such a powerful shore connection is not common in marinas at present. However, envisioning a future development towards a more sustainable port framework, the presence of powerful shore connections, supplied by PV plants for providing a renewable source for recharging the ships energy storage systems, will surely be a common feature. Thus, the configuration C3 is ready to be used in a future Zero Emission MARina, by exploiting carbon free navigation capabilities.

## V. PROPULSIVE CONFIGURATIONS COMPARISON

By means of the power demand from loads and propulsion, and the daily operative profile (Table II), the daily fuel consumption can be determined. Although the total power demand of propulsion and onboard loads is the same for all the proposed propulsive configurations, the resulting fuel consumption will differ due to the different machinery size, their efficiencies, and also by the use of the energy storage system (if present). The fuel consumption calculation is based on data coming from motor and generators commercial, by applying to the provided full load consumption a correction factor consisting in the loading percentage. Then, the Table II daily operative profile allows to determine the aggregated daily fuel consumption in *liters of fuel per hour*. The detailed results are shown in Table IV, while in Fig.6 are graphically compared the total values. Since the different configurations have an impact also on the ship's weight, a comparison regards the weight of the components that are changed in the proposed configurations is given in Table V and Fig. 7.

As it can be seen from the results, the configuration C0 is the one with the highest fuel consumption. This is because the propulsion Diesel engines and the Diesel generators are always running, despite being at low load for most of the time. With respect to the original configuration, configuration C1 uses 1.15% less fuel, while configuration C2 uses 2.96% less and configuration C3 saves nearly 8.68% of the fuel. Such a result was expected, since the introduction of electric propulsion and

TABLE IV. DAILY FUEL CONSUMPTION

| Mode | time | Fuel consumptions (l/h) | | | |
|---|---|---|---|---|---|
| | | *C0* | *C1* | *C2* | *C3* |
| **A** | 3h 36 m | 39.05 | 40.60 | 40.60 | 39.05 |
| **B** | 2h | 268.41 | 270.00 | 270.50 | 266.50 |
| **C** | 3h 45m | 75.30 | 74.00 | 74.50 | 73.94 |
| **D** | 2h 24m | 43.60 | 42.50 | 31.50 | - |
| **E** | 15m | 28.80 | 26.50 | 26.60 | - |
| **F** | 3h 36m | 29.50 | 27.50 | 27.50 | 29.50 |
| **G** | 8h 24m | 25.35 | 24.15 | 24.15 | 23.35 |
| **TOTAL** | **24 h** | **1390.75 l** | **1374.15 l** | **1349.63 l** | **1269.99 l** |

TABLE V. ELECTRIC POWER AND PROPULSION SYSTEMS WEIGTH

| Configuration | Weight [t] |
|---|---|
| C0 | 10.71 |
| C1 | 8.50 |
| C2 | 9.61 |
| C3 | 14.92 |

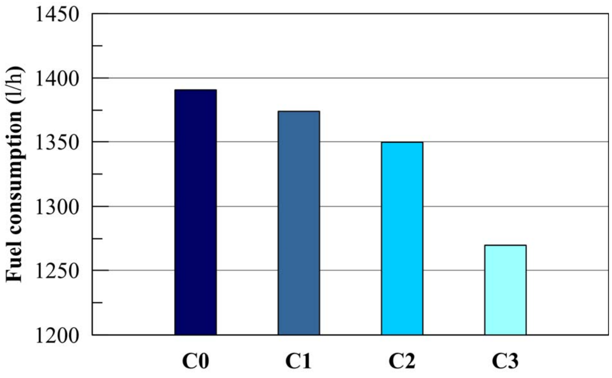

Fig. 6. Daily fuel consumptions

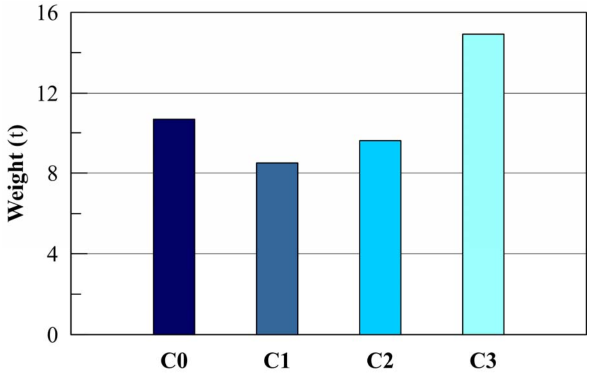

Fig. 7. Electric power and propulsion system weight.

an integrated power system (powering both propulsion and onboard loads) is proven to be more efficient than a segregated system when there is a highly variation in the daily load [10].

Moreover, the full electric configuration C1, while achieving fuel savings in respect to the base case C0, it is still lacking in respect to the hybrid configuration C3. This is due to the significant difference between propulsion and onboard loads powers, which calls for an oversized onboard power station in configuration C1, with a consequent loss of efficiency due to the several energy conversion's stages. The installation of an energy storage system (configuration C2) allows mitigating such an issue, leading to additional fuel savings, despite increasing the ship's weight.

Instead, configuration C3 presents the lowest fuel consumption, with a significant reduction in respect to the other configurations. Such a result is enabled by the using the electric motors to only achieve low speed navigation, thus limiting their size to a level that is comparable with the power required by the service loads. Therefore, the resulting onboard power station is not oversized as it is in configurations C1 and C2. At the same time, the maximum speed is achieved by using the mechanical propulsion, thus removing unnecessary efficiency losses (due to several energy conversion stages) in a condition where the power delivered to the propellers is significant. Such a result is remarkable, despite considering the significant increase in electric power and propulsion systems weight required to achieve it (Refer to Table V and Fig.7).

Finally, both configurations C2 and C3 achieve fuel consumption reductions by exploiting the energy storage system, thanks to the possibility of performing operative modes D and E in ZEM navigation. It has to be remarked that in the fuel consumption study no reference is made to battery recharge during navigation. In fact, it is assumed that the yacht starts its daily routine with charged batteries, by recharging them during the night by means of a shore connection.

## VI. CONCLUSIONS

In this paper, different auxiliary propulsion system configurations for a luxury sailing yacht have been considered. Comparative analyses have been carried out, to define the best solution in terms of fuel consumption. Specifically, different operative modes have been examined. Based on the power demand and a daily profile for the ship, the fuel consumption has been evaluated for the four configurations. The hybrid-electric solution, in parallel configuration with an onboard energy storage system (i.e. configuration C3), was presented in more detail, to give an example of the possible operation of such a complex electric power and propulsion system.

By means of the results in terms of fuel consumption, it has been demonstrated that configuration C3 is the more efficient in spite of its higher weight. Moreover, such a configuration is able of coupling low fuel consumptions with the well-known advantages of hybrid propulsion systems, such as reduced noise and pollutant emissions, which are among the most significant drivers for a modern yacht. In terms of costs, the conventional propulsion system has a lower CAPEX in respect to the parallel Diesel-electric hybrid propulsion here proposed. However, the latter becomes competitive if the total-life costs are considered. Indeed, the lower daily fuel consumption (nearly 9% for the considered daily operative profile) and the lower running hours of the Diesel propulsion engines allow attaining advantages in terms of OPEX. Moreover, the possibility of performing zero emissions navigation is an additional feature that enables sailing in areas that otherwise are interdicted to the yacht, being itself a point worth an increase in the acquisition costs for the ship.

Finally, it is worth to be noted that the Zero-Emission concept can be considered effective to enhance the eco-friendliness of a luxury yacht only if it is correctly integrated with the land infrastructure (the marinas were the yacht will be berthed). In fact, being berthing the most long-lasting activity in a yacht's life, the emission reduction in the marina is a significant step towards an increased sustainability. Furthermore, if the shore connection that allows to recharge the onboard energy storage system is supplied by means of renewable energy sources installed in the marina premises, the resulting ship's navigation can be surely defined as a zero-emissions one.

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