Assessment of energy efficiency of a motor yacht depending on routes and sailing area

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Abstract. The report presents an analysis of luxury charter yachts which are a specific class of vessels that, in order to meet the schedules and increased requirements of the owners regarding the luxury of the services offered, have relatively high energy consumption for their gross tonnage, compared to other passenger ships. The study focuses on the analysis of energy efficiency of luxury yachts by calculating the energy efficiency index (EEDI). This involves comparing different parameters that affect the value of the EEDI and can lead to energy savings. The report presents theoretical and experimental studies of the energy costs of a 70-meter luxury yacht for charter trips. With the use of the design data of the ship's electrical equipment at different operating modes, at different routes, under different conditions, dependences for analysis of the optimal modes of movement are obtained, which leads to the realization of maximum savings of electricity and primary energy.

1. Introduction

Powerful motor yachts are designed for pleasure, they carry very few passengers and their energy efficiency requirements have almost no profile. A novelty on the cruise market, are the ultra-luxury expedition motor yachts. This relatively new type of ship is entering the market at a rapid pace of development. As the number of willing passengers continues to increase, operators seek to pre-determine their routes, serving selected interests and customer groups. Luxury motor mega yachts use modern technology to create a unique and exclusive trip. In an effort to reduce the global carbon emission of the maritime industry, the International Maritime Organization (IMO) has adopted rules to reduce greenhouse gases in terms of the efficiency of the offshore power plant. The strictest requirements are for emission control zones (ECA). Namely:

- Baltic and North Sea
- Coastal waters of the United States and Canada
- Caribbean Sea
- Mediterranean Sea
- Coast of Japan
- The Strait of Malacca, etc.
2. State of problem
The study on the implementation of EEDI in the yachting industry must be examined in detail, taking into account the energy efficiency requirements that are mandatory for all ships with a gross tonnage of more than 400 GT built after 1 January 2013. The equation that applies to EEDI is directly related to the benefits of operating a particular ship or its transport activities. Luxury motor yachts are designed for pleasure, they carry very few passengers, the calculations on the useful work or the number of passengers will not meet the requirements imposed by the IMO. It is therefore more difficult to determine any direct benefit or work done than other cruise ships, as the carrying capacity of cargo and passengers per nautical mile is very low. The final version of the achieved EEDI equation is provided by the IMO MEPC 62/WP. 15, ANNEX 1.

\[
At EEDI = \left( MEE + AEE - ERIT \right) \cdot \frac{1}{TW}
\]

Where: MEE - CO₂ emissions from main engines [tCO₂.DWT]; AEE - CO₂ emissions caused by auxiliary engines [tCO₂.DWT]; ERIT - emission reductions from innovative technologies [tCO₂.DWT]; TW - transport work [DWT];
The calculation of MEE, AEE, ERIT and TW is performed by formulas 2 and 3.

Calculation of MEE - emissions from the main engines:

\[
MEE = \left( \prod_{j=1}^{n} f_j \right) \left( \sum_{i=1}^{n_{ME}} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)} \right)
\]

Where: PME (i) [kW] - 75% of the maximum continuous load (MCR) of the main engines.

\[
P_{ME(i)} = 0.75 \cdot (MCR_i - P_{PTO})
\]

Where: PPTO [kW] - 75% of the nominal mechanical power of the shaft generator divided by efficiency on the shaft generator; PME: Main engine power (kW), PME (i) is 75% of the total rated installed power (MCR) after deducting shaft generators, of course. CFME (i) [t-CO₂ / t-Fuel] - environmental impact factor for fuels; SFCME (i) [t-Fuel / kWh] - specific fuel consumption of main engines at 75% MCR load; f - correction factor taking into account the influence of specially designed energy efficient elements of the ship.

Instead, the IMO guidelines advise the use of 1 if there are none, as is the case with luxury yachts. Usually this correction factor is very important as it takes into account the ratio of LBP (Length between perpendiculars) and installed power (MCR). Reducing the average weight of the installed power on board a luxury yacht will result in a correction of this value, which will be less than 1.

As seen in the above EEDI equation, there are different correction factors and constants. Some of these coefficients will have a direct impact and they are also applicable to yachts.

IMO provides simplified formulas that can be used, depending on the installed capacity. Unless different from those shown below:

If:

\[
\sum MCR_{ME(i)} > 1000kW, P_{AE} = 0.025 \times (MCR_{ME} + 250)
\]

and if:

\[
\sum MCR_{ME(i)} < 1000kW, P_{AE} = 0.05 \times MCR_{ME}
\]
Where: SFC - Specific fuel consumption \([\text{g/kWh}]\) is provided by the engine manufacturers on board the yacht. In the case of yachts, ordinarily marine diesel and gas oil are used, as results carbon content equal to 87.44% and \(C_f\) measure in t-CO\(_2\)/t-Fuel equals to 3.206 (according to IMO MEPC EEDI circular and ISO 8217).

3. Proposals for assessing the energy efficiency of a motor yacht according to the different sailing regimes in different areas

We will do an experimental study of the relationship between the optimal speed of a luxury motor yacht, the route, energy costs and EEOI (Energy Efficiency Indicator), which means "optimal yacht speed", which improves operational energy efficiency [1, 2, 3]. The yacht with traditional propulsion, with a length of 70.54 m, class LR X 100 A1 SSC, G6, XLMC, UMS is considered. Main engines: 2xCaterpillar 3516B (2x1825kW @ 1800 rpm), generators: 3 x 200Kw, max. speed 17Kn, total power 4894 hp. The capacity of the fuel oil tanks is 204,000 l. This study will analyze the design data of a motor yacht and accordingly will propose an idea for improving energy efficiency in relation to different sailing areas and IMO requirements in these areas. Improving the efficiency of a power plant essentially involves burning less fuel and thus releasing less carbon into the atmosphere. The most important function of a yacht is to provide a high-quality form of recreation for guests on board. How well each ship performs in this function is reflected in the "luxury" goal. The speed range is 13 knots for cruising speed and 17 knots for maximum speed. With the Greenhouse Gas Strategy 2050, the IMO aims to reduce carbon intensity by 40% over the next decade by 2030 and by a total of 50% (intensity 70%) by 2050 [4, 5]. When calculating the cost of yacht fuel, you must first understand how far the yacht will travel. On average, marine diesel engines burn about 0.4 kilograms of fuel per hour per unit of horsepower. Another important factor is the meteorological conditions in the area in which the yacht is chartered, such as the condition of the water, wind, resistance and weight of the vessel, which affect the amount of fuel consumed. After mapping the route and calculating the distance in nautical miles in combination of fuel consumption per hour and the expected travel time, we can calculate our fuel costs on the yacht for a given route in a certain area. The ratio of GT to installed power (kW) is an important aspect for shipbuilders, as it can provide them with a quick and easy method for predicting whether a yacht is EEDI efficient [6].

We can calculate the average amount of CO\(_2\) emissions from the main engines of the yacht (tonne of CO\(_2\)), it can be calculated by multiplying the average daily fuel consumption of the yacht by the CO\(_2\) emission factor of marine fuels (tonne CO\(_2\)/tonne of fuel). The analysis is based on the following assumptions:

- The yacht uses MGO as fuel when chartered to SECA, and HFO when chartered outside SECA (main engines). Auxiliary engines use MGO throughout the route.
- We assume that the fuel consumption function is cubic (the daily fuel consumption is proportional to the power of the sailing speed) and that the consumption does not vary depending on the fuel used.
- The yacht is provided for weekly routes.
- The route (series of preferred ports) is not fixed.
- Revenues for the service are fixed.

Energy efficiency is a measure of CO\(_2\) emissions. CO\(_2\) emissions are measured in kg/h at each yacht mode. The most important thing is to determine the area of navigation. The Mediterranean, the Caribbean and the Bahamas are the most popular destinations. However, there are destinations that are more preferred. For the analysis considered the most popular destinations, such as the Mediterranean for the summer season and the Caribbean for the winter season. The data considered can be found in table 1, which represents the maximum, minimum and average percentage of time for each mode of operation of the yacht.

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Table 1. Yacht operating modes based on maritime traffic

| Type     | Cruising [%] | Crossing [%] | Max. Speed [%] | Manoeuvring [%] | At Anchor [%] | In Port [%] |
|----------|--------------|--------------|----------------|-----------------|---------------|-------------|
| Maximum  | 22.92        | 18.58        | 1.12           | 3.36            | 67            | 78.04       |
| Minimum  | 1.8          | 0            | 0.14           | 0.14            | 10.21         | 6.23        |
| Average  | 8.4          | 8.03         | 1.3            | 1.3             | 38.97         | 42.66       |

According to previous calculations, maintenance costs are measured in relation to the output power of these components, the maintenance of the engines and generators installed in the yacht, and are presented in table 2.

Table 2. Maintenance costs of the main diesel engines and generator sets for the given yacht

| Type            | Number Installed | Power Output [kW] | Maintenance [usd/hour] | Operational hour per year |
|-----------------|------------------|-------------------|------------------------|--------------------------|
| Main Engine     | 2                | 1825              | 5.11                   | 1591                     |
| Generator Set   | 3                | 200               | 3.05                   | 5006                     |

It is known that yachts often spend their time away from their home ports, either in anchorages or in other ports. First, the amount of CO₂ emissions per hour is calculated for each mode of operation of the yacht. The hourly emissions for the different operating modes are then combined with the operating profile, thus relating to the annual operating hours of the set mode. In this way, the total annual CO₂ emissions are quantified.

The percentage of the different operating modes in relation to the total working period are shown in figure 1.

Figure 1. Yacht operating modes based on maritime traffic
A characteristic feature of luxury yachts is the significantly longer period in port or at anchor compared to the periods of sailing. The maintenance costs of the main diesel engines and generator sets for the given yacht are shown in figure 2.

![Figure 2. Maintenance costs of the main diesel engines and generator sets for the given yacht](image)

An essential feature is the significantly higher hourly usability of the generators compared to the main engines. This is determined by the longer stays in port.

4. Conclusion
The report examines the specifics of energy consumption of luxury yachts for charter trips. The definitions for Energy Efficiency Design Index (EEDI) and their applicability for luxury yachts are considered. The results show quantitative dependences on the ratios between the different operating modes, energy consumption and maintenance costs. The significant difference between duration of regimes "sailing-harbour" shows the need for in-depth study of issues related to energy efficiency and environmental impact of yachts for various operating modes.

5. References
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Acknowledgments
The project discussed herein is supported by the European Regional Development Fund through the Operational Programme “Science and Education for Smart Growth” under contract UNITe № BG05M2OP001-1.001-0008. Project name: “National center of mechatronics and clean technologies”.