Optimization of Hybrid Propulsion System of Yacht

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by

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Abstract

One of the biggest issues marine industry faces is the enormous cost of fuels. Cargo vessels cannot avoid these costs and shipowners of merchant type vessels the current time period are charged with very big amount of expenses considering fuels. The solution to this problem has begun in one smaller part of the whole shipping industry, the yacht industry. More and more owners require lower fuel consumption in their yachts and yards have done it reality. The hybrid propulsion systems are being installed continuously in new built yachts as “they grant the highest standards in terms of noise and vibration reduction” (Giancarlo Mussino, Owner’s Representative, Sinos S.A.), fact that is necessary in luxury vessels.

This Thesis investigates the minimization of fuel consumption for a specific itinerary by choosing the right combination of diesel engine, electric motor’s power and capacity of battery . Using dynamic programming a MATLAB written code produces the total amount of fuel for this specific itinerary. Consequently, the best combination of parts of propulsion system is achieved. The best choice is the one with the lowest value of the total fuel consumption. Another useful for captain’s duties output is the exact value of diesel engine power and electric motor power in each time step. Therefore, the yacht operates in auto pilot mode because it is determined from the start that in this engine mode reaches the required service speed and fixed duration of itinerary with the lowest amount of fuel.

Βελτιστοποίηση Υβριδικής Προωστήριας Εγκατάστασης Σκάφους Αναψυχής

Περίληψη

Ένα από τα μείζονα ζητήματα που καλείται να αντιμετωπίσει καθημερινά ο χώρος της ναυτιλίας είναι τα υπερμεγέθη κόστη των καυσίμων για την κίνηση των πλοίων. Τα πλοία μεταφοράς φορτίου είναι αδύνατο να αποφύγουν αυτά τα έξοδα και οι πλοιοκτήτες τη δεδομένη χρονική περίοδο πληρώνουν υπέρογκα ποσά στα καύσιμα. Η λύση στο παρόν πρόβλημα έχει βρεθεί αλλά αφορά μια μικρότερη αγορά, αυτή των σκαφών αναψυχής. Όλο και περισσότεροι ιδιοκτήτες σκαφών αναψυχής απαιτούν μικρότερη κατανάλωση καυσίμων για την πρόωση. Οι κατασκευάστριες εταιρείες έχουν εκκινήσει και εισάγουν σε όλο και περισσότερα καινούρια σκάφη αναψυχής την υβριδική πρόωση, καθώς όπως επισημαίνει ο αντιπρόσωπος της εταιρείας Sinos S.A. , Giancarlo Mussino, «παρέχει τα υψηλότερα επίπεδα μείωσης θορύβου και δονήσεων», γεγονός απαραίτητο σε πολυτελή σκάφη αναψυχής.

Η παρούσα Διπλωματική Εργασία ερευνά την ελαχιστοποίηση της κατανάλωσης καυσίμου, για δεδομένο ταξίδι, επιλέγοντας τον ορθότερο - για μια συγκεκριμένη γάστρα - συνδυασμό κινητήρα diesel, ισχύος ηλεκτροκινητήρα και χωρητικότητα μπαταρίας. Κάνοντας χρήση του Δυναμικού Προγραμματισμού, ένας κώδικας γραμμένος στην γλώσσα προγραμματισμού MATLAB , παράγει την συνολική ποσότητα καυσίμου για ένα δεδομένο ταξίδι. Συνεπώς, επιτυγχάνεται η εύρεση του καλύτερου συνδυασμού τμημάτων προωστήριας εγκατάστασης. Η βέλτιστη λύση είναι εκείνη με την μικρότερη τιμή της συνολικής κατανάλωσης καυσίμου. Επιπροσθέτως, μια χρήσιμη - για τα καθήκοντα πλοήγησης του σκάφους - έξοδος του κώδικα είναι η χρονική ιστορία τιμών ισχύος και ροπής του κινητήρα diesel και η αντίστοιχη για την ισχύ και την ροπή του ηλεκτροκινητήρα. Συνεπώς, το σκάφος αναψυχής λειτουργεί σε σύστημα αυτόματου πιλότου αφού είναι καθορισμένο εξαρχής ότι στην παρούσα λειτουργία της προωστήριας εγκατάστασης επιτυγχάνεται τόσο η υπηρεσιακή ταχύτητα και η συγκεκριμένη διάρκεια ταξιδιού με ταυτόχρονη ελαχιστοποίηση της ποσότητας απαραίτητου για πρόωση καυσίμου.

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CONTENTS

Introduction

By 2013, as reported in Gard's site [9], "diesel engines were first introduced to merchant shipping in 1912 and it is estimated that approximately 85 per cent of merchant vessels are now powered by them". As a result, the global maritime industry uses diesel engine as their main means of propulsion because of the adequate fuel costs, the simple operation and their longevity. As in merchant vessels, also yacht industry includes the diesel engines in the majority of global fleet. Nonetheless, because of the desire for even better engine performance and the continuous environmental concern, have led the manufacturers to design and produce new power units more environmentally friendly and with more efficient power management. As a result, the combination of diesel engines, electric motors and batteries started to take place. The last six years, the first diesel-electric hybrid propulsion systems started to appear more and more in yachts.

The hybrid propulsion in yachts offers a variety of advantages. To start with, yachts can operate in a big range of cruising modes from full electric to only diesel mode. More specifically, the most common modes are the zero-emission mode, the diesel-electric mode, the hotel mode and the diesel mode. Each one is used in the right time of the voyage and in order to meet the requirements needed. Another point in favor of using hybrid propulsion in yachts is that in electric mode there is a smooth and silent running. When the yacht operates at low speeds, it's a totally emission-free voyage. It should also be mentioned that the maneuverability is high-level. On the other hand, when the yacht operates in diesel mode, the higher power delivered from the engines contributes to travelling longer distances and in higher speed. To sum up, the hybrid propulsion offers the opportunity to combine both high performance but also a peaceful but with all the comforts available voyage for every kind of owner.

In the present work, a parallel hybrid diesel-electric propulsion system is selected. For a certain itinerary, the total fuel consumption (in kg) will be computed. Given a certain vessel's speed profile, the power needed from each engine or motor (on each time step) will be calculated in such a manner that the total power need (on each time step) will be satisfied and the total fuel consumption at the end of the itinerary will be the minimum. The data for the diesel engines are gathered from the fuel consumption maps of their manufacturers as a function of engine speed and power of the engine. In the end, takes place the comparison of all the combinations of propulsion system parts and is figured out the one that dominates with the lowest fuel consumption for this certain itinerary.

Determination of type of yacht used

In the present work, it is decided to deal with the so called “mega yacht”. Interchangeably the term “super yacht” is also used to describe this type of yacht. The definition of a “ mega yacht ” refers to any yacht over 78 feet (24 m) in length. This type of yacht is synonymous with luxury and as a result a very big amount of energy is necessary to achieve both the propulsion and the comfort hotel needs.

Specifically, in the present thesis a fairly large yacht type is selected, about 80 plus meters long. The power requirements for reaching a cruise speed of 14 knots are about 5000 kW, mix of diesel engine and electric motor power offer. There is a number of scenarios of hybrid power units’ configuration taken into account later on the present work. For each combination the total fuel consumption for a certain itinerary ,i.e., for a certain speed profile, will be calculated. In the end, a conclusion will take place and the best combination for a large mega yacht of 80 plus meters long with a demand of around 5000 kW of power will be found out.

Thesis Structure

In this work, hybrid diesel-electric propulsion is examined from the point of the finding the best combination of ICE engine, electric motor and battery capacity in order to minimize the fuel consumed in a certain itinerary. For these reasons, it is selected to refer to each part of the hybrid propulsion system as theoretical as practical. Additionally, it’s mentioned how the optimization method works, the results of each combination and the final decision on which is the best to choose.

In more detail, Chapter 1 depicts the configuration of the hybrid propulsion system. Chapter 2 describes the mathematical equations and approach given to the problem. Chapter 3 is about the electric motor (or generator) and its modeling. Chapter 4 is about the battery, its modeling and the quasistatic approach to the problem. Chapter 5 refers to the optimization tool. Chapter 6 provides with the results of the work. Finally, Chapter 7 concludes with the future work that can take place.

CHAPTER 1 : Hybrid Propulsion System Configuration

In the present work, the hybrid diesel electric propulsion system consists of two diesel engines, two electric motors/generators and a battery pack. It is selected that all of these parts are connected in a parallel hybrid propulsion arrangement. On each of the two propeller shafts, each diesel engine is connected directly to one electric motor. The two electric motors are also connected with the battery pack. The diesel engine and the electric motor are moving at the same engine speed.

In Fig. 1 there is a display of the parallel propulsion system configuration. It's taken from a video of "BoatTEST.com" and the company named "e-MOTION" [7] . It is mentioned that the parallel system is ideal for planing hull yachts but can also be installed in semi-displacement hulls.

Key characteristics of parallel hybrid propulsion systems and differences from serial ones [8]

To begin with, the main difference from serial hybrid propulsion systems is that in the parallel ones the combustion engine and the electric motor, simultaneously or separately, can power the propeller. During normal operation, the parallel hybrid propulsion system uses both the combustion engine and the electric motor in order to maximize the efficiency and the performance and minimize the fuel consumption. Combustion engine is usually used in high-speed mode while electric motor is ideal to be used at low speeds but can also provide extra power when required. Another point that should be mentioned is that in serial hybrid propulsion system, it needs heavier batteries. As a result, with the parallel hybrid propulsion system the vessel is lighter.

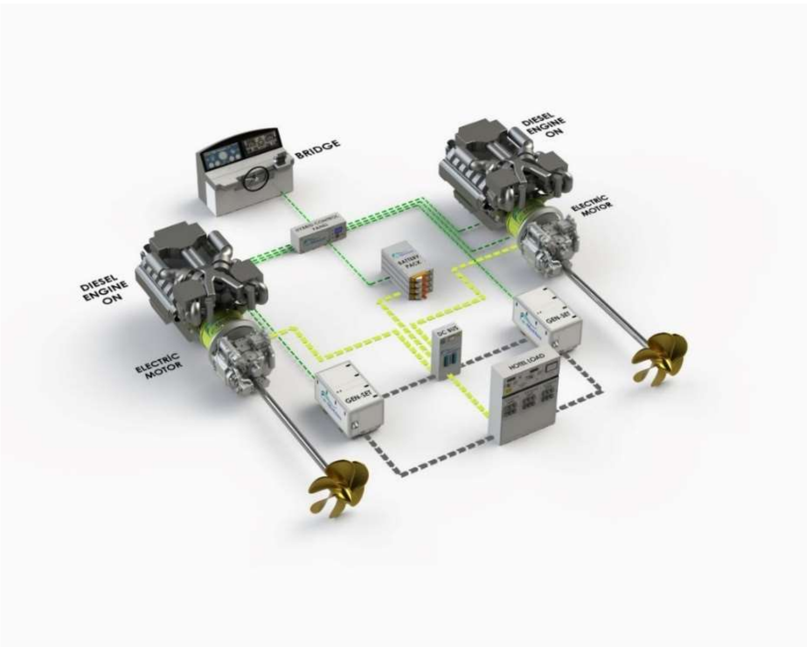


Figure 1: Parallel Hybrid Propulsion System Configuration

As it concerns the ICE used in the present work, basic information about them are listed below:

The first ICE is a turbocharged CATERPILLAR® 16-cylinder 4-stroke marine diesel engine, model CAT 3516C HD, shown in Fig. 2, producing 2100 kW at 1600 RPM. The loading diagram is shown (Rating D) in Fig. 3. The engine is designed to be compliant to IMO II as it concerns the emissions and the fuel consumption rates are in accordance with ISO 3046-1.

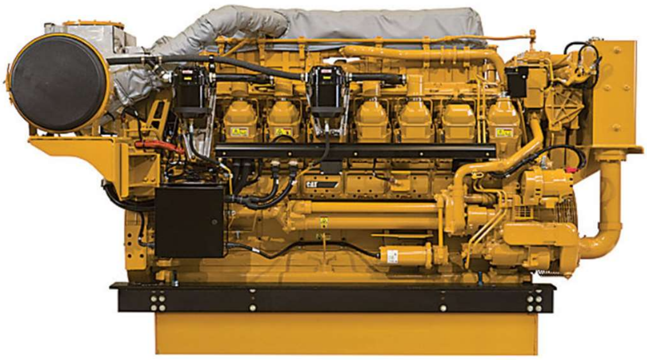


Figure 2: Engine CAT 3516C HD.

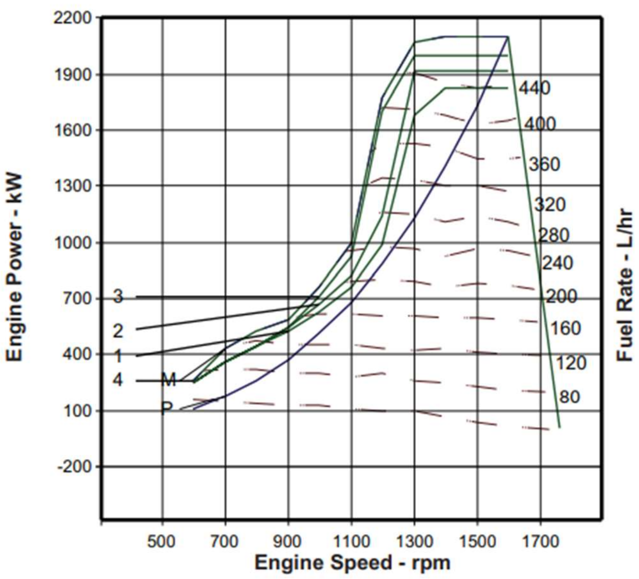


Figure 3: Loading diagram of CAT 3516C HD.

Note: Lines 1,2,3,4 are zone limits, P depicts a random propeller demand and M is max power curve.

The second ICE is a turbocharged CATERPILLAR® 6-cylinder 4-stroke marine diesel engine, model CAT C280-6, shown in Fig. 4, producing 1900 kW at 900 RPM. The engine's performance is shown in Fig. 5. The engine is designed to be compliant to IMO II as it concerns the emissions.

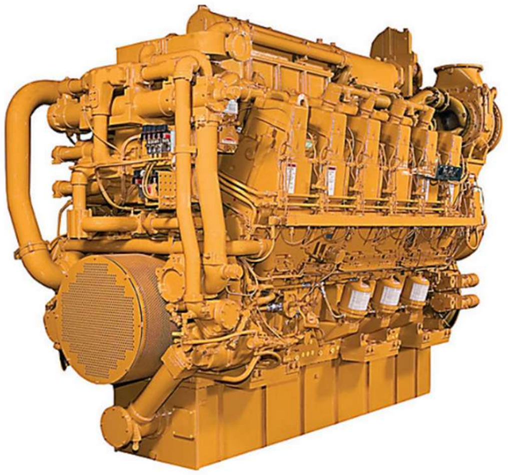


Figure 4: Engine CAT C280-6.

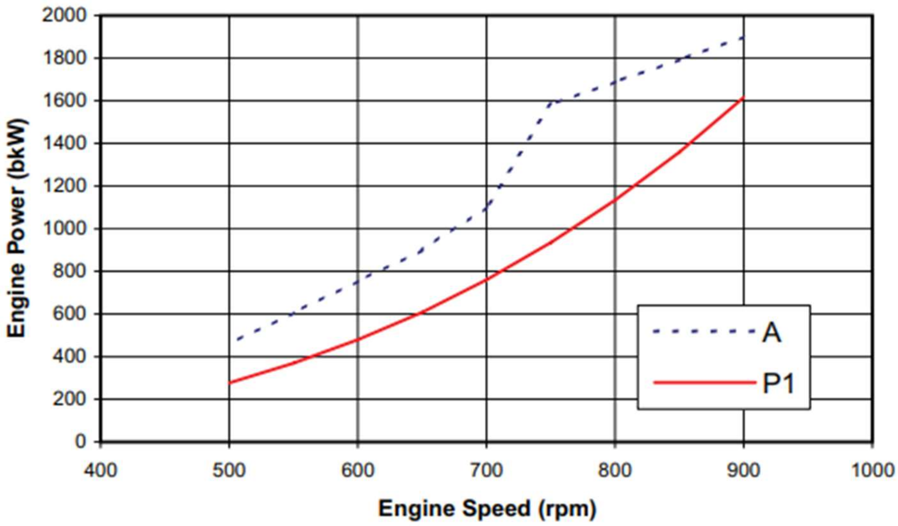


Figure 5: Performance of CAT C280-6.

Note: Line A is a zone limit and line P1 depicts a random propeller demand.

The third ICE is a turbocharged CATERPILLAR® 8-cylinder 4-stroke marine diesel engine, model CAT C280-8, shown in Fig. 6, producing 2460 kW at 1000 RPM. The engine's performance is shown in Fig. 7. The engine is designed to be compliant to IMO II as it concerns the emissions.

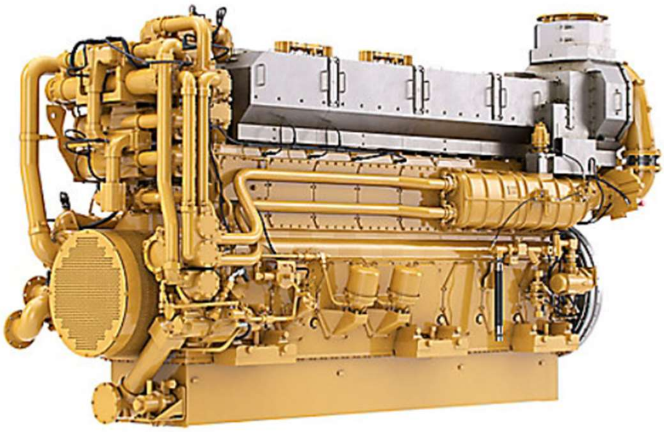


Figure 6: Engine CAT C280-8.

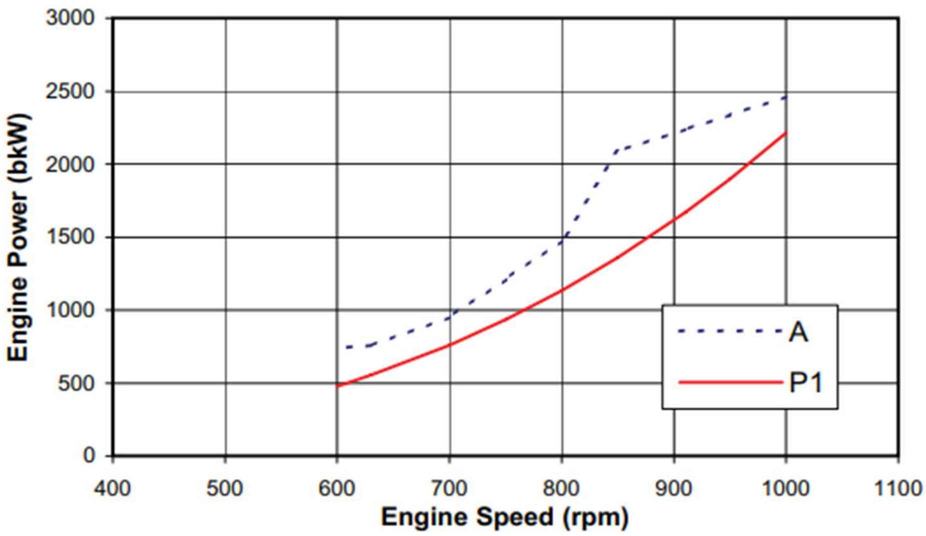


Figure 7: Performance of CAT C280-8.

Note: Line A is a zone limit and line P1 depicts a random propeller demand.

The fourth ICE is a turbocharged CATERPILLAR® 16-cylinder 4-stroke marine diesel engine, model CAT C175-16 , shown in Fig. 8, producing 2000 kW at 1600 RPM. The engine's performance concerning power, torque and BSFC is shown in Fig. 9. The engine is designed to be compliant to IMO II as it concerns the emissions.

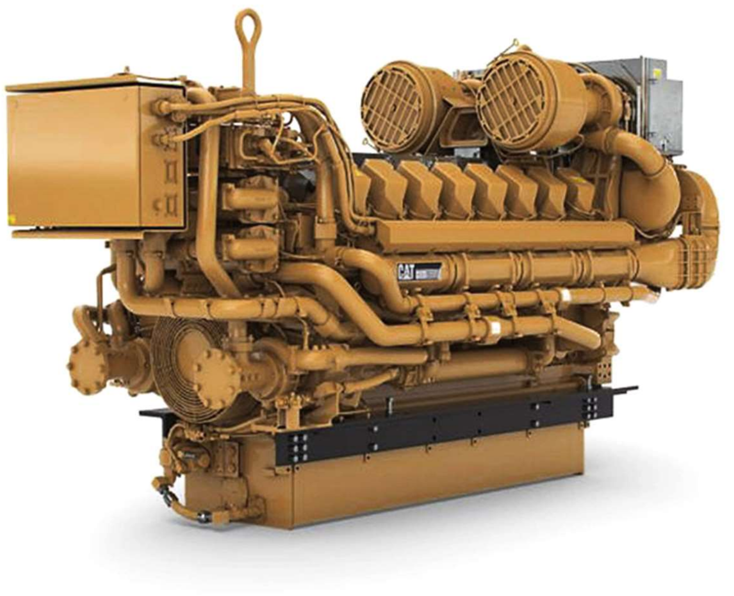


Figure 8: Engine CAT C175-16

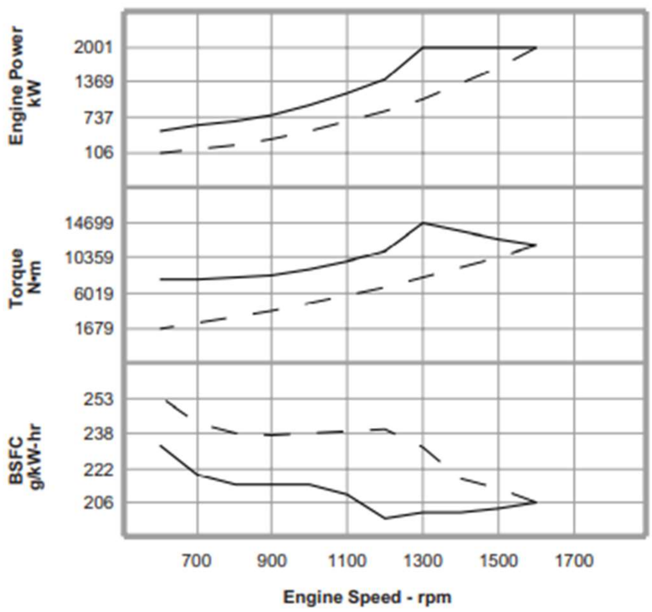


Figure 9: Performance of CAT C175-16.

Note: Continuous line is max power curve and dashed line depicts a random propeller demand.

As it concerns the electric motor, there aren't specific ones in the present work. That's because the max power of the electric motor is running in indefinite range as one of the two decision variables. The other one is the battery capacity. As a result, the present work is focused on having available determinate diesel engines and using a range of max power of electric motors and battery pack total capacities in order to find the magnitudes' combination with the lowest total fuel consumption within a certain itinerary.

More specifically, the equation describing the problem of choosing the right combination is the one below:

$$Diesel\ Engine\ \ MCR\ + Electric\ Motor\ Magnitude + Battery\ Magnitude \quad (1.A)$$

The exact values of the above used are seen in Table 2.

It has to be mentioned that electric motors can run in engine speed as the range of diesel engines selected in the present work operate. As a result, the transmission of the generated torque from the two engines to the shaft takes place without a big amount of power losses. This means that the total combinations of propulsion system operate efficiently.

Regarding the battery pack, the range selected in the present work is in the context of the magnitude of capacity used in such constructions. There is extended range used in the combinations in order to find the most beneficial solution. However, it should not be forgotten that the bigger the capacity the bigger the cost to buy, maintain and replace of battery cells and also the bigger the weight of the vessel, which has negative impact on power needed to reach a certain vessel's speed.

CHAPTER 2 : Problem's primary determination equations

To start with, there is the need of some of the basic principles of ship propulsion to be used. Afterwards, there are equations about the fuel consumption, the power conversion in an electric motor and the variation of the state of charge of a battery. In order to provide a full view of the problem the equations used is necessary to be presented as below:

Propeller's curve

Based on scientific brochure "P254-04-04 "Basic Principles of Ship Propulsion" MAN B&W Diesel A/S" [10], for a clean hull low-speed ship the resistance is proportional to the square of the ship's speed. Consequently, the required power ($P_{PROPELLER}$) is proportional to the cube of the ship's speed (($N_{PROPELLER}$). For the present work, a non-variable pitch propeller is selected.

As a result:

$P_{PROPELLER} = c_1 * (N_{PROPELLER})^3$, where c_1 is a constant. (2.A)

The above equation precisely expresses the propeller law as it says: " the necessary power absorbed by the propeller is proportional to the cube of the propeller speed".

Equation between vessel's speed and propeller's RPM

$$V_S = k_1 * (N_{PROPELLER})^{1.4} \quad (2.B)$$

Equation of speed reducer

A speed reducer is needed in order to decrease the rpm produced from the engines (N_{SHAFT}) and match those needed on the propeller ($N_{PROPELLER}$) in order to achieve the required vessel's speed (V_S). Therefore, a reduction factor is defined as below:

$$\lambda = \frac{N_{SHAFT}}{N_{PROPELLER}} \quad (2.C)$$

Equation between propeller's power and shaft's power

The exiting power of the engines' system (P_{SHAFT}) isn't the same as the one that the propeller receives ($P_{PROPELLER}$). This is due to the shaft's inertia and the friction within the bearings. Therefore, the power reaching the propeller is defined as below (with the assistance of an efficiency factor " η_{SHAFT}") :

$$P_{PROPELLER} = \eta_{SHAFT} * P_{SHAFT} \quad (2.D)$$

Equations (2.A) and (2.C) yield the following result:

$$P_{PROPELLER} = c_1 * (\frac{N_{SHAFT}}{\lambda})^3 = c_2 * (N_{SHAFT})^3 \quad (2.E)$$

As a result, a connection is created between $P_{PROPELLER}$ and N_{SHAFT}.

Equations (2.B) and (2.C) yield the following result:

$$V_S = k_1 * (\frac{N_{SHAFT}}{\lambda})^{1.4} = k_2 * (N_{SHAFT})^{1.4} \quad (2.F)$$

As a result, a connection is created between V_S and N_{SHAFT}.

Equations (2.D) and (2.E) yield the following result:

$$\eta_{SHAFT} * P_{SHAFT} = c_2 * (N_{SHAFT})^3 \, , \quad (2.G)$$

where:

- $P_{SHAFT} = c_3 * (N_{SHAFT})^3$ (2.G.1)
- $P_{SHAFT} = P_{DIESEL} + P_{EL.MOTOR}$ (2.G.2)

Each moment the required power must be satisfied by the sum of diesel engines' power and electric motors' power. There are different operation modes in which the hybrid propulsion system is working. As a result, it can be mentioned that P_{DIESEL} is always greater than or equal to zero. On the other side, $P_{EL.MOTOR}$ ranges from (-) $P_{EL.MOTOR,MAX}$ to (+) $P_{EL.MOTOR,MAX}$. This takes place because when generating, the electric motor operates as a generator and absorbs the extra power given from the diesel engine in order to charge the battery cells.

Equations (2.F) and (2.G.1) yield the following result:

$$P_{SHAFT} = \text{constant} * (V_S)^{\frac{3}{1.4}} \qquad (2.H)$$

<u>Fuel consumption polynomial</u>

$FuelRate = f(N_{DIESEL}, P_{DIESEL})$ in the form below: (2.I)

$$\text{Fuel Rate} = p_{03} * (P_{DIESEL})^3 + p_{21} * P_{DIESEL} * (N_{DIESEL})^2 + p_{12} * (P_{DIESEL})^2 * N_{DIESEL} + p_{30} * (N_{DIESEL})^3 + p_{02} * (P_{DIESEL})^2 + p_{20} * (N_{DIESEL})^2 + p_{11} * P_{DIESEL} * N_{DIESEL} + p_{01} * P_{DIESEL} + p_{10} * N_{DIESEL} + p_{00}$$

The fuel consumption is calculated from the above polynomial after gathering the necessary data from the manufacturer's datasheet and fuel consumption map.

For the calculation of the constants p_{ij} ($i \in [0,3]$ & $j \in [0,3]$) is used the MATLAB command "poly33". With this command the data gathered from the fuel consumption map of the diesel engine are fitted into a polynomial. The fuel consumption in each moment results from the combination of diesel engine's speed and power at this certain operation point as a two-variate polynomial function $f(N_{DIESEL}, P_{DIESEL})$. The degree of the polynomial is the third. As a result, after scanning the whole territory of the diesel engine map given from its manufacturer, it's known for each combination of diesel engine's speed and power, inside the operation limits, the fuel that is consumed that certain moment. In order to calculate the total fuel consumption, a time integral is used, because the consumption map gives results in the form of "L/hr." More specifically, the fuel rate for each time step is summed and then the total quantity is multiplied by this time step. After the necessary conversions in units, the final result is given in kg.

Willan's model for electric motor's power transformation

For motoring:

$$P_{EL.MOTOR} = e * P_{EL.MOTOR,ELECTRICAL} - P_0 , \quad P_{EL.MOTOR,ELECTRICAL} > 0 \qquad (2.J)$$

For generating:

$$P_{EL.MOTOR} = \frac{P_{EL.MOTOR,ELECTRICAL}}{e} - P_0 , \quad P_{EL.MOTOR,ELECTRICAL} < 0 \qquad (2.K)$$

where $P_{EL.MOTOR}$ is the mechanical power output of the electric motor, $P_{EL.MOTOR,ELECTRICAL}$ is the electric power, P_0 represents the power losses occurring after the conversion of the energy (heat losses, friction etc.) and e is the "indicated efficiency", i.e., the maximum efficiency that can be obtained when P_0 equals to zero. In other words, e and P_0 are the Willan's model coefficients, related with power conversion efficiency. As a convention it is considered that $P_{EL.MOTOR,ELECTRICAL}$ is positive when the electric energy converter operates as an electric motor and negative when it operates as a generator.

State of Charge (SOC) time variation [15] , [16] , [17]

$$\frac{dSOC}{dt} = \frac{(-100)}{Q_{NOM}} * \frac{U_{OC} - \sqrt{(U_{OC})^2 - 4 * P_{EL.MOTOR,ELECTRICAL} * Ri}}{2 * Ri} \qquad (2.L)$$

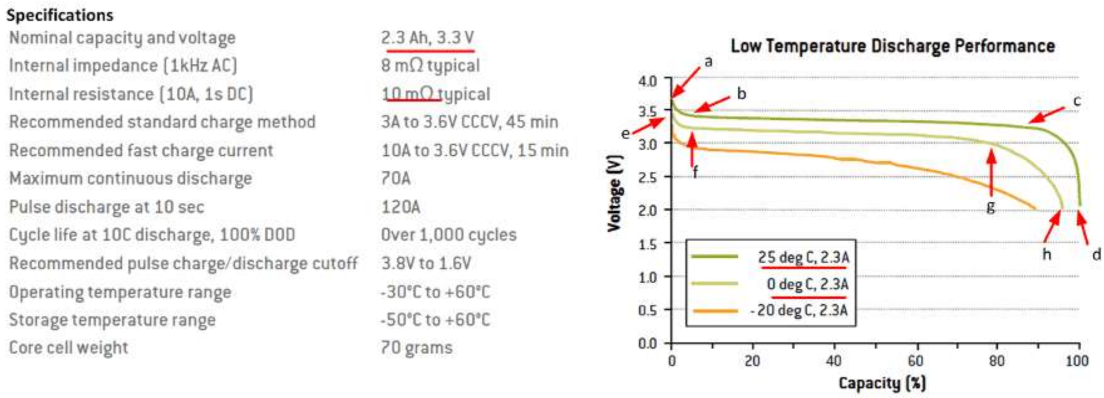
It is considered necessary to mention the definition of the state of charge of a battery. It's defined as the ratio of the available capacity Q(t) to the total capacity ,i.e., the nominal capacity Q_{NOM} :

$$SOC(t) = \frac{Q(t)}{Q_{NOM}} \qquad (2.M)$$

A fully charged battery has a SOC of 100% while a fully discharged as SOC of 0%. Practically, the battery cells usually are not allowed to discharge below a certain value ,e.g., 50% and when the battery reaches this SOC level starts to charge again. This is also important in order to conserve the health of the battery. As a result, the yacht owner won't need to replace the battery packs shortly and will save money in the long run.

Below, in the sector of quasi-static modeling, an analysis of the equation of SOC time variation will take place and it will be proven how and from which this arises. In general, it’s about the variation of the state of charge of the battery as a function of the open-source voltage U_{OC} and the electric power $P_{EL.MOTOR,ELECTRICAL}$.

An example of the above mathematical relation is given in Fig. 10. In the figure there are detailed parameters extracted from the A123 ANR26650M1 battery data sheet.



Specifications

Nominal capacity and voltage	2.3 Ah, 3.3 V
Internal impedance (1kHz AC)	8 mΩ typical
Internal resistance (10A, 1s DC)	10 mΩ typical
Recommended standard charge method	3A to 3.6V CCCV, 45 min
Recommended fast charge current	10A to 3.6V CCCV, 15 min
Maximum continuous discharge	70A
Pulse discharge at 10 sec	120A
Cycle life at 10C discharge, 100% DOD	Over 1,000 cycles
Recommended pulse charge/discharge cutoff	3.8V to 1.6V
Operating temperature range	-30°C to +60°C
Storage temperature range	-50°C to +60°C
Core cell weight	70 grams

Figure 10: A123 ANR26650M1 battery data sheet

CHAPTER 3 : Electric Motor/ Generator Modeling

Information about the machines

Electric motors convert the electrical energy, that comes as an output of the batteries, into mechanical energy and specifically torque at the shaft. Electric generators operate in the opposite direction of energy converting the absorbed extra mechanical energy from the diesel engine into electrical one. Electric machines in general made their first appearance at the mid of 19th century and changed a lot the ship industry. Nowadays, merchant navy uses generators to assist either propulsion needs or hotel services. In addition to this, new yachts are being built with hybrid propulsion systems. Soon, full electric yachts are scheduled to be built where the electric machines will play star role. As a result, electric motors and generators are more and more necessary in the shipping and yachting industry.

For the conversion of mechanical energy into electrical energy and vice versa the most useful tools are the Faraday's law and the Lorentz's law. For the operation of a generator the changing magnetic flux through the generator coils produces an induced EMF (Electromotive Force), which results in a flow of induced current to electrical devices or batteries connected to the generator. In general, the two electric machines operate due to the electromagnetic forces that connects the mechanical motion and the electrical phenomena.

Referring to yachts and especially to hybrid propulsion ones, electric motors and generators play the key role of converting either the electrical power derived from the battery into mechanical power to contribute to the yacht's propulsion or the surplus mechanical power from the diesel engine into electrical one in order to charge the battery. These operations are taking place under the high efficiency and the reliability that marine electric machines offer to the hybrid yacht industry.

Concerning the built up of these machines, the main two components are the rotor and the stator. The rotor is the moving (or rotating more specifically) part of an electromagnetic system in the electric machine. The rotation is being conducted due to magnetic fields which produce a torque around the rotor's axis. The stator is the non-moving, fixed component in the machine. That part of the machine produces the magnetic field that drives the rotating armature. In the generator, the stator converts the rotating magnetic field to electric current.

To view the mechanism by the practical way, the electric motor operates as a positive value when contributing to the vessel's propulsion and as a negative factor when absorbs energy from the diesel engine in order to charge the batteries. As a result, the motor can reach the maximum power that can deliver either in order to produce power for vessel's forwarding or to offer energy to battery cells and recharge them in order to be fully charged whenever needed.

Modeling

In motor modeling approaches the two options to choose from are the quasi-static modeling and the dynamic one. In the present work the quasi-static modeling is chosen. One quasi-static model usually used in propulsion plants modeling is the Willan's model. It's about a linear dependency between the input power to the electric motor from either the diesel engine or the battery pack and the output one of the electric motor either to the battery pack or to the shaft. In other words, when motoring the Willan's approach connects the input electrical power with the output torque (or mechanical power) in a linear dependency. Respectively, when generating the Willan's approach connects the input mechanical power (or torque) with the output electrical power in a linear dependency.

Willan's model

When motoring:

A commonly used quasi-static model that connects the output torque and rotating speed to the shaft with the required power input from the battery. In other words, this model connects the output mechanical power with the input electrical power from the battery. The expression to describe the above is the following:

$$Q_{EL.MOTOR} * \omega_{SHAFT} = e * P_{EL.MOTOR,ELECTRICAL} - P_0 \text{ , where } P_{EL.MOTOR,ELECTRICAL} > 0 \quad (3.A)$$

or

$$P_{EL.MOTOR} = e * P_{EL.MOTOR,ELECTRICAL} - P_0 \text{ , where } P_{EL.MOTOR,ELECTRICAL} > 0 \quad (3.B)$$

When generating:

A commonly used quasi-static model which connects the output power to the battery with the input torque and rotating of the shaft. More specifically, the model connects the output electrical power to the battery with the input mechanical power from the shaft. The expression to describe the above is the following:

$$Q_{EL.MOTOR} * \omega_{SHAFT} = \frac{P_{EL.MOTOR,ELECTRICAL}}{e} - P_0 \text{ , where } P_{EL.MOTOR,ELECTRICAL} < 0 \quad (3.C)$$

or

$$P_{EL.MOTOR} = \frac{P_{EL.MOTOR,ELECTRICAL}}{e} - P_0 \text{ , where } P_{EL.MOTOR,ELECTRICAL} < 0 \quad (3.D)$$

Concerning the above mentioned, $P_{EL.MOTOR}$ is the mechanical power produced or absorbed from the electric motor, ω_{SHAFT} is the rotational speed, $Q_{EL.MOTOR}$ is the input/output torque of the electric motor, $P_{EL.MOTOR,ELECTRICAL}$ is the input/output electrical power of the battery, P_0 represents the power losses occurring after the energy conversion (friction, heat losses, etc.) and e is the "indicated" efficiency, i.e., the maximum efficiency that can be obtained when P_0 is zero. Thus e represents the energy conversion process efficiency (mechanical to electrical energy and vice versa).

As it's already mentioned above, the relation between the mechanical power (or torque) and the electrical power as inputs and outputs of the electric motor is linear. Because of the non-variable P_0, the linear relationship mentioned above depends only on factor e. The parameters e and $\frac{1}{e}$ are the ones that play the role of the slope in the mathematical equations (3.A) – (3.D). Therefore, the factor e and the factor P_0 are described as below:

$$e = 0.9598 \tag{3.E}$$

$$P_0 = EM_{max} * 3.851789 \tag{3.F}$$

where EM_{max} the maximum mechanical power the electric motor can deliver.

These values are taken from the Thesis of Nikolaos Planakis [12] as the most accurate way to express them. For two selected values of EM_{max} , Fig. 11 – Fig. 14 show the relationship between mechanical power and electrical power:

For $EM_{max} =$ 200 kW:

When motoring:

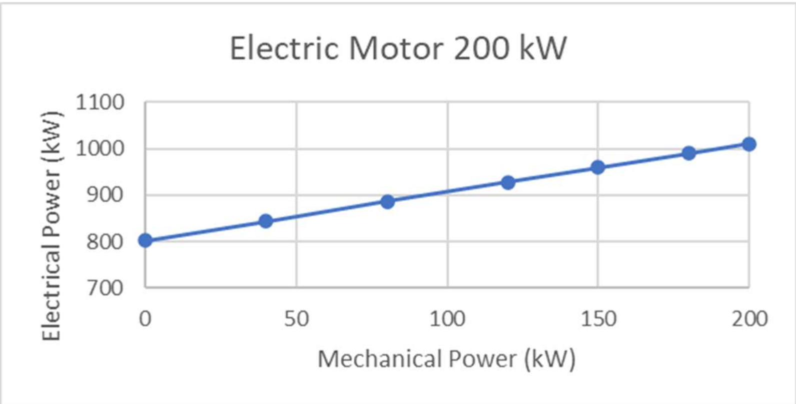


Figure 11: Willan's model results for EM$_{max}$ 200kW in motoring mode.

When generating:

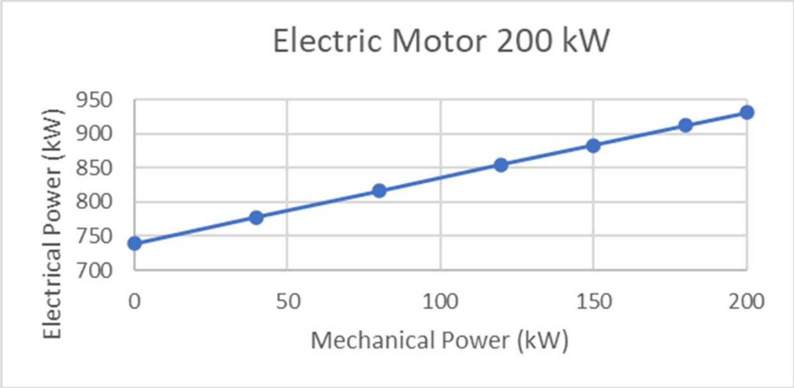


Figure 22: Willan's model results for EM_{max} 200kW in generating mode.

For $EM_{max} = 500$ kW:

When motoring:

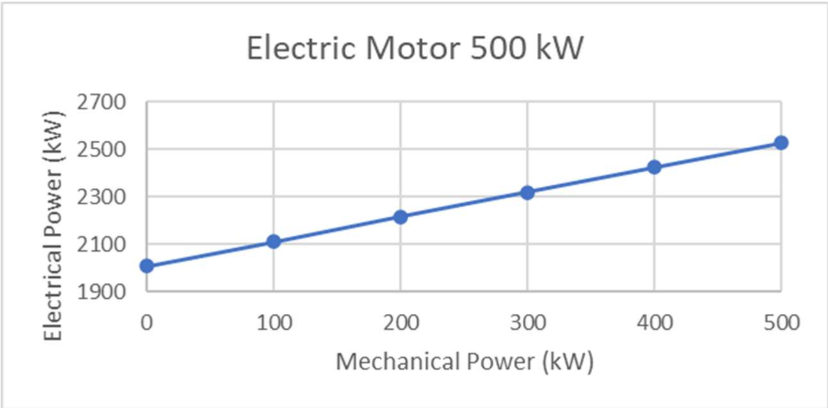


Figure 33: Willan's model results for EM_{max} 500kW in motoring mode.

When generating:

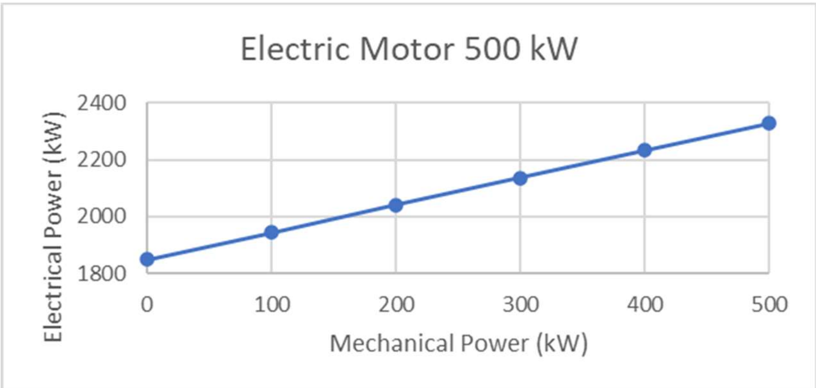


Figure 44: Willan's model results for EM_{max} 500kW in generating mode.

CHAPTER 4 : Batteries

Why Lithium - Ion batteries? [1], [2], [3], [4]

Lithium – Ion batteries are the solution to many inherent limitations or disadvantages that lead acid batteries have. For instance, they are lighter as it concerns the cell's weight, and their size is smaller as well. As a result of the lesser size the user can pack bigger amount of energy in the same space and that results to better performance of the whole battery. Having lighter batteries with the similar capacity affects positively the vessel's buoyancy, speed and maneuverability. Another advantage of Lithium – Ion batteries over lead acid ones is the better efficiency at an equal voltage and amperage (98 % compared to 80 % respectively).

Lifespan of Lithium - Ion batteries are up to 10 times longer than a typical lead acid counterpart, with almost no maintenance required at all to optimize this lifespan and performance. Then it is worth mentioning that Lithium - Ion have an average lifecycle usually between 3.000 - 5.000 cycles, whereas for lead acid batteries the average one is between 500 - 1.000 cycles. Additionally, Lithium - Ion batteries require less recharge time, charging approximately five times faster than lead acid batteries. Another major benefit of using Lithium - Ion technology is that it is eco-friendly compared to lead acid ones because the latter can often leak acid, which can pollute with toxic substances the sea water and the aquatic ecosystems as well.

Nowadays, Lithium - Ion batteries are being built to withstand more efficiently oceanic turbulence. Furthermore, Lithium - Ion technology is generally equipped with an internal battery management system (BMS), which detects dangerous conditions and shuts the battery down to prevent damage or overheating. In addition, Lithium - Ion batteries are sealed and protected from moisture and water splashing.

The only disadvantage of Lithium batteries compared to other types of battery is that they are the priciest of the different types of marine batteries. But that is just the upfront cost. But if it is taken into consideration that they last more than the other types (upwards of 10 years), the money is being saved in the long run.

Modeling

Batteries in marine hybrid propulsion plants play the important role of transforming the electrical energy in chemical form and vice versa in order either to store energy or transmit it if it is required by the electric motors.

Each battery cell is characterized by two quantities. The first is the maximum power that it can provide to the propulsion plant, which can be translated as the rate of energy that the battery can provide to the propulsion plant which is product of voltage and current. The other is the nominal capacity describing the amount of electricity a battery can supply in terms of Coulombs or Ampere-hours.

A magnitude that must be mentioned is the state of charge of the battery. It is defined as the remaining capacity each moment as a percentage of the nominal one. Thus, this dimensionless magnitude is expressed as below:

$$SOC(t) = \frac{Q(t)}{Q_{NOM}} \qquad (4.A)$$

The battery charge, and therefore the state of charge is difficult to be calculated directly. As a result, it is calculated indirectly from the charge equilibrium which is expressed from:

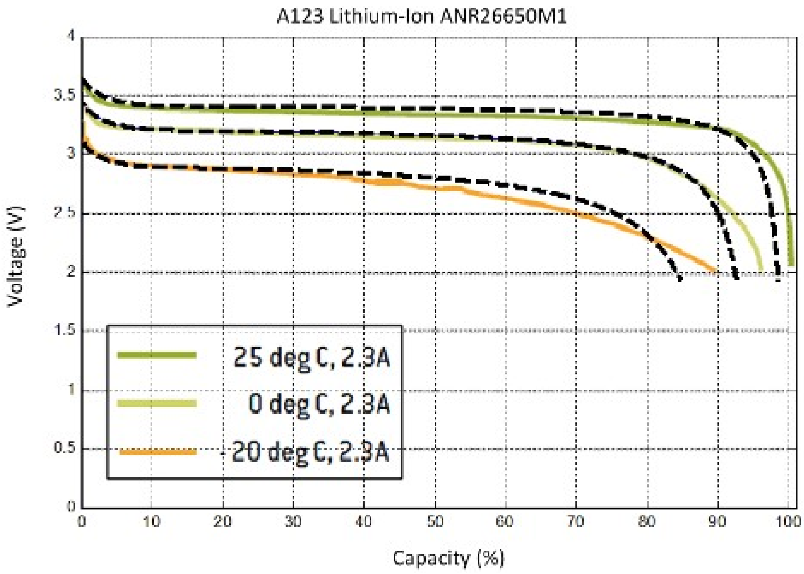
$$\dot{Q}(t) = -I_b(t) \qquad (4.B)$$

At this point, must be mentioned that there is a certain margin of the percentage of battery capacity that can be used during the operation of the vessel, in order to maximize battery life. More specifically, there is a maximum value of SOC that can be reached during charging and a minimum value of SOC that can also be achieved during discharging. This feature is expressed by the specific energy of battery. The following attributes of a battery pack are required when operating in hybrid power plants:

- High specific energy
- Long cycle life
- Low initial and replacement costs
- High reliability.

It’s worth mentioning that the battery cells are connected in parallel or/and in series. The parallel connection is used to increase the total capacity of the battery and the series one to increase the voltage.

In the present work, the battery behavior consists of two parts: the linear and the non-linear. In other words, the battery voltage is a function of the SOC. From 10-20% to 80-90% of SOC the behavior of the battery is linear. For the remaining values of SOC, the behavior is non-linear. Most of the operation of the batteries is held in the linear part. However, efforts are taking place in order to understand and model the non-linear part also. Two typical voltage-SOC diagrams are presented in Fig. 15,16.



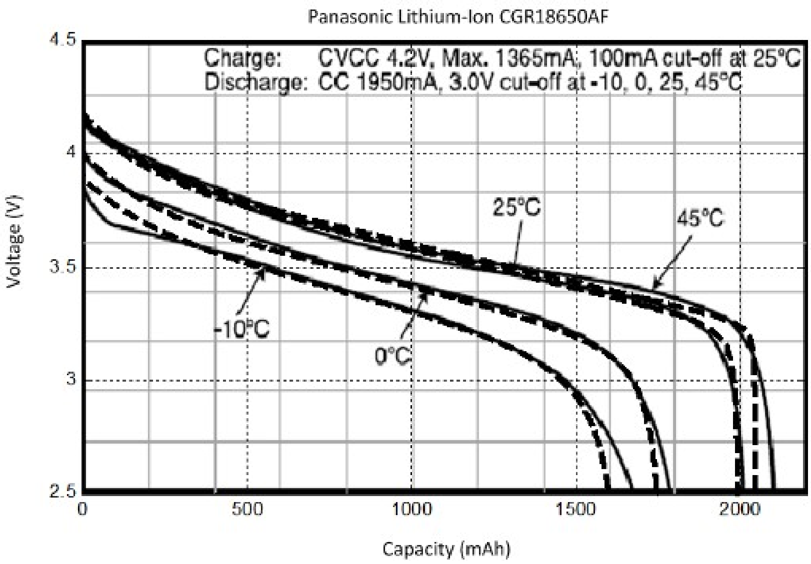


Figure 15,16: Battery’s voltage behavior as a function of capacity [16]

Quasi-static model

The quasi-static model is based on the equivalent circuit, which is presented in Fig. 17.

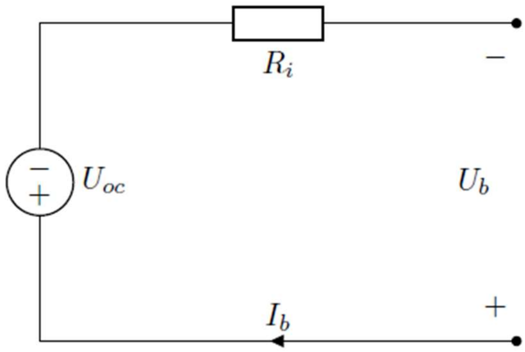


Figure 17: Equivalent circuit of quasi-static battery model

In the equivalent circuit model, there are a voltage source and a resistance. The first component refers to open-source voltage and represents the equilibrium potential of the battery. This quantity depends on the charge level and the following relationship express it.

$$U_{oc}(t) = c_2 * SOC(t) + c_1 \quad (4.C)$$

As it concerns the resistance, it is about the internal resistance of the battery cell. This includes the ohmic resistance, the charge-transfer resistance and the diffusion resistance. Consequently, the sum of the above is represented by the total internal resistance as below:

$$R_i = R_o + R_{ct} + R_d \quad (4.D)$$

The terminal battery voltage is calculated via the Kirchhoff's voltage law:

$$U_b(t) = U_{oc}(t) - R_i(t) * I_b(t) \quad (4.E)$$

In the present work, the input/output power of the battery is denoted by $P_b(t)$. As a result, the relation between the current, the required/delivered power and the terminal voltage is the following:

$$I_b(t) = \frac{P_b(t)}{U_b\,(t)} \quad (4.F)$$

By combining the past two relations, the following expression for the terminal voltage occurs:

$$[U_b\ (t)]^{\ 2} - U_{oc}(t) * U_b\ (t) + P_b(t) * R_i(t) = 0 \qquad (4.G)$$

The solution of the above equation is:

$$U_b(t) = \frac{U_{oc}(t)}{2} + \sqrt{\frac{[U_{oc}\ (t)]^2}{4} - P_b(t) * R_i(t)} \qquad (4.H)$$

As a result of the above, the battery current is calculated as:

$$I_b(t) = \frac{U_{oc}(t) - \sqrt{[U_{oc}\ (t)]^2 - 4 * P_b(t) * R_i(t)}}{2 * R_i(t)} \qquad (4.I)$$

Consequently, the state of charge is calculated via the following equation:

$$\frac{dSOC}{dt} = -\frac{100}{Q_{nom}} * \frac{U_{oc}(t) - \sqrt{[U_{oc}\ (t)]^2 - 4 * P_b(t) * R_i(t)}}{2 * R_i(t)} \qquad (4.J)$$

Finally, it must be mentioned that the configuration of the battery cells is made up of cells connected in parallel or/and in series, consisted of N_S cells in series and N_P in parallel. As it concerns the voltage and the resistance, the expressions are as below:

$$U_{oc} = N_S * U_{cell} \qquad (4.K)$$

and

$$R_i = R_{cell} * \frac{N_S}{N_P} \qquad (4.L)$$

The total capacity of the battery is calculated as below:

$$Q_o = N_P * Q_{cell} \qquad (4.M)$$

As Michele Maggi, CEO and founder of company named “e-MOTION”, said it can easily be observed from the parallel hybrid propulsion system of the video of “BoatTEST.com”, where Maggi presents their products, that the operating total voltage of the battery is about 650V. The same’s magnitude battery voltage is selected for the present work, as it is the most reliable available for one hybrid diesel-electric yacht.

CHAPTER 5 : Optimization in MATLAB

The present work is based on creating a useful tool in order to find the best combination of Diesel Engine, Generator/Electric Motor and capacity of battery pack in order to minimize the fuel consumption in a predetermined itinerary of a hybrid diesel electric mega yacht.

First of all, it is necessary to point out that the present work can be used for hybrid diesel electric yachts of all sizes because the decision elements are variables that can change based on user input. So that it meets the requirements, an enriched library with all the necessary data is the only but an important addition that would be needed for those that want to use this tool professionally. As it concerns the present work, below in the text it is specifically mentioned at which values the analysis takes place.

To get the job started, an introductory MATLAB script is created. Its main goal is to let the user the freedom needed to insert some necessary data. For instance, the user inserts the speed profile of the yacht for one certain itinerary. In addition, the user has to insert the MCR of the diesel engine, the MCR of the electric motor, the battery characteristics needed and the file produced from the fuel consumption map. Including all the above, the introductory MATLAB script produces necessary information. For example, the values of the constants of the third-degree fuel consumption polynomial needed for the computation of the total fuel consumption for the certain itinerary of the yacht.

Afterwards, there are some scripts where the total problem is described, including the Willan's approach for the conversion of the energy before and after the electric motor, the calculation of the state of charge of the battery each moment, the cost function needed for the optimization and the creation of grids needed with the final data for the whole itinerary. As it is said above, the optimization takes place with the application of the dynamic programming method, using the MATLAB function *dpm*. An analysis of this optimization tool and the theory behind will take place below, based on research articles and papers published by ETH Zürich.

Dynamic Programming

As in the present work, it deals with a deterministic problem the *dpm* function is the best choice to get the optimization done because of its high efficiency in this kind of problems. This function uses Bellman's dynamic programming algorithm. In general, the user's only duty is to provide the equations and the objective function needed so as to get the desired result. Inside the programming tool the state variable, the input variables and the constraints needed are entered from the user in the programming section. In the present work, it's about a discrete-time problem, as the inputs are being given in a non-continuous way but in function with time steps.

The *dpm* function is eligible for solving optimal control problems (OCP), but it can also provide solution for any other problem if it's about dynamic programming. For example, a problem solution mathematical system for this function, can be written as below [18] :

$$min_{u(t)}\, J\big(u(t)\big) \tag{5.A}$$

$$\dot{x}(t) \;=\; F(x(t), u(t), t) \tag{5.B}$$

$$x(0) = \; x_0 \tag{5.C}$$

$$x(t_f) \;\in\; [x_{f\,,min}\,, x_{f,max}] \tag{5.D}$$

$$x_t \;\in\; X(t) \;\subset\; R^n \tag{5.E}$$

$$u_t \;\in\; U(t) \;\subset\; R^n \tag{5.F}$$

The cost functional is the above:

$$J(u(t)) \;=\; G(x(t_f)) \;+\; \int_0^{t_f} H(x(t), u(t), t)\, dt \tag{5.G}$$

Bellman's dynamic programming algorithm

The discrete-time model is given by the following relation:

$$x_{k+1} \;=\; F_k(x_k, u_k)\,, \quad k \;=\; 0,1,\ldots, N-1 \tag{5.H}$$

where the state variable $x_k \in X_k$ and the control signal $u_k \in U_k$.

Furthermore, an analysis of the basic algorithm is given below. Let π be a control policy, where π is defined as $\pi = \{\mu_0, \mu_1, \ldots, \mu_{N-1}\}$ and also let the discretized cost of relation (5.G) using π having as initial state $x(0) = x_0$ be:

$$J_\pi(x_0) = g_N(x_N) + \varphi_N(x_N) + \sum_{k=0}^{N-1} h_k(x_k, \mu_k(x_k)) + \varphi_k(x_k) \tag{5.I}$$

where:

$g_N(x_N) + \varphi_N(x_N)$ is the final cost, as the $g_N(x_N)$ is the final cost in relation (5.G) and $\varphi_N(x_N)$ is like an additional penalty function if needed in order strengthening a constraint on the final state (5.D). As it concerns the function $h_k(x_k, \mu_k(x_k))$, it's about the cost of applying the control $\mu_k(x_k)$ at x_k, according to $H(x(t), u(t), t)$ of the relation (5.G). In addition, relation (5.E) speaks about constraints. These are imposed by $\varphi_k(x_k)$ for $k = 0,1,\ldots,N-1$. There is an optimal value of control policy that minimizes the cost function. This is symbolized as π^0 and the relation is written as below:

$$J^0(x_0) = min_{(\pi \in \Pi)} J_\pi(x_0) \tag{5.J}$$

where Π is the set of all admissible policies.

Based on relation (5.A), which expresses the optimality, this algorithm evaluates the optimal " cost-to-go " function $J_k(x^i)$, as it's called, at each node in the discretized state-time space via the backward in time procedure:

1. End cost calculation step

$$J_N(x^i) = g_N(x^i) + \varphi_N(x^i) \tag{5.K}$$

2. Intermediate calculation step for $k = N - 1$ to 0

$$J_k(x^i) = min_{(u_k \in U_k)}\{ h_k(x^i, u_k) + \varphi_k(x^i) + J_{k+1}(F_k(x^i, u_k))\} \tag{5.L}$$

The optimal control is produced by the argument that minimizes the right-hand side of the relation (5.L) for every x^i at time index k of the discretized state-time space.

Regarding the " cost-to-go " function $J_{k+1}(x)$ used in relation (5.L), it's assessed only on discretized points in the state space. As it concerns the output of the model function $F_k(x^i, u_k)$, it's a continuous variable inside the state space that can be betwixt the state grid's nodes. Therefore, the $J_{k+1}(F_k(x^i, u_k))$ should be evaluated aptly. It's known that it's possible to use plenty methods in order to identify the right form of the cost-to-go $J_{k+1}(F_k(x^i, u_k))$ using advanced interpolation methods or even the nearest-neighbor estimation. Referring to the *dpm* function, as it's the tool that is used in the present work, the method used is the linear interpolation of the J_{k+1}. Taking into account that there is equally time spacing in the inputs, it should be mentioned that the computational cost for this interpolation is low compared to the cost induced by the model evaluations.

To continue, it has to be referred that the output of the relations (5.K) and (5.L), is an optimal control signal map. This is used as the tool to detect the optimal control signal during a forward simulation of the discrete-time model (5.H), given an initial state x_0 to generate the optimal state route. Generally, the complexity of the dynamic programming algorithm is exponential in the number of state and input variables.

The *dpm* function

Concerning the MATLAB function used in the present work, it is the solution tool of the discretized version of the optimal control problem, referring to relations (5.A) to (5.G), via the dynamic programming algorithm presented above. Sometimes the dynamic programming algorithm may need a lot of time to run and the solution is to choose only the forward simulation. In contrast with the above, as it concerns the present work, both the backward and the forward simulations are running. As a result, there is adequate accuracy in the outcome.

Moreover, the *dpm* function [14] contains some specific structures. For example, the *problem structure (prb)*, in which there are two very important parameters: the time step T_s of the model description and the problem length *N*. The latter can be described as the number of time steps T_s in the problem. These are defined by the user before the start of the simulations and must be ascertained that the value of T_s is the same in the input data sheet and that the number of the total points to operate is equal to *N*. Another useful parameter is the vectors *W { . }* . They have length equal to *N* and include time variant data for the model.

Another structure that the algorithm contains is the *grid* structure *(grd)*. In this structure the total state and input grids and constraints are included. The *grd* structure is assembled from cell arrays and for each state variable and each input one, a cell is available. For instance, for a problem with two state variables there are the following in the *grd* structure:

- *grd.X{1}* , *grd.X{2}* and
- *grd.Xn{1}.lo* , *grd.Xn{2}.lo* etc.

More specifically, using this algorithm the user finds in the coding section the following expressions about the *grid* structure:

- *Nx{ . }* : number of grid points in state grid
- *Xn.{ . }.lo* : lower limits for each state
- *Xn.{ . }.hi* : upper limits for each state
- *XN.{ . }.lo* : final state lower constraints
- *XN.{ . }.hi* : final state upper constraints
- *X0{ . }* : initial value
- *Nu{ . }* : number of grid points in input grid
- *Un{ . }.lo* : lower limits for each input
- *Un{ . }.hi* : upper limits for each input

Moreover, another structure in this dynamic programming algorithm is the *options structure (options)*. This structure is like an instruction section for how to use this algorithm. For instance, there is an option called *UseLine* which shows whether the boundary line is used or not. It should be mentioned that this line is important because it increases the accuracy of problems with final state constraints. More *options* that the user of this algorithm can use are shown below:

- *HideWaitbar* : hide waitbars when running the dynamic programming.
- *Warnings* : show warnings.
- *SaveMap* : determines if the optimal cost-to-go is saved.
- *UseLine* : use boundary line method.
- *FixedGrid* : using the original grid as specified in *grd* or adjust the grid to the boundary lines.
- *Iter* : maximum number of iterations when inverting model.
- *Tol* : minimum tolerance when inverting model.
- *InfCost* : cost of infeasible states and inputs of the model
- *gN {1}* : cost matrix at the final time.

As it concerns the output of this dynamic programming tool, these are two structures named *results (res)* and *dp-output(dyn)*. The former structure includes the results after the forward simulation of the model. The latter is associated with the optimal control map and the optimal cost-to-go. It has to be mentioned that when the boundary line method is used, the *dyn* structure contains the lines.

Additionally, using this algorithm the user finds in the coding section the following expressions about the *res* structure:

- *X{ . }* : state trajectories
- *C{ . }* : cost trajectory
- *I* : infeasible vector
- *Signals* : all the signals that were saved in the model function

Furthermore, using this algorithm the user finds in the coding section the following expressions about the *dyn* structure:

- *B.hi* : *Xo, Uo{ . }, Jo* contains the cost, input and state for the upper boundary line
- *B.lo* : *Xo, Uo{ . }, Jo* contains the cost, input and state for the lower boundary line
- *Jo{ . , . }* : optimal cost-to-go
- *Uo{ . , . }* : optimal control input

In order to be used in the dynamic programming tool, all the model equations needed must be in the correct form. Generally, the model function should have the below format:

```
function [X, C, I, signals] = sample_model(inp,par)
```

where the *input* structure *(inp)* is generated by the *dpm* function. It should also be referred the importance of inputs and outputs having the same size. The *par* structure can contain any parameter user defines as necessary in order to be included in the model function. Finally, *signals* contain any user defined internal signals in model.

How *dpm* function is used for a hybrid yacht optimization ?

As already mentioned, the parameter to minimize in the present work is the total fuel consumption in a certain itinerary. This is happening using a quasi-static discrete time model. It is selected to have only one state variable and this is the state of charge of the battery of the hybrid yacht. As it concerns the ICE, data are gathered from the fuel consumption map of the engine, as the fuel rate is a function of the speed engine and the power. The electric motor is modeled with the assistance of the Willan's approximation. The battery is modeled by the aid of the quasi-static model based on the equivalent circuit.

The final relation in order to achieve the goal of the present work is the following, summarizing all the equations used:

$$x_{k+1} = f(x_k, u_k) + x_k \ , \qquad k = 0,1,\ldots,N-1 \tag{5.M}$$

where x_k is the state of charge of the battery and u_k is the torque split.

As it concerns the optimization of the fuel consumption, and more specifically the minimization of the total fuel mass consumed for a certain itinerary, it is contained in the following relation:

$$J = \sum_{k=0}^{N-1} \Delta m_f(u_k, k) \, * \, T_s \tag{5.N}$$

for a hybrid diesel-electric yacht with a certain speed profile, where $\Delta m_f \, * \, T_s$ is the fuel consumption in each time step T_s. Taking into account the necessary initial values, final state constraints and upper and lower limits for the state variable, the final result is derived using the dynamic programming tool.

In Table 1, there are the input data of the present work:

inp.X{1}	SOC	State Of Charge
inp.U{1}	uTice	ICE Torque
inp.U{2}	uTel	Electric Motor Torque
inp.W{1}	SE	Speed Engine
inp.W{2}	Tload	Total Torque Load
inp.Ts	Time step	-

Table 1: Input data for *dpm*

CHAPTER 6 : Results

The present work uses the *dpm* MATLAB function for calculating the total fuel consumption for a certain itinerary. There are some diesel engines selected, a range of electric motor maximum delivery power and another range of battery capacity. Each diesel engine is combined with some different values of the other two magnitudes. In the end of this chapter, the total of all combinations is compared in order to find the best configuration for the type of yacht selected in the present thesis. In Table 2 all the combinations are mentioned:

No.	Diesel Engine – MCR (kW)	El. Motor – Max Power (kW)	Battery Capacity (Ah)
1.1	2100	200	500
1.2	2100	400	1000
1.3	2100	500	1400
1.4	2100	600	1500
1.5	2100	800	2200
1.6	2100	1000	2500
2.1	1900	100	500
2.2	1900	200	1000
3.1	2460	100	1500
4.1	2000	500	1500
4.2	2000	800	2500

Table 2: Propulsion system parts combinations

where:

- Diesel Engine A (No. 1.1 – 1.6) is the CAT 3516C HD.
- Diesel Engine B (No. 2.1 – 2.2) is the CAT C280-6.
- Diesel Engine C (No. 3.1) is the CAT C280-8.
- Diesel Engine D (No. 4.1 – 4.2) is the CAT 175-16 DITA.
- The first column refers to a numeration system for the combinations.
- The second column refers to MCR of diesel engines.
- The third column refers to maximum power of electric motors.
- The fourth column refers to the total capacity of the battery pack.

Results Analysis

In order to have a clear view of what the results exactly are, there is an analysis and explanations about what the figures show. Some representative figures are being analyzed and the analysis includes all the necessary information. The totality of results and figures of all the combinations are shown after the present subchapter "Results Analysis". To start with, the Fig. 18 is chosen because it depicts the vessel's speed profile:

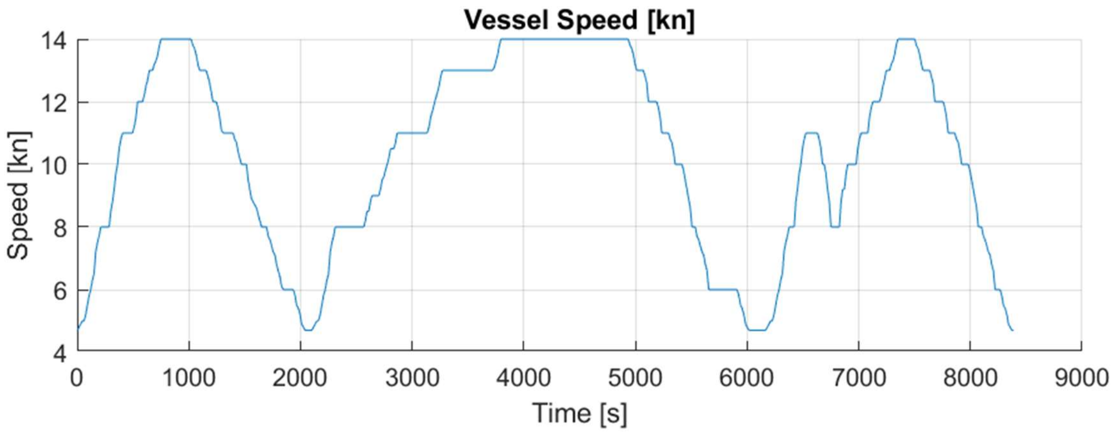


Figure 18: Vessel's speed profile

As it can be observed from Fig. 18, the yacht operates for about two-and-a-half -hour voyage, starting to increase speed gradually and when reaching the top speed needed after keeping pace for some time, then starts to decrease speed. The same takes place two times more times before the end of the voyage with the differences of keeping constant speed for more time and more different speeds in the second "step" profile than the first one, which show that it maybe operates in open sea. Another difference noted in the third "step" profile of the total speed profile is the fact that there is a smaller "step" at its start. Then, it follows a continuous increasing speed until a certain distance from the destination when it starts slowing down but in a faster way than before.

The above it's a sample speed profile and as a result the effect to the total fuel consumption is unique. For alterative speed profiles, the code and the optimization tool can operate effectively and the user will get obviously different results. This is deemed necessary to point out in order to clarify that the code and the *dpm* function can work in a variety of speed profiles and not only in the one selected in the present work.

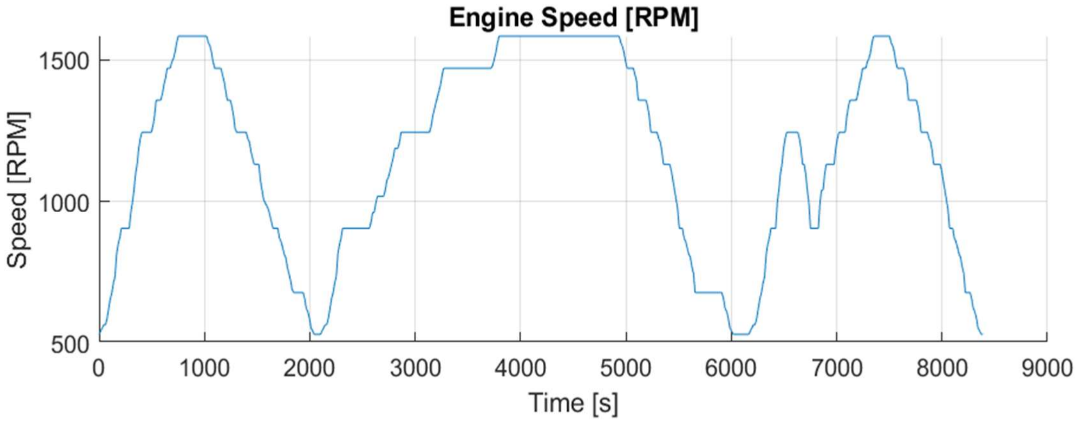


Figure 19: Engine speed profile for combinations of CAT 3516C-HD diesel engine

Concerning Fig. 19,51,63 and 70 which are each diesel engine combinations' speed profile, a similarity with Fig. 18,50,62,69 can be noticed and that's because the speed that the engines run is proportional to vessel's speed given by the following equation:

$$RPM = Vs * \frac{RPMmax}{Vsmax} \quad (6.A)$$

Subsequently, Fig. 40 – 44 are selected as indicative so that data produced can be interpreted. Thereafter, Fig. 40 is the representative figure about the diesel engines' operation and Fig. 41 the one about the electric motors' operation during the selected speed profile.

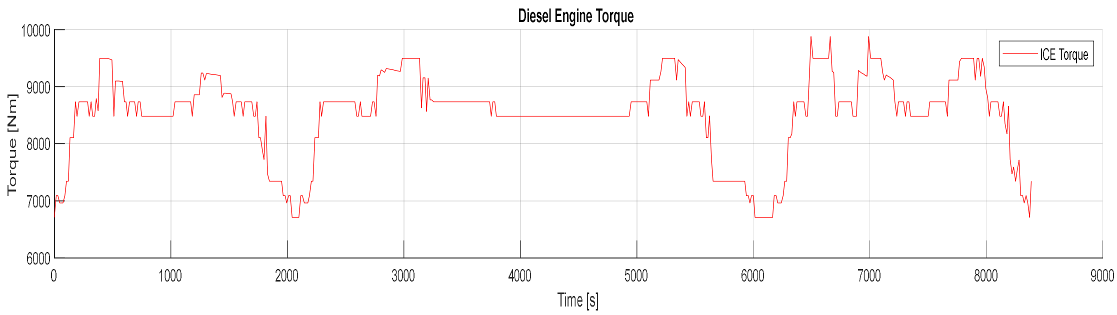


Figure 40: Diesel Engine Torque for combination No. (1.5)

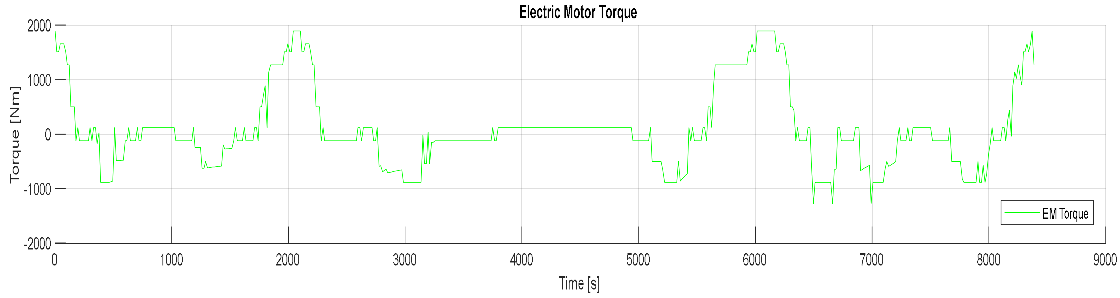


Figure 41: Electric Motor Torque for combination No. (1.5)

When electric motor's torque is positive, i.e., when motoring, then the motor contributes to the total required power in order to achieve the propulsion speed in that time and as a result the batteries' capacity decreases. Obviously, when the motor contributes to the total power, the diesel engine provides less power and the fuel economy is achieved. Many peaks can be noticed such as these on about 2100 s point and on the last seconds, and some constant positive electric motors' torque values such as these between 800 and 1000 s and between 5700 and 5900 s. This results in receiving for an acceptable period of time the propulsion plant a remarkable amount of power from the electric motors. Moreover, it's clear that most of the time the electric motor offers power to the propulsion plant which keeps the fuel consumption in lower levels than using only the diesel engines to forward the vessel and confirms the value of installing this machines in the marine industry.

On the other side, when electric motor's torque is below zero, i.e., when generating, it means that this period of time the electric motor absorbs the extra energy from what it's needed to move the vessel in the required speed, in order to charge the batteries. As it's said above, the time that electric motor consumes mechanical power is less than those that contributes to reach the required power. Another interesting fact is that when in generating mode, the peaks are lower in absolute value and the time that they reach their peaks is also shorter than the corresponding duration of positive peaks when in motoring.

It can also be noted that when the vessel sails in constant speed, also the engines operate in constant mode without altering the power delivering or receiving. This eliminates the power losses these time periods and helps keeping the total power at a constant level. On the other hand, when the vessel's speed changes continuously, power accelerations and slowdowns appear, increasing power losses and as a result having lower efficiency at the torque that reaches the propeller.

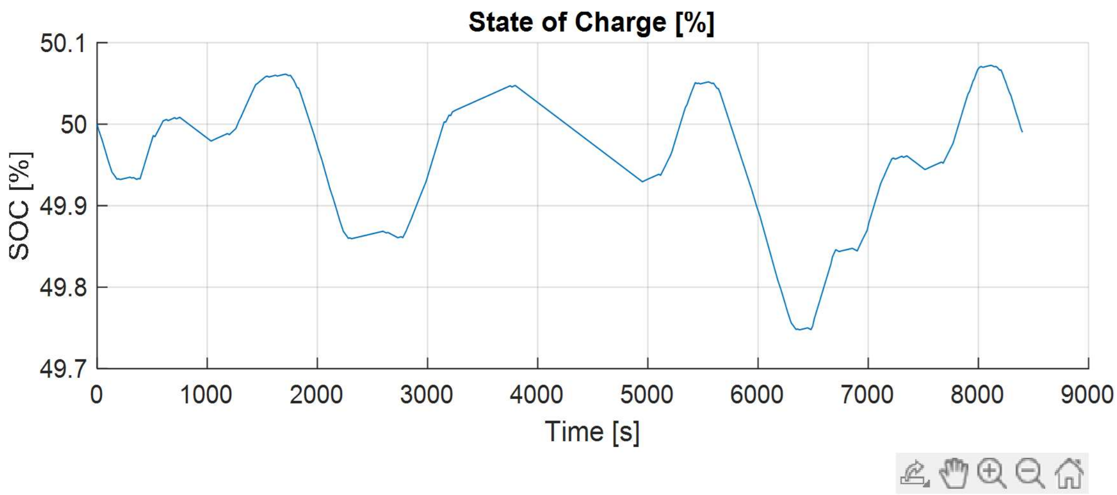


Figure 43: State of charge alteration over time for combination No. (1.5)

Regarding the state of charge alteration during the voyage, it can be noted that there aren't big fluctuations as it concerns the value. In other words, as Fig. 43 depicts the SOC ranges between 49.7 and 50.1%. On the contrary, Fig. 43 shows a lot of in number fluctuations with increases and decreases during the voyage. For instance, the biggest variations is from 1800 to 2200 s and from 5500 to 6200 s. In both of these time periods, it can be seen in Fig. 41 that there are positive "steps" in the electric motor power profile.

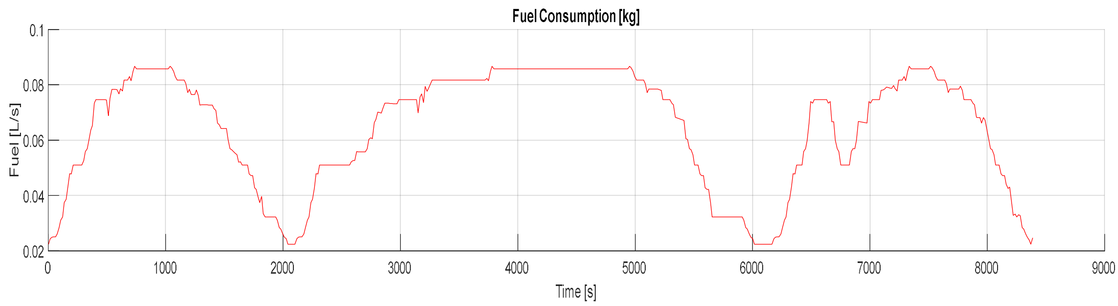


Figure 44: Fuel consumption for combination No. (1.5)

Finally, as it concerns the fuel consumption diagram, the fuel rate in L/s measurement unit is depicted. The integral of the above diagram is equal to the total fuel liters consumed for the certain voyage selected. As a result, it needed to convert the liters into kg in order to have the exact fuel mass consumed. As it is depicted in Fig. 44, the fuel rate follows the speed profile. In other words, when the vessel operates in higher speeds, needs more fuel to achieve them. From 3800 to 5000 s, when the vessel reaches for a long period of time the maximum speed, the fuel rate remains also at its top. To conclude, this behavior of the fuel rate is reasonable because the main provider of power is the diesel engine and when the vessel operates in low speed the fuel rate will be small and respectively when it operates in high speed the fuel rate is greater.

Results for totality of combinations

To continue with, the speed profile, for the certain itinerary the yacht operates in the present work, is common for all combinations. It is considered that approximately a two and a half hours itinerary is a sufficient sample to get all the necessary information. Moreover, for each combination, the diagrams below depict the alteration of the state of charge of the battery over time, the alteration of the torques of diesel engines and electric motors over time and the fuel rate during the itinerary.

CAT 3516C HD

To start with, the vessel' speed profile and the corresponding engine speed profile for the combinations of CAT 3516C HD diesel engine are depicted in Fig. 18,19:

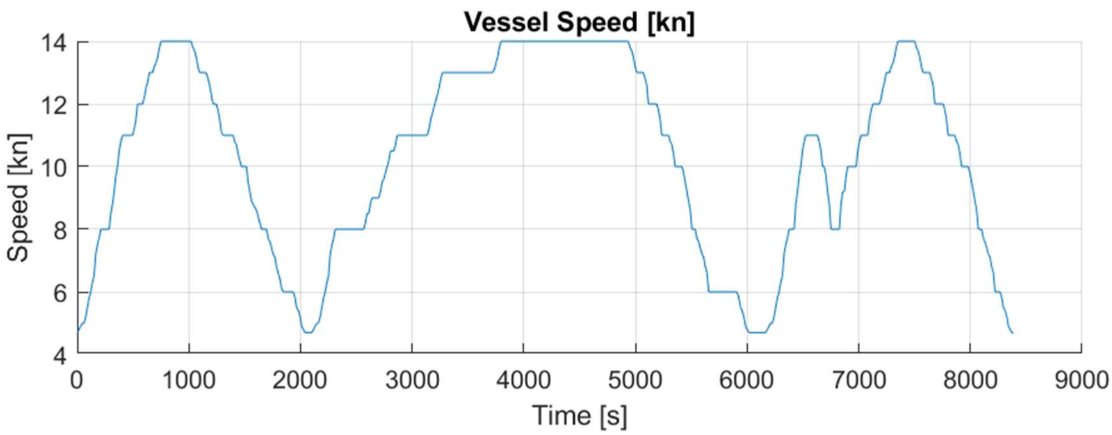


Figure 18: Vessel's speed profile

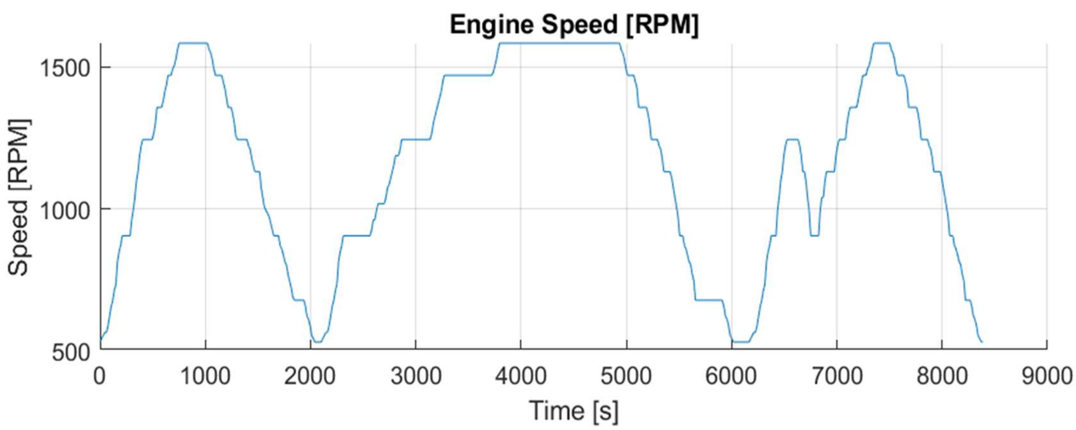


Figure 19: Engine speed profile for combinations of CAT 3516C-HD diesel engine

Combination 1.1

Below, there are the diagrams for the combination No. (1.1) which has the following propulsion system parts data:

Diesel Engine – MCR (kW)	El. Motor – Max Power (kW)	Battery Capacity (Ah)
2100	200	500

Table 3: Combination No. (1.1) data

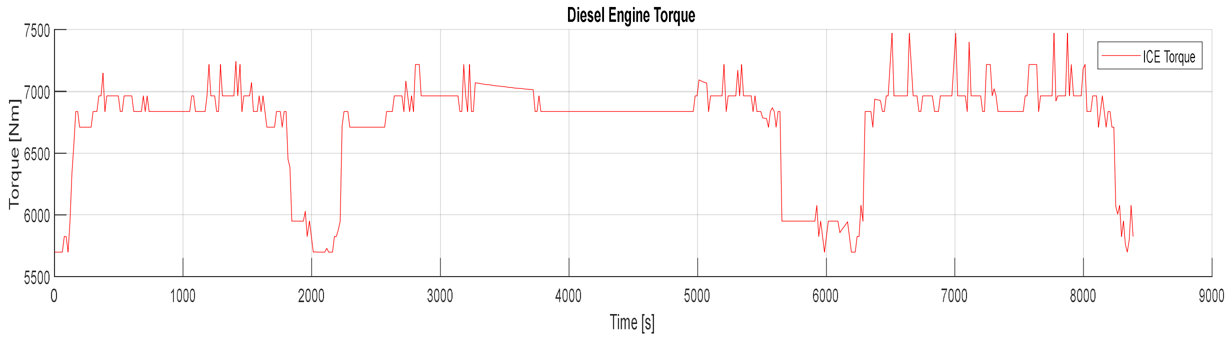


Figure 20: Diesel Engine Torque for combination No. (1.1)

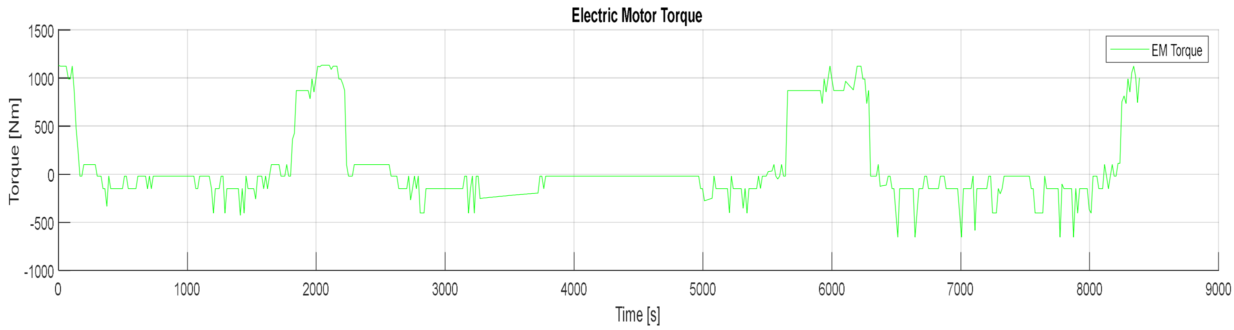


Figure 21: Electric Motor Torque for combination No. (1.1)

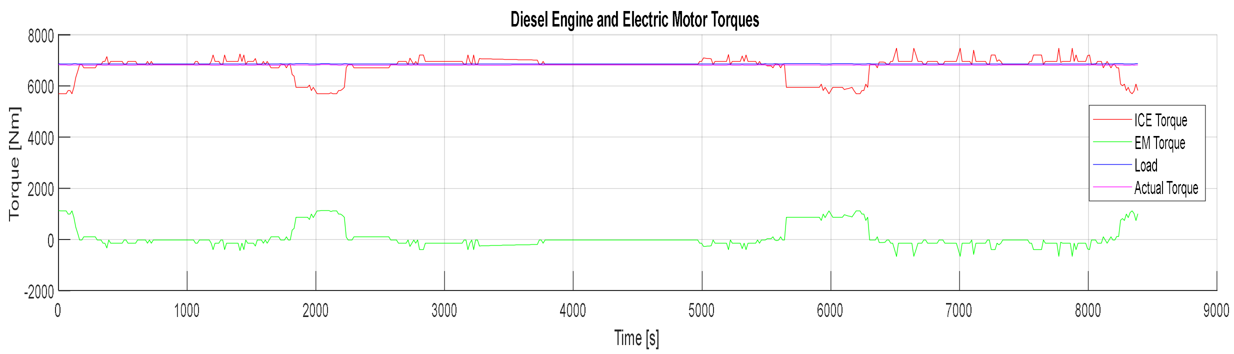


Figure 22: ICE Torque, EM Torque, Load and Actual Torque for combination No. (1.1)

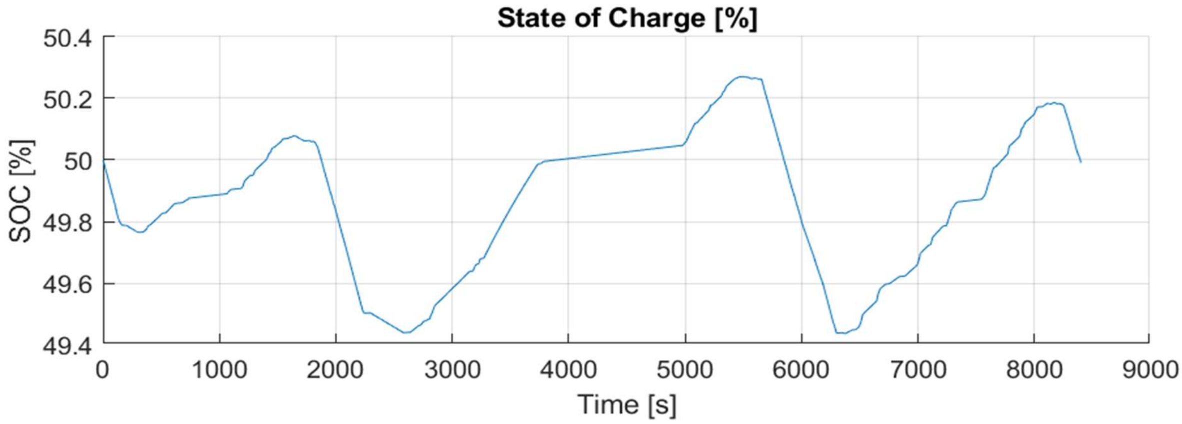


Figure 23: State of charge alteration over time for combination No. (1.1)

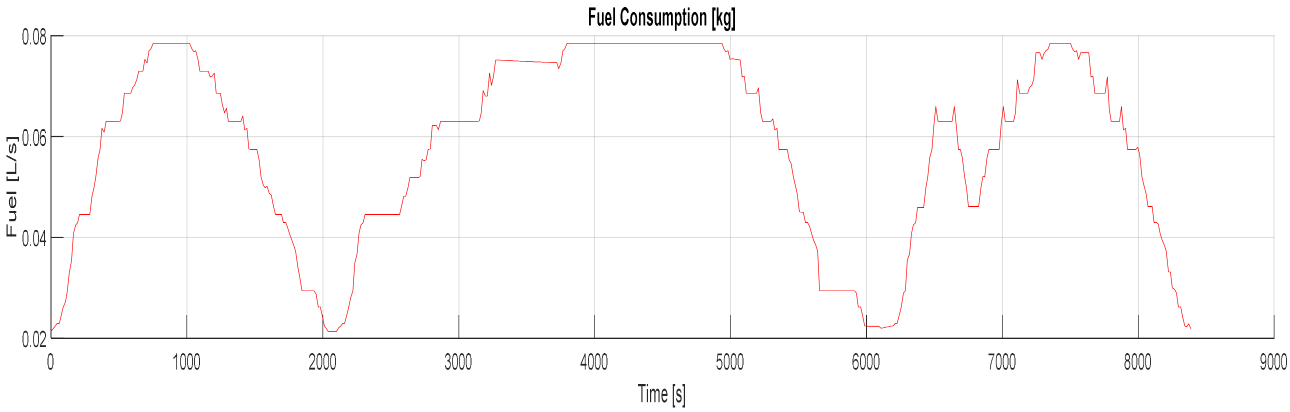


Figure 24: Fuel consumption for combination No. (1.1)

The integral of the above diagram gives 488 L. By multiplying the liters with the density of the marine diesel, which is 0.9 $\frac{kg}{L}$, the result that occurs is 439.2 kg. This results to total fuel consumption for this certain itinerary for the yacht's propulsion system configuration No. (1.1) is calculated at 439.2 kg.

Combination 1.2

Below, there are the diagrams for the combination No. (1.2) which has the following propulsion system parts data:

Diesel Engine – MCR (kW)	El. Motor – Max Power (kW)	Battery Capacity (Ah)
2100	400	1000

Table 4: Combination No. (1.2) data

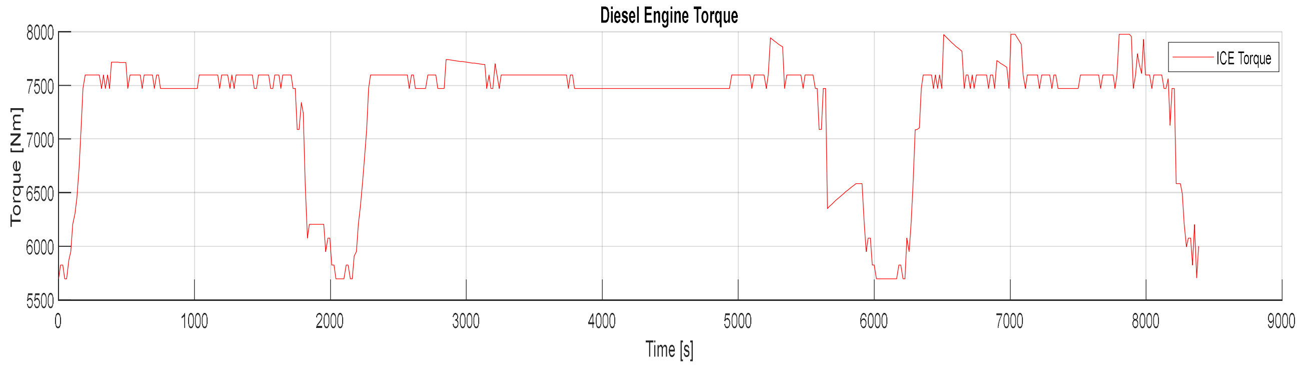


Figure 25: Diesel Engine Torque for combination No. (1.2)

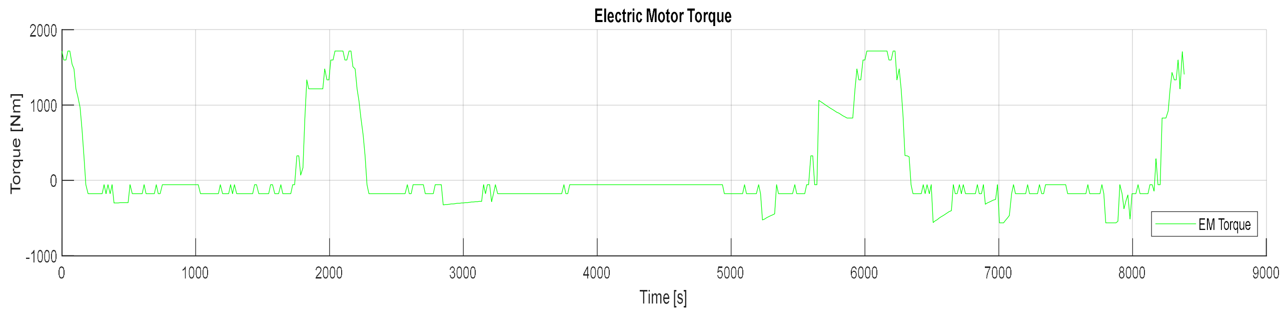


Figure 26: Electric Motor Torque for combination No. (1.2)

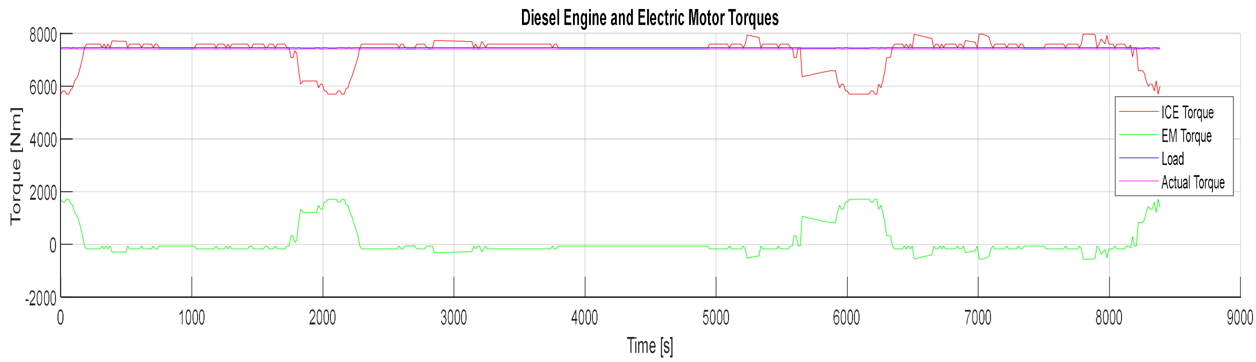


Figure 27: ICE Torque, EM Torque, Load and Actual Torque for combination No.(1.2)

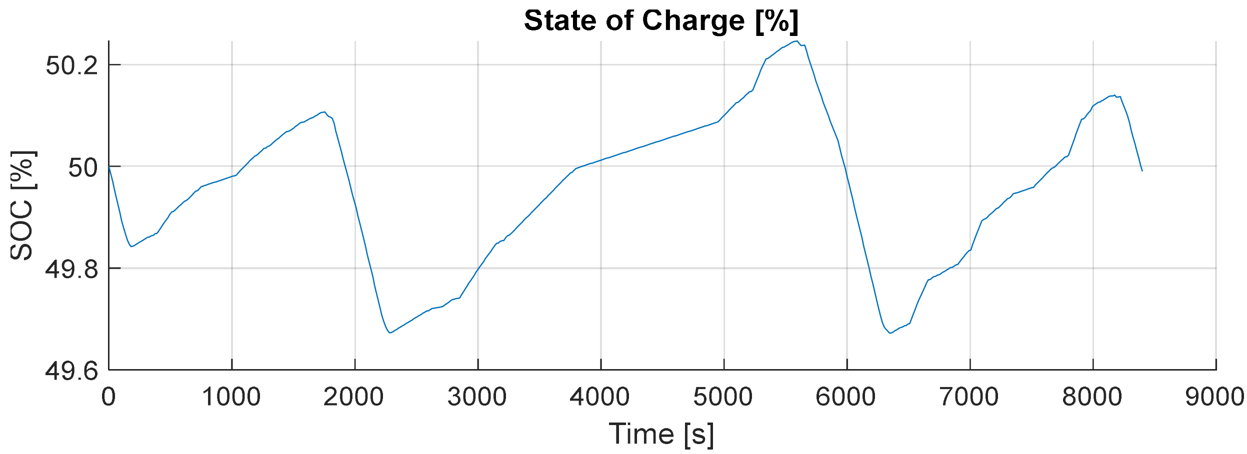


Figure 28: State of charge alteration over time for combination No. (1.2)

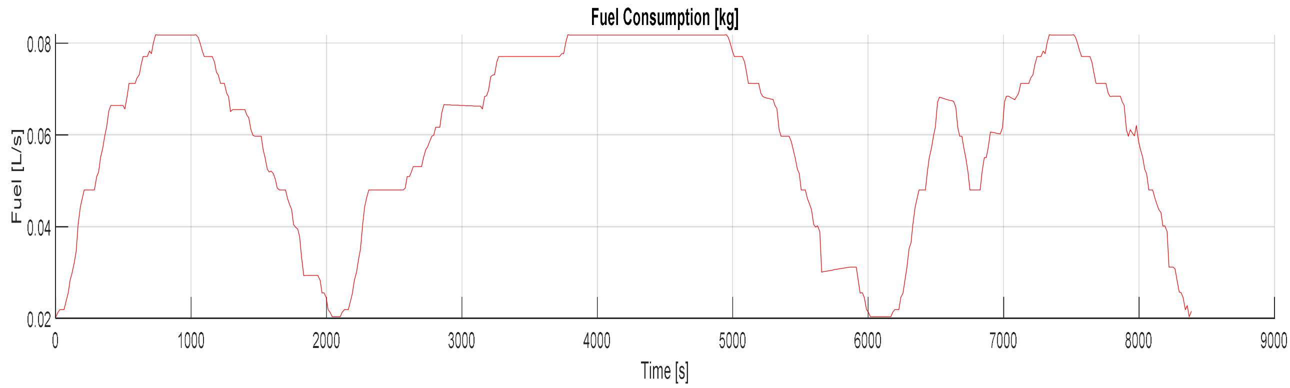


Figure 29: Fuel consumption for combination No. (1.2)

The integral of the above diagram gives 507 L. By multiplying the liters with the density of the marine diesel, which is 0.9 $\frac{kg}{L}$, the result that occurs is 456.3 kg. This results to total fuel consumption for this certain itinerary for the yacht's propulsion system configuration No. (1.2) is calculated at 456.3 kg.

Combination 1.3

Below, there are the diagrams for the combination No. (1.3) which has the following propulsion system parts data:

Diesel Engine – MCR (kW)	El. Motor – Max Power (kW)	Battery Capacity (Ah)
2100	500	1400

Table 5: Combination No. (1.3) data

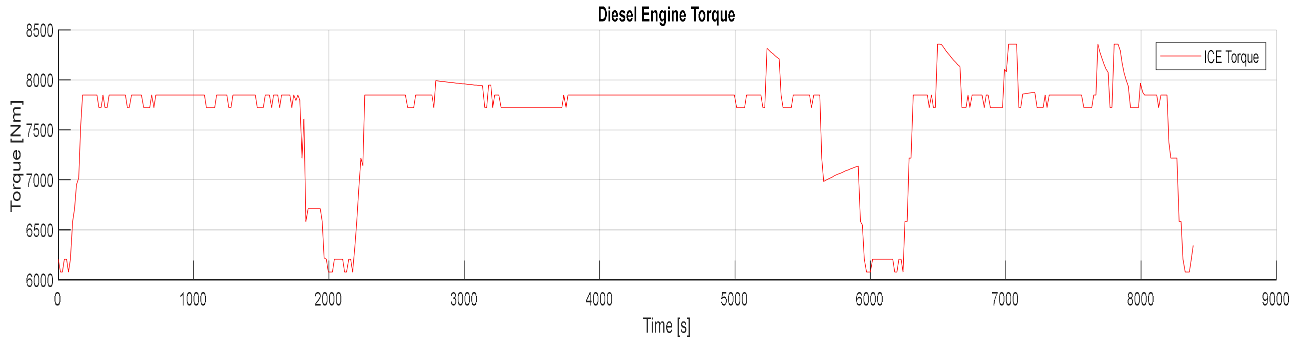


Figure 30: Diesel Engine Torque for combination No. (1.3)

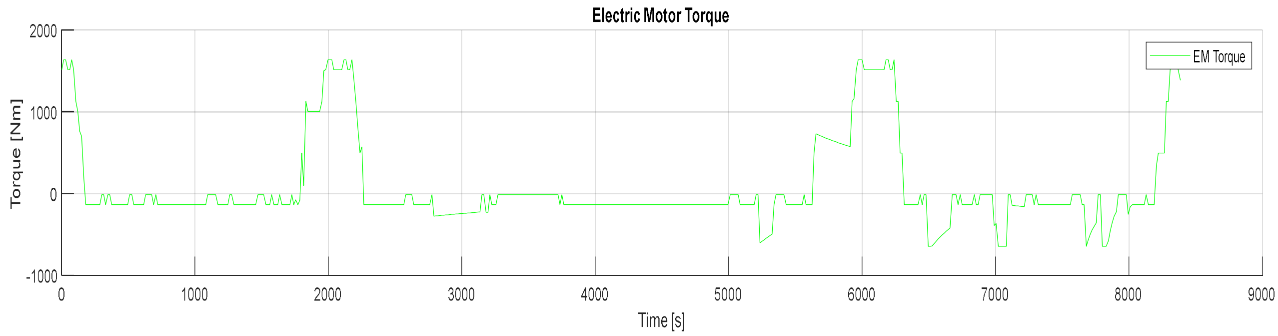


Figure 31: Electric Motor Torque for combination No. (1.3)

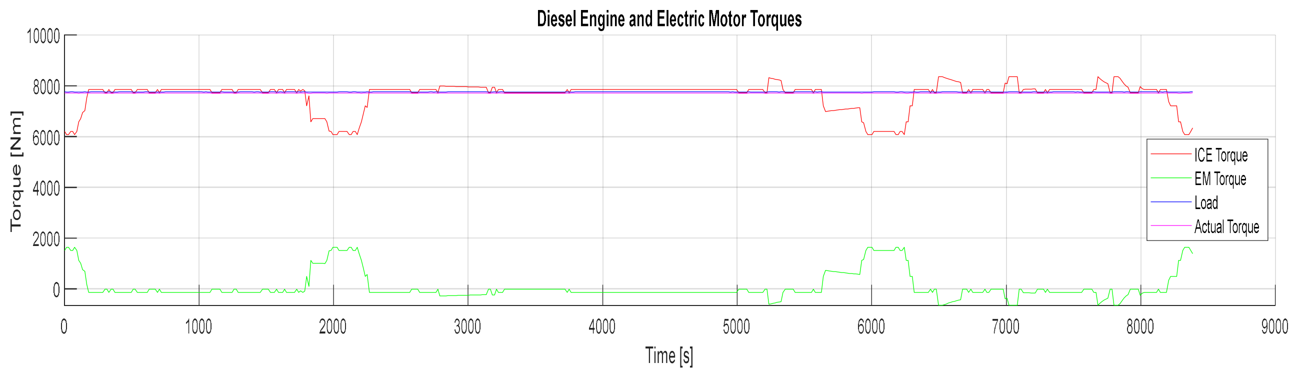


Figure 32: ICE Torque, EM Torque, Load and Actual Torque for combination No.(1.3)

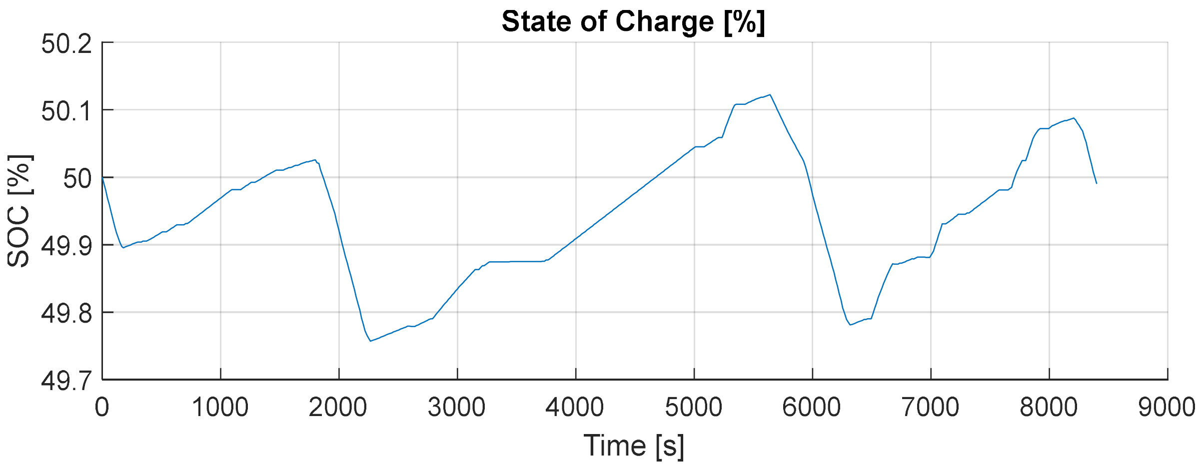


Figure 33: State of charge alteration over time for combination No. (1.3)

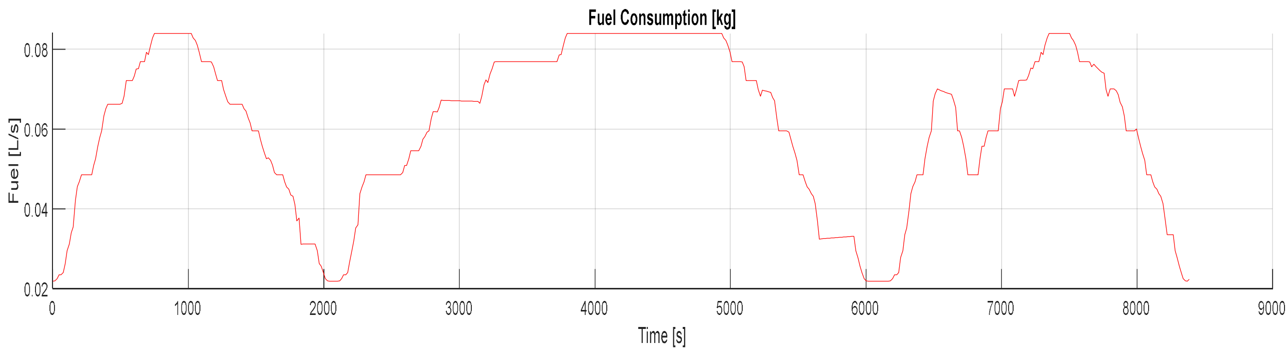


Figure 34: Fuel consumption for combination No. (1.3)

The integral of the above diagram gives 516 L. By multiplying the liters with the density of the marine diesel, which is 0.9 $\frac{kg}{L}$, the result that occurs is 464.4 kg. This results to total fuel consumption for this certain itinerary for the yacht's propulsion system configuration No. (1.3) is calculated at 464.4 kg.

Combination 1.4

Below, there are the diagrams for the combination No. (1.4) which has the following propulsion system parts data:

Diesel Engine – MCR (kW)	El. Motor – Max Power (kW)	Battery Capacity (Ah)
2100	600	1500

Table 6: Combination No. (1.4) data

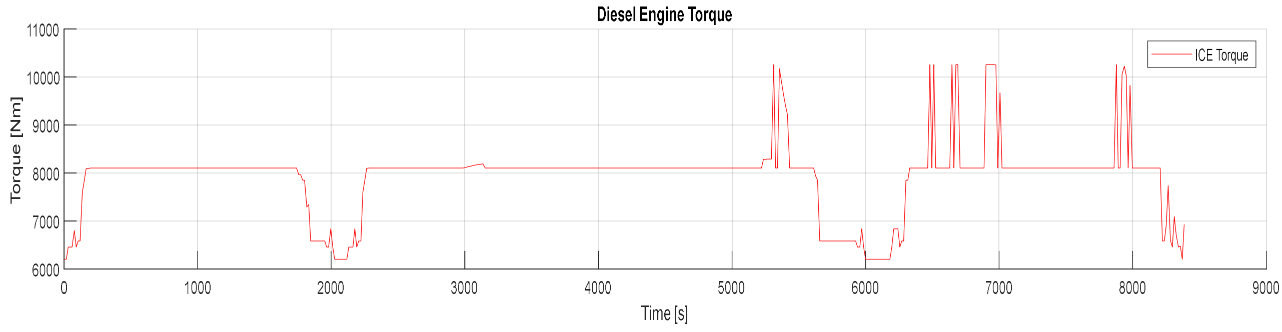


Figure 35: Diesel Engine Torque for combination No. (1.4)

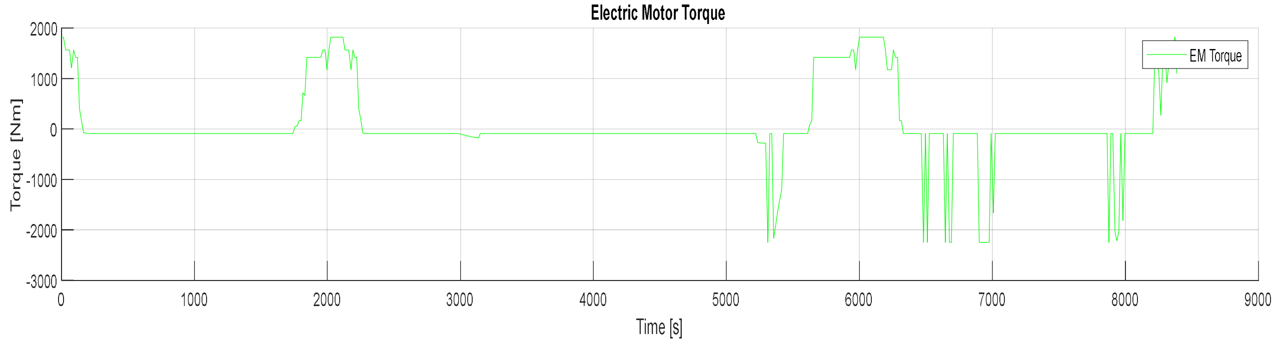


Figure 36: Electric Motor Torque for combination No. (1.4)

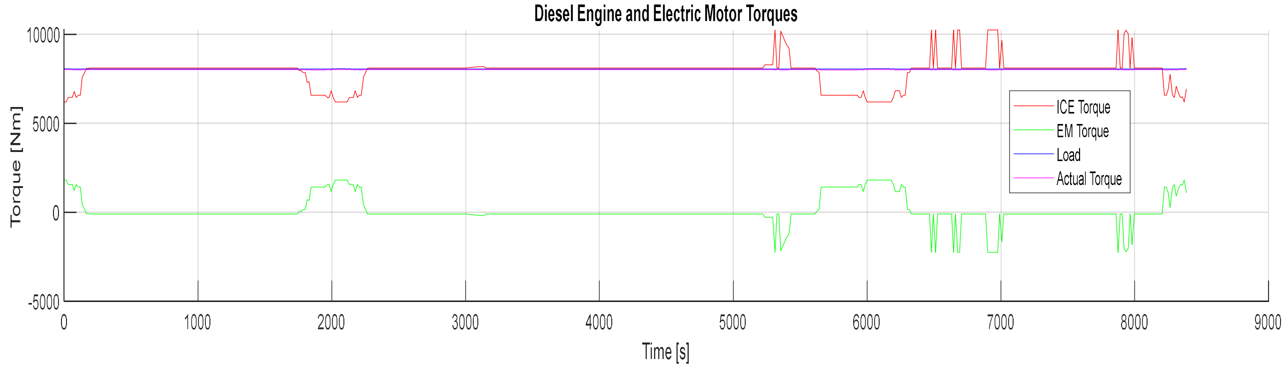


Figure 37: ICE Torque, EM Torque, Load and Actual Torque for combination No.(1.4)

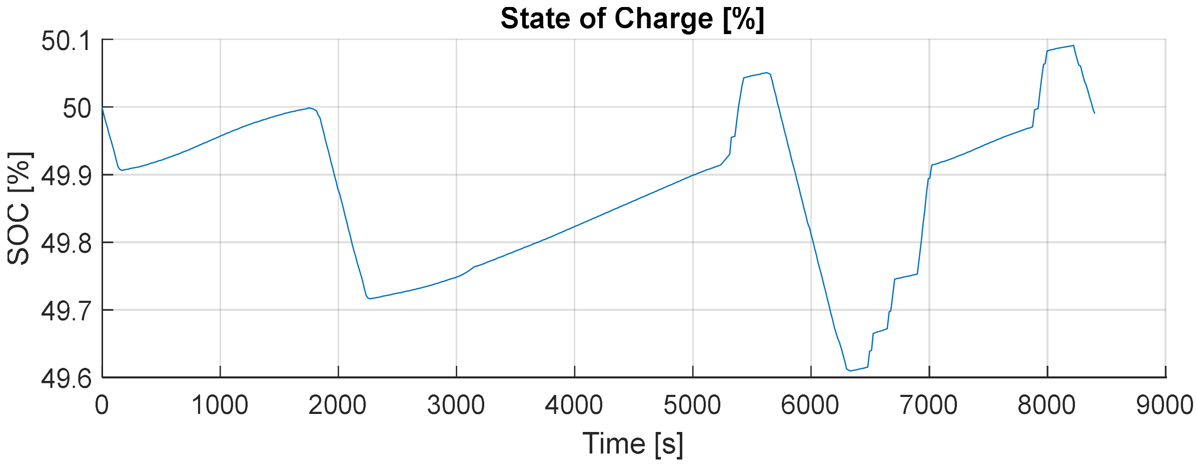


Figure 38: State of charge alteration over time for combination No. (1.4)

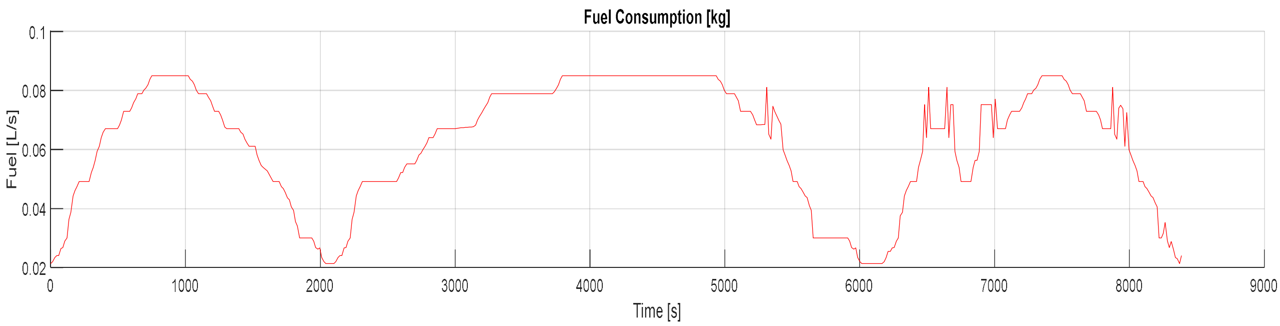


Figure 39: Fuel consumption for combination No. (1.4)

The integral of the above diagram gives 525 L. By multiplying the liters with the density of the marine diesel, which is 0.9 $\frac{kg}{L}$, the result that occurs is 472.5 kg. This results to total fuel consumption for this certain itinerary for the yacht's propulsion system configuration No. (1.4) is calculated at 472.5 kg.

Combination 1.5

Below, there are the diagrams for the combination No. (1.5) which has the following propulsion system parts data:

Diesel Engine – MCR (kW)	El. Motor – Max Power (kW)	Battery Capacity (Ah)
2100	800	2200

Table 7: Combination No. (1.5) data

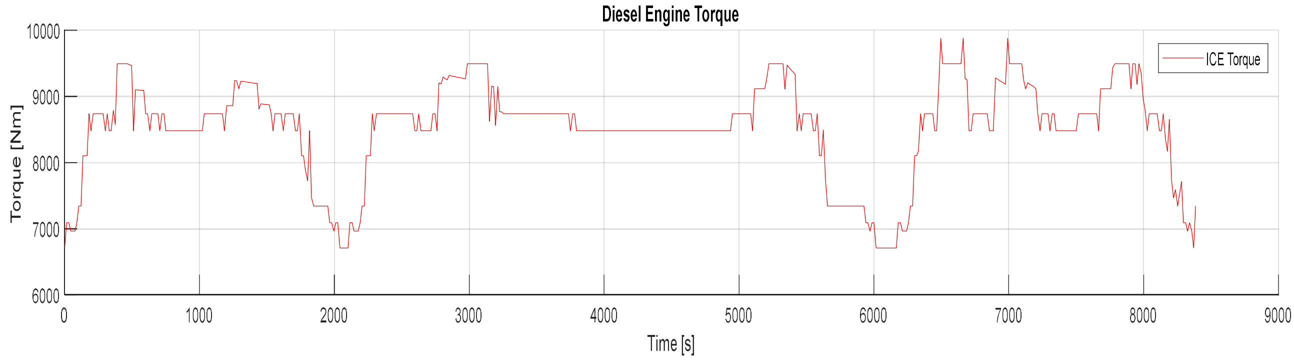


Figure 40: Diesel Engine Torque for combination No. (1.5)

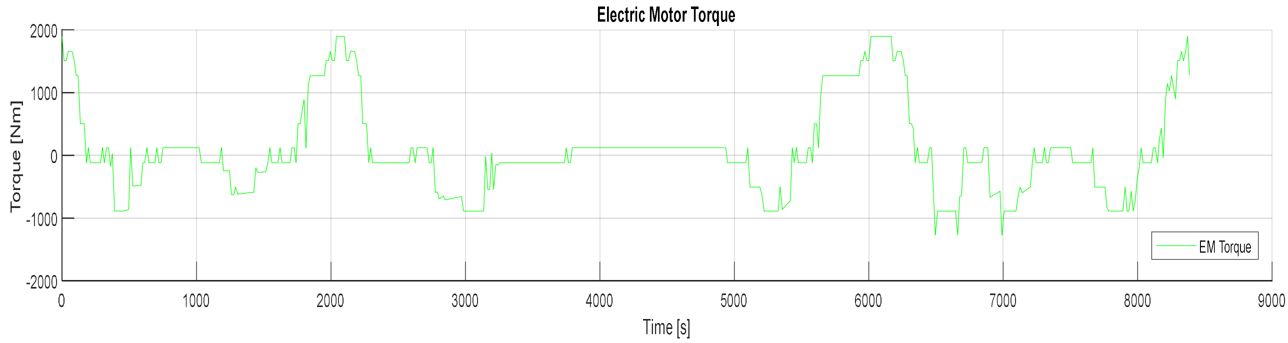


Figure 41: Electric Motor Torque for combination No. (1.5)

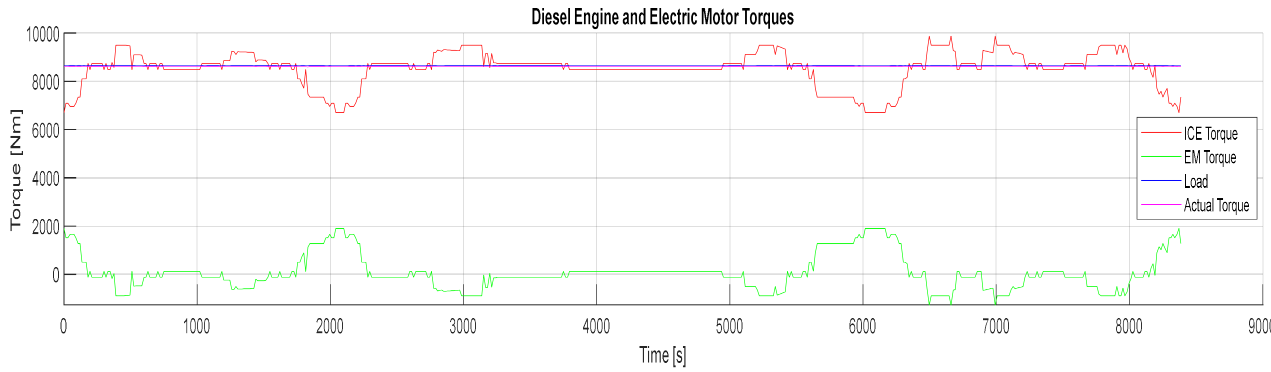


Figure 42: ICE Torque, EM Torque, Load and Actual Torque for combination No.(1.5)

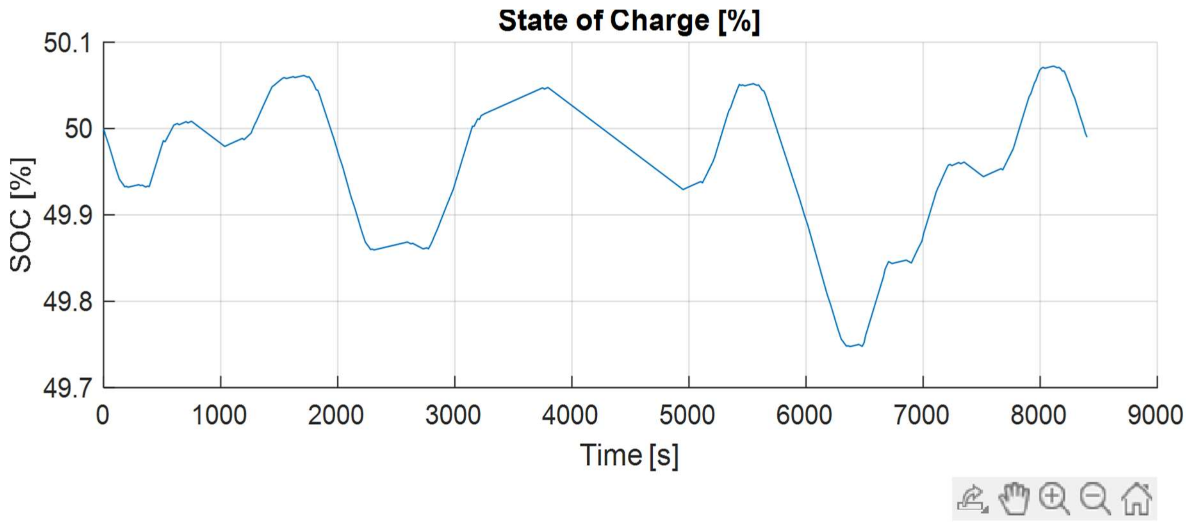


Figure 43: State of charge alteration over time for combination No. (1.5)

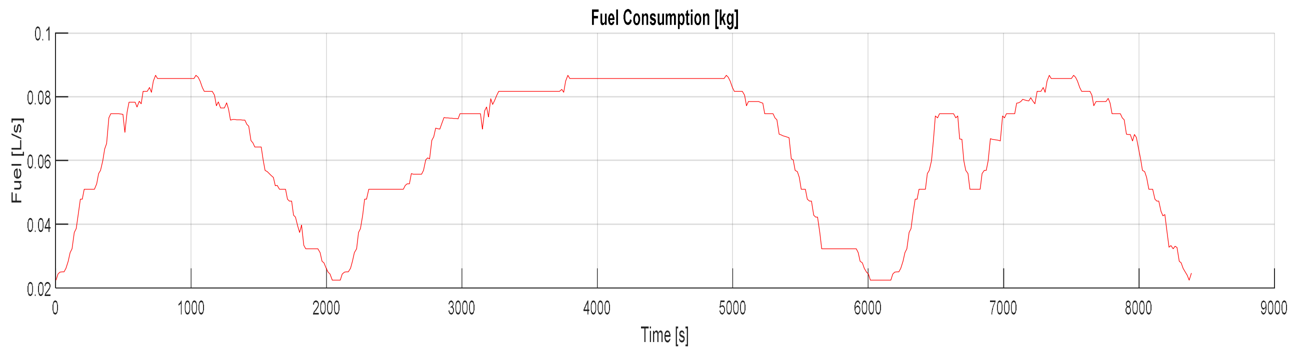


Figure 44: Fuel consumption for combination No. (1.5)

The integral of the above diagram gives 543 L. By multiplying the liters with the density of the marine diesel, which is 0.9 $\frac{kg}{L}$, the result that occurs is 488.7 kg. This results to total fuel consumption for this certain itinerary for the yacht's propulsion system configuration No. (1.5) is calculated at 488.7 kg.

Combination 1.6

Below, there are the diagrams for the combination No. (1.6) which has the following propulsion system parts data:

Diesel Engine – MCR (kW)	El. Motor – Max Power (kW)	Battery Capacity (Ah)
2100	1000	2500

Table 8: Combination No. (1.6) data

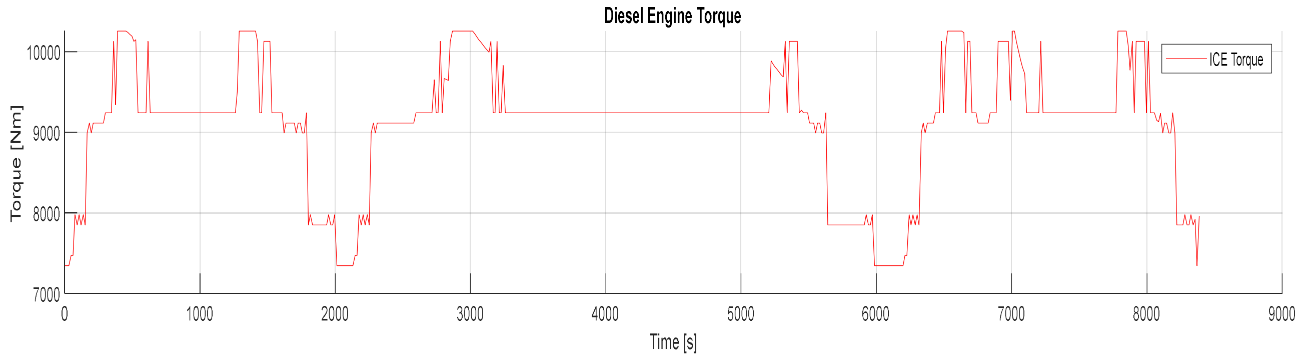


Figure 45: Diesel Engine Torque for combination No. (1.6)

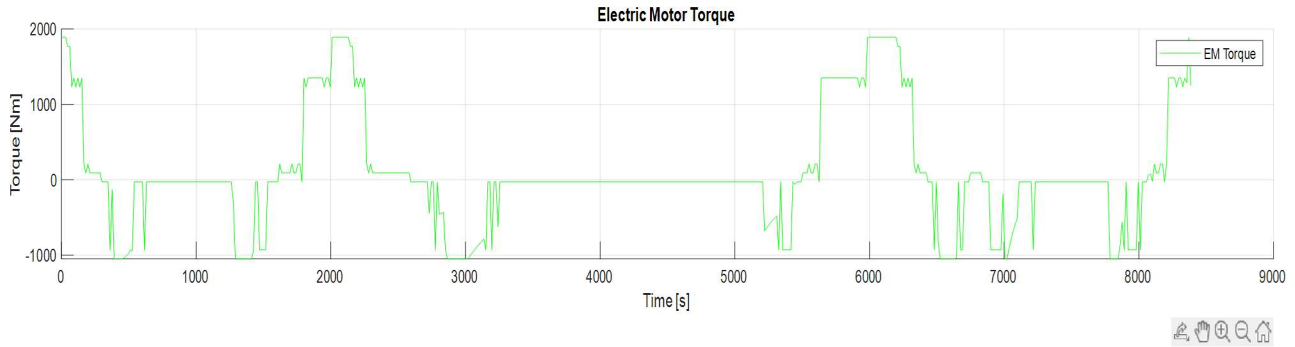


Figure 46: Electric Motor Torque for combination No. (1.6)

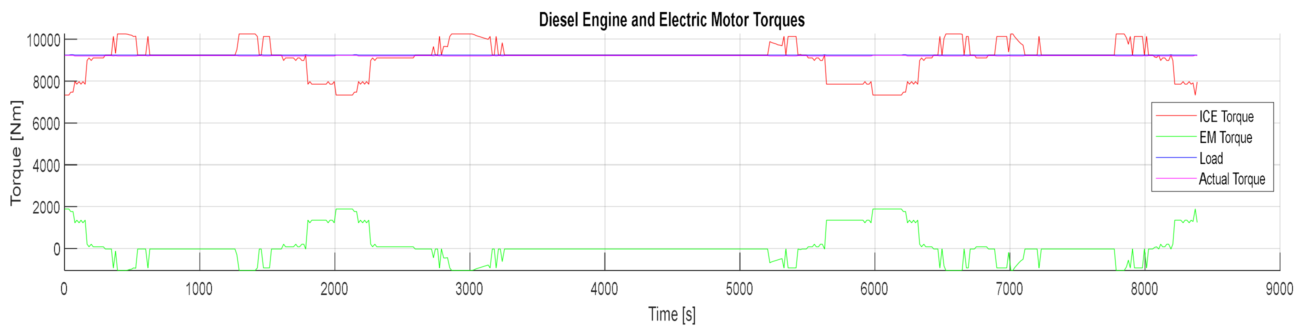


Figure 47: ICE Torque, EM Torque, Load and Actual Torque for combination No.(1.6)

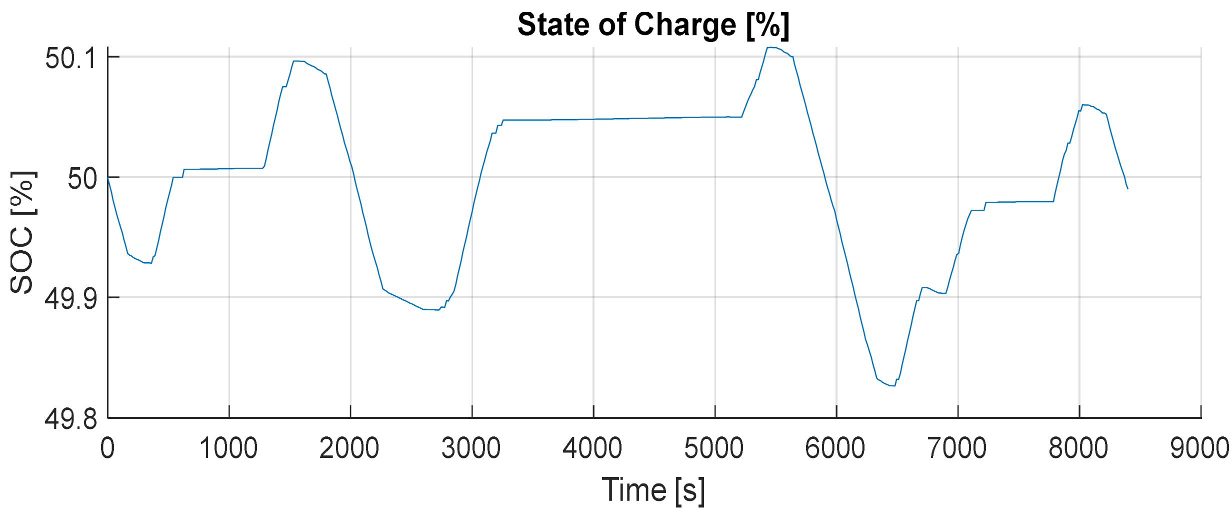


Figure 48: State of charge alteration over time for combination No. (1.6)

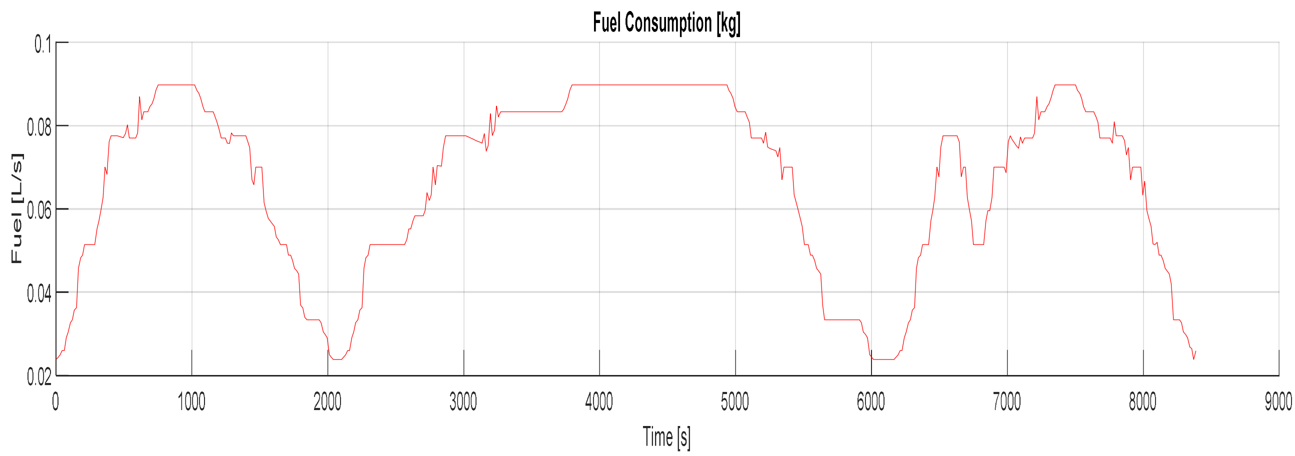


Figure 49: Fuel consumption for combination No. (1.6)

The integral of the above diagram gives 560 L. By multiplying the liters with the density of the marine diesel, which is 0.9 $\frac{kg}{L}$, the result that occurs is 504 kg. This results to total fuel consumption for this certain itinerary for the yacht's propulsion system configuration No. (1.6) is calculated at 504 kg.

CAT C280-6

As it concerns the combinations of diesel engine CAT C280-6, the vessel' speed profile and the corresponding engine speed profile are depicted in Fig. 50,51 :

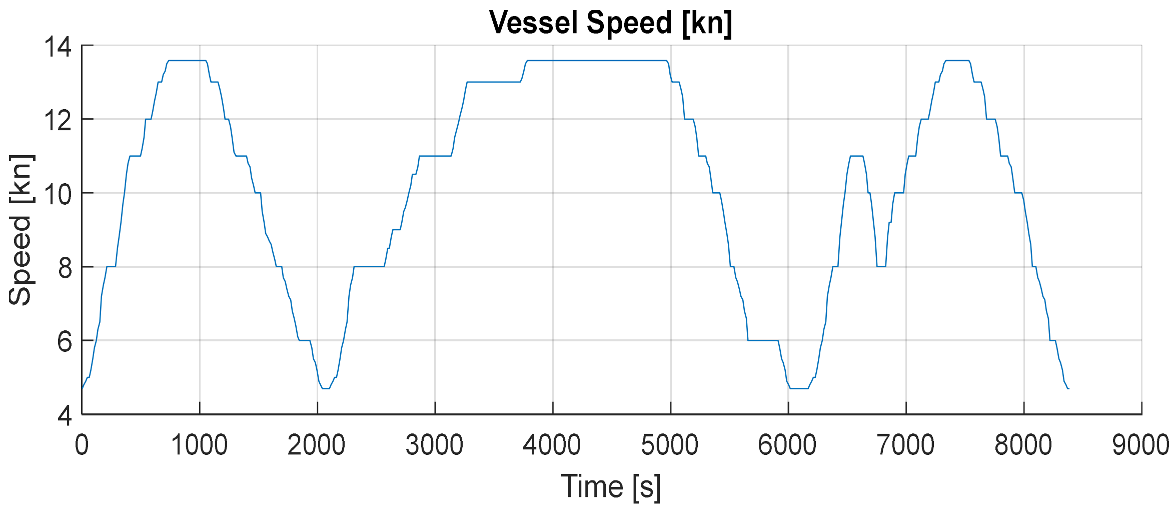


Figure 50: Vessel's speed profile

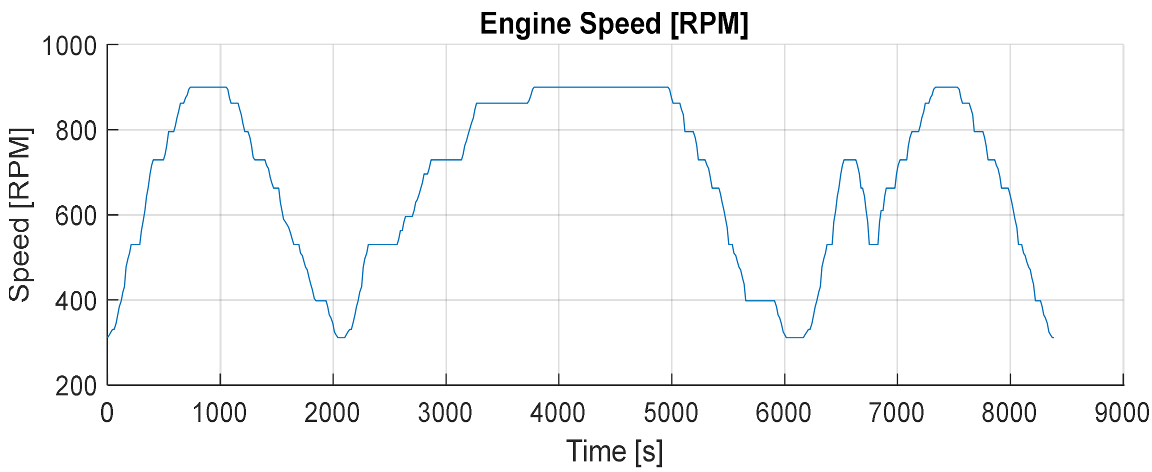


Figure 51: Engine speed profile for combinations of CAT C280-6 diesel engine

Combination 2.1

Below, there are the diagrams for the combination No. (2.1) which has the following propulsion system parts data:

Diesel Engine – MCR (kW)	El. Motor – Max Power (kW)	Battery Capacity (Ah)
1900	100	500

Table 9: Combination No. (2.1) data

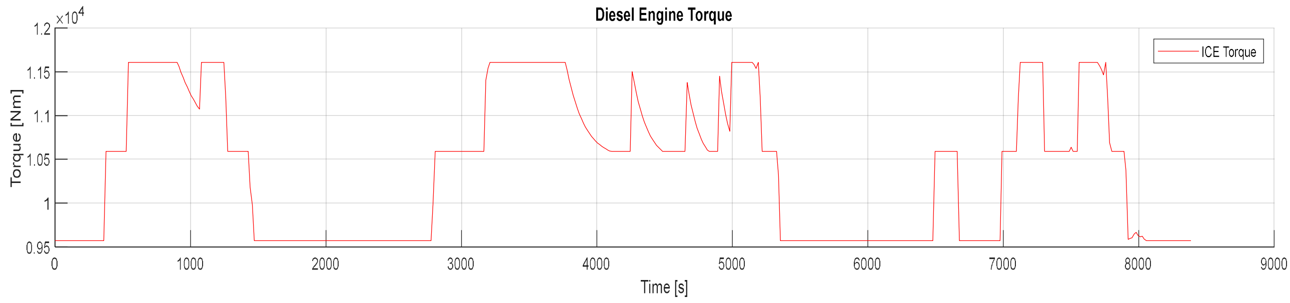


Figure 52: Diesel Engine Torque for combination No. (2.1)

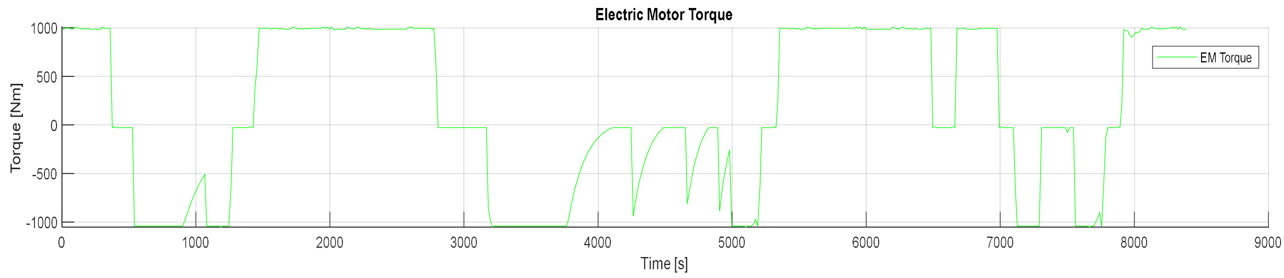


Figure 53: Electric Motor Torque for combination No. (2.1)

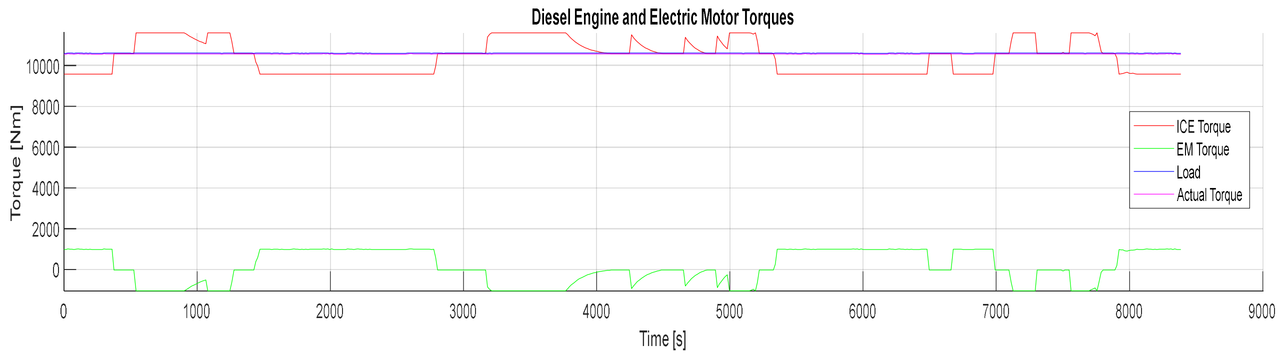


Figure 54: ICE Torque, EM Torque, Load and Actual Torque for combination No.(2.1)

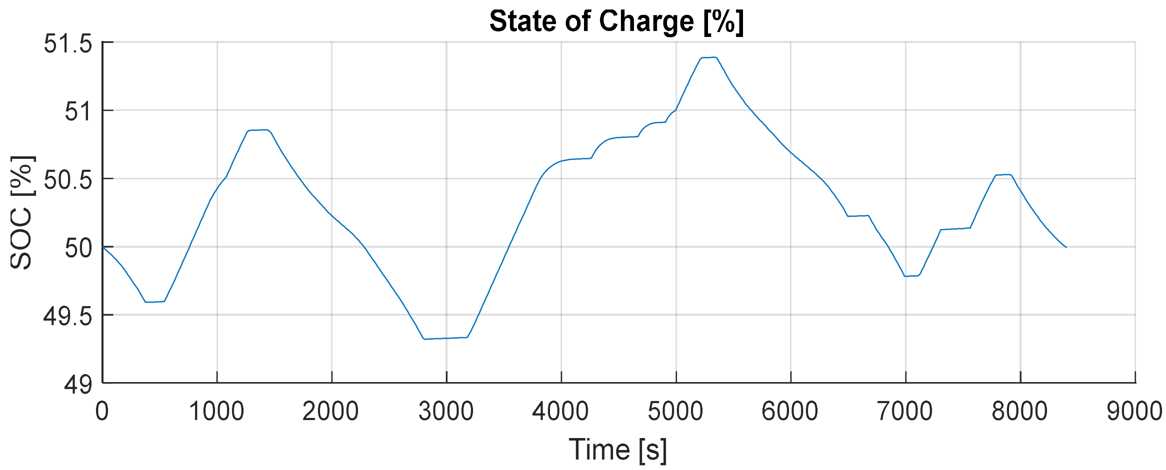


Figure 55: State of charge alteration over time for combination No. (2.1)

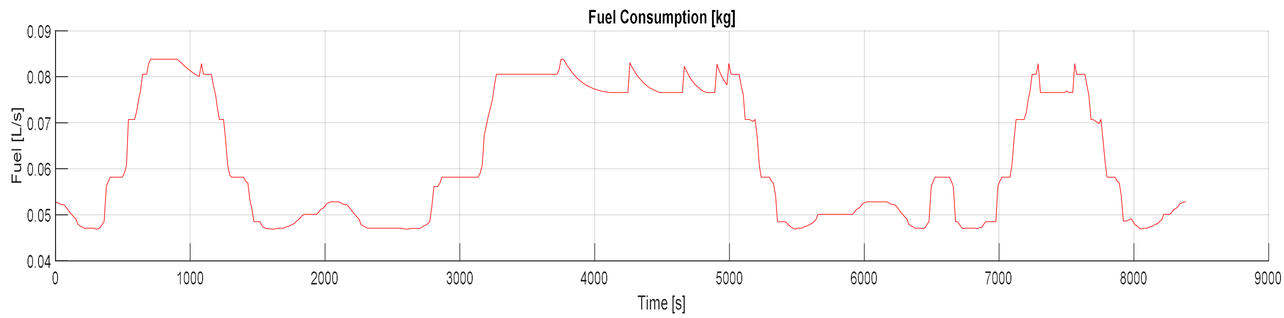


Figure 56: Fuel consumption for combination No. (2.1)

The integral of the above diagram gives 523 L. By multiplying the liters with the density of the marine diesel, which is 0.9 $\frac{kg}{L}$, the result that occurs is 470.7 kg. This results to total fuel consumption for this certain itinerary for the yacht's propulsion system configuration No. (2.1) is calculated at 470.7 kg.

Combination 2.2

Below, there are the diagrams for the combination No. (2.2) which has the following propulsion system parts data:

Diesel Engine – MCR (kW)	El. Motor – Max Power (kW)	Battery Capacity (Ah)
1900	200	1000

Table 10: Combination No. (2.2) data

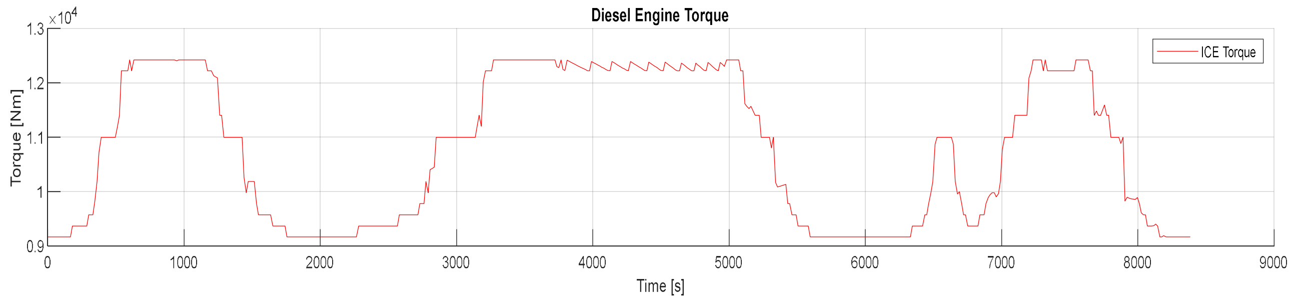


Figure 57: Diesel Engine Torque for combination No. (2.2)

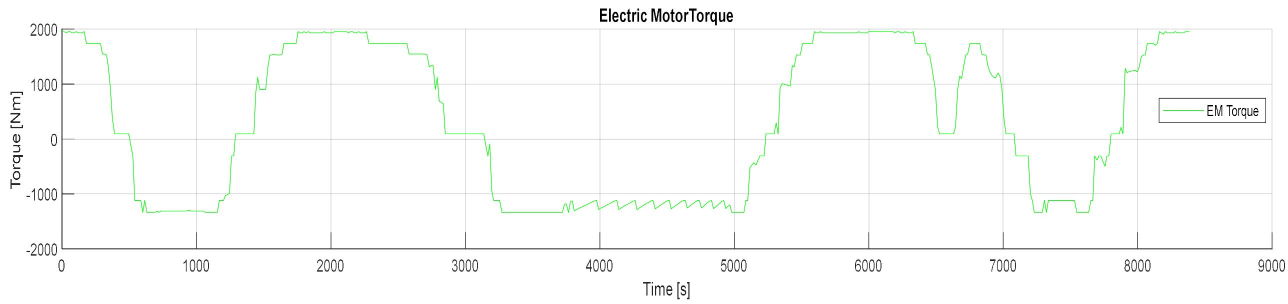


Figure 58: Electric Motor Torque for combination No. (2.2)

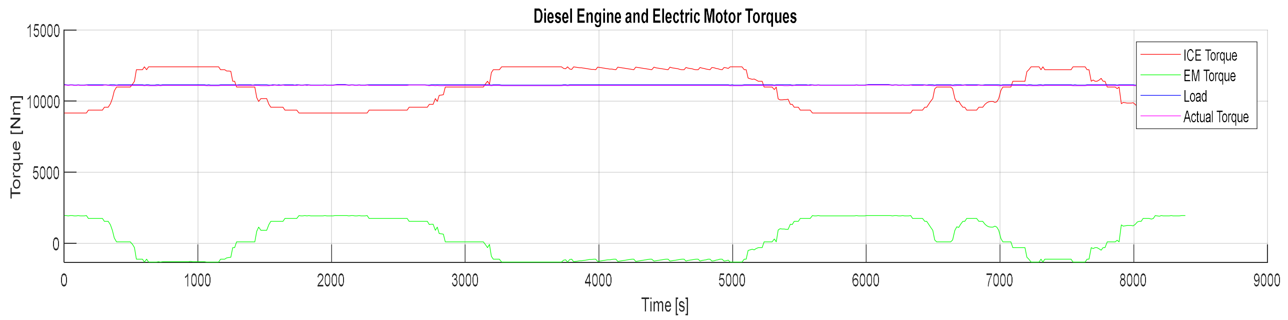


Figure 59: ICE Torque, EM Torque, Load and Actual Torque for combination No.(2.2)

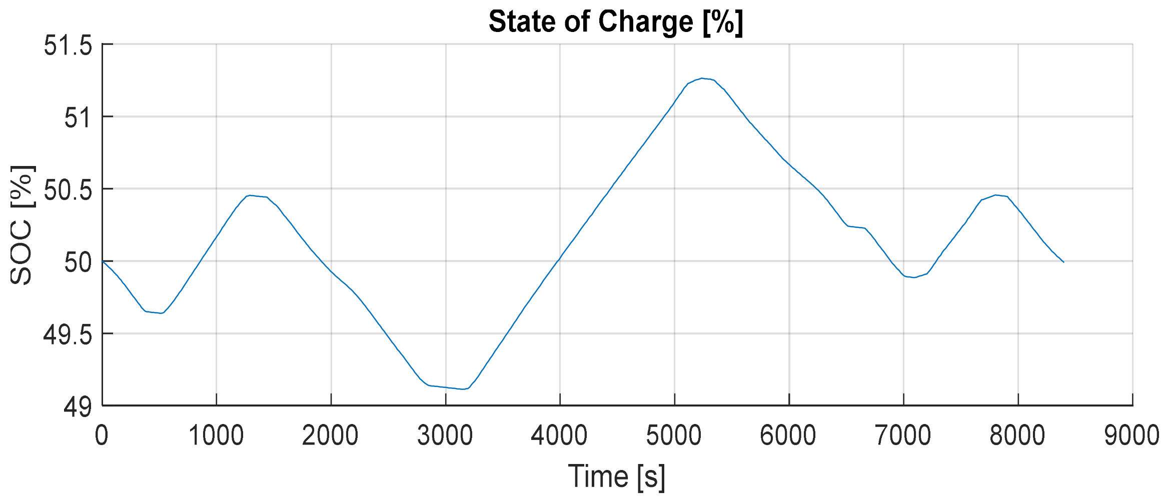


Figure 60: State of charge alteration over time for combination No. (2.2)

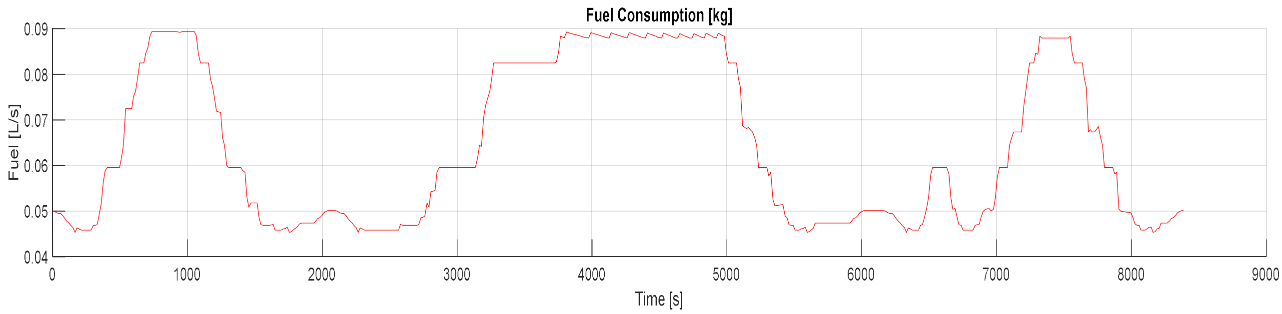


Figure 61: Fuel consumption for combination No. (2.2)

The integral of the above diagram gives 539 L. By multiplying the liters with the density of the marine diesel, which is 0.9 $\frac{kg}{L}$, the result that occurs is 485.1 kg. This results to total fuel consumption for this certain itinerary for the yacht's propulsion system configuration No. (2.2) is calculated at 485.1 kg.

CAT C280-8

As it concerns the combinations of diesel engine CAT C280-8, the vessel' speed profile and the corresponding engine speed profile are depicted in Fig. 62, 63:

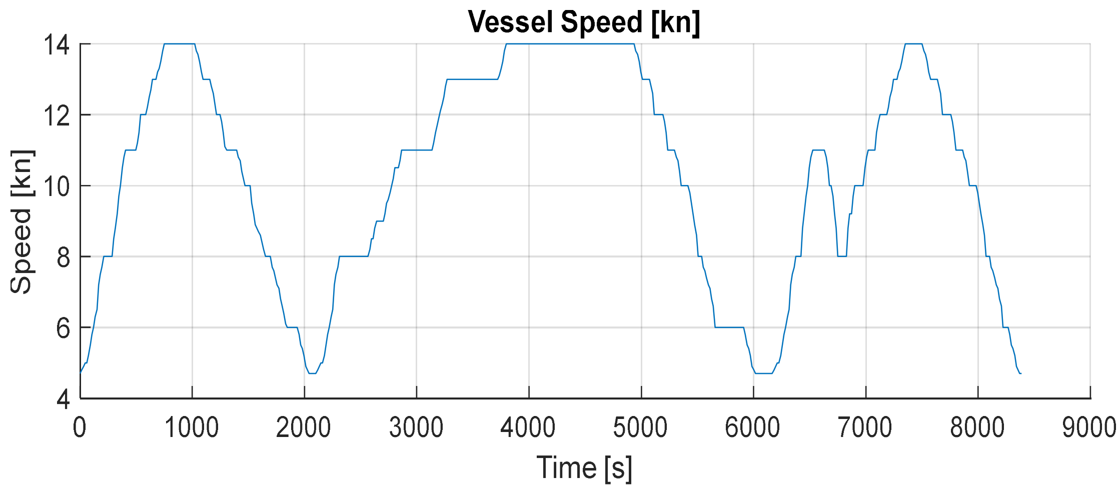


Figure 62: Vessel's speed profile

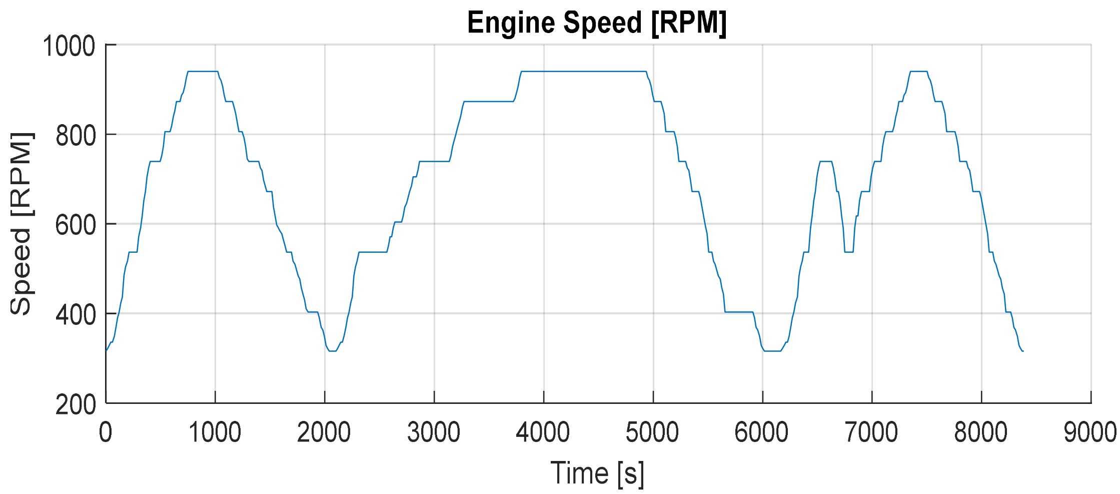


Figure 63: Engine speed profile for combinations of CAT C280-8 diesel engine

Combination 3.1

Below, there are the diagrams for the combination No. (3.1) which has the following propulsion system parts data:

Diesel Engine – MCR (kW)	El. Motor – Max Power (kW)	Battery Capacity (Ah)
2460	100	1500

Table 11: Combination No. (3.1) data

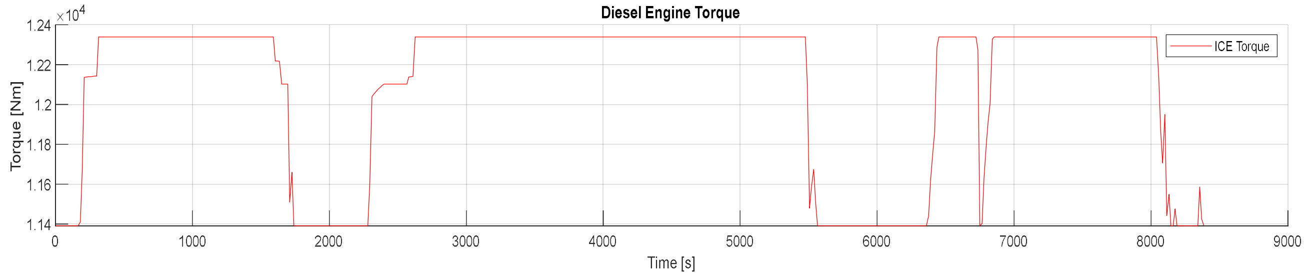


Figure 64: Diesel Engine Torque for combination No. (3.1)

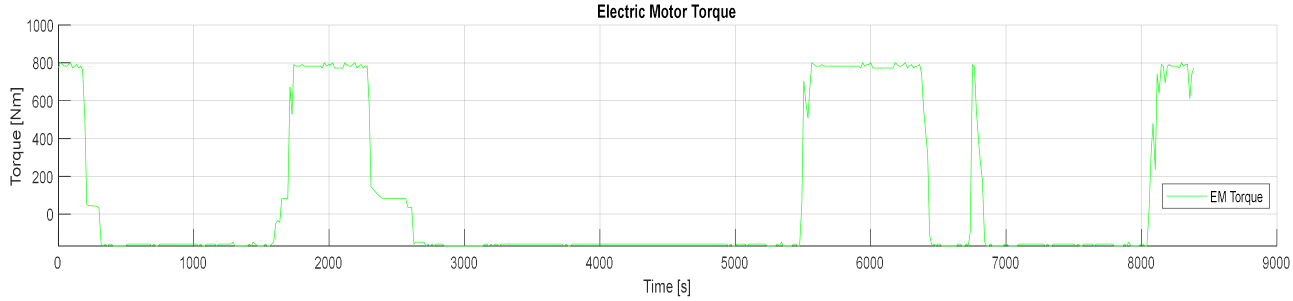


Figure 65: Electric Motor Torque for combination No. (3.1)

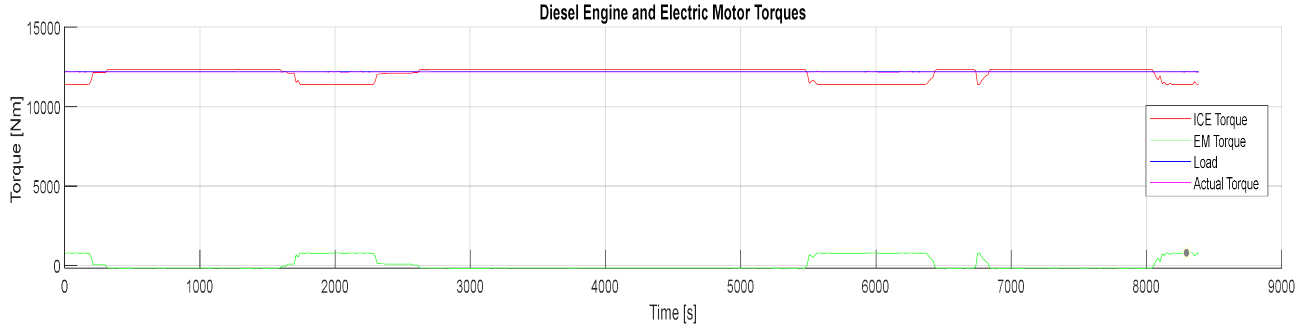


Figure 66: ICE Torque, EM Torque, Load and Actual Torque for combination No.(3.1)

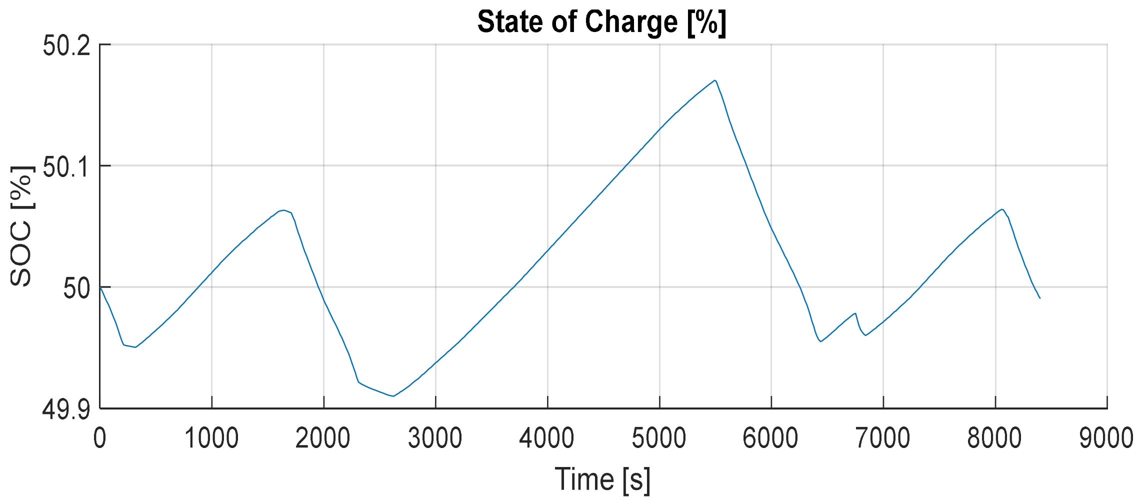


Figure 67: State of charge alteration over time for combination No. (3.1)

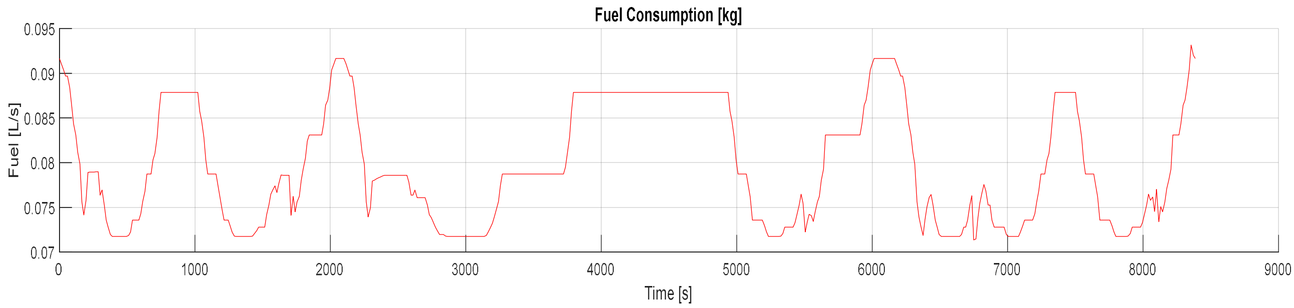


Figure 68: Fuel consumption for combination No. (3.1)

The integral of the above diagram gives 670 L. By multiplying the liters with the density of the marine diesel, which is 0.9 $\frac{kg}{L}$, the result that occurs is 603 kg. This results to total fuel consumption for this certain itinerary for the yacht's propulsion system configuration No. (3.1) is calculated at 603 kg.

CAT C175-16 DITA

Furthermore, the vessel' speed profile and the corresponding engine speed profile for the combinations of CAT C175-16 DITA diesel engine are depicted in Fig. 69, 70:

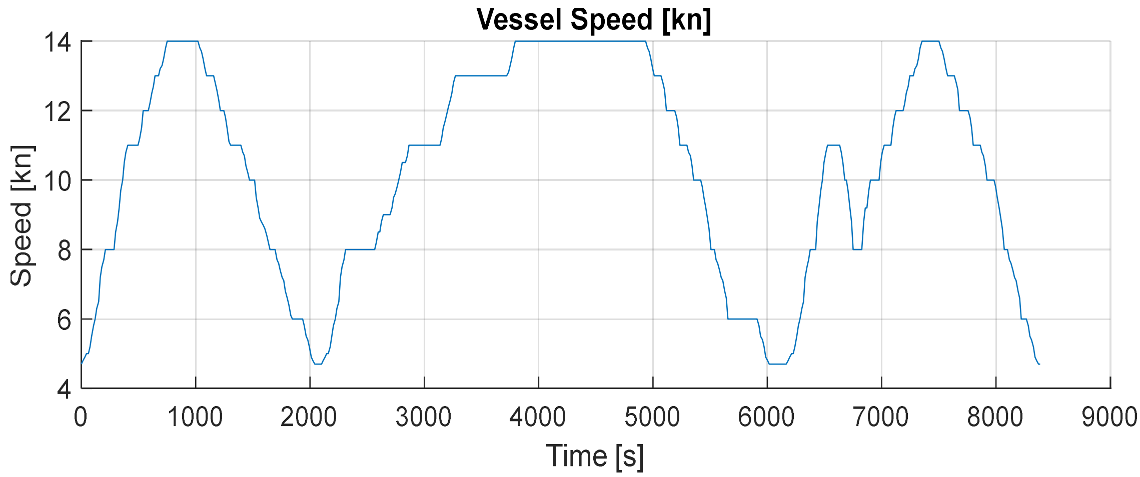


Figure 69: Vessel's speed profile

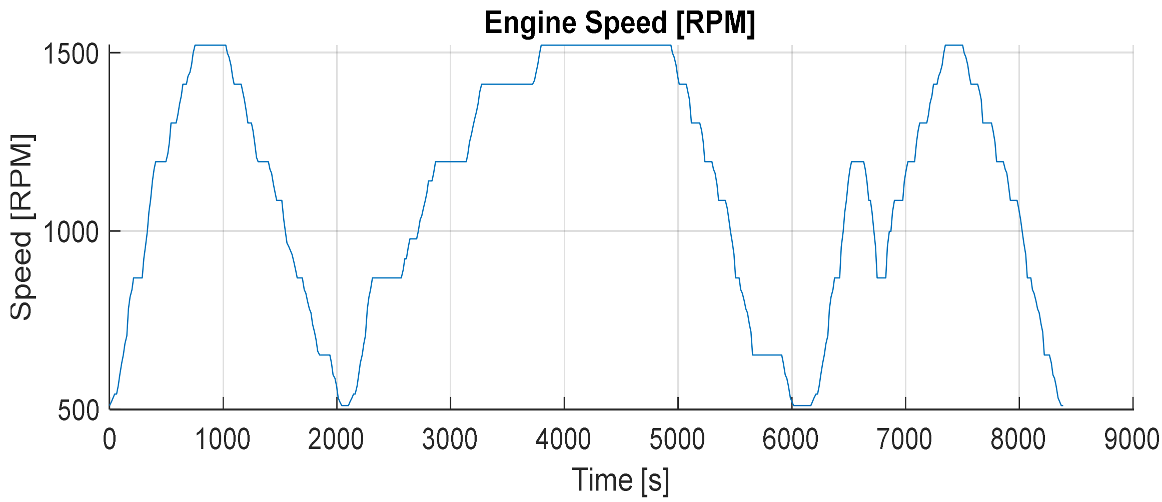


Figure 70: Engine speed profile for combinations of CAT C175-16 DITA diesel engine

Combination 4.1

Below, there are the diagrams for the combination No. (4.1) which has the following propulsion system parts data:

Diesel Engine – MCR (kW)	El. Motor – Max Power (kW)	Battery Capacity (Ah)
2000	500	1500

Table 12: Combination No. (4.1) data

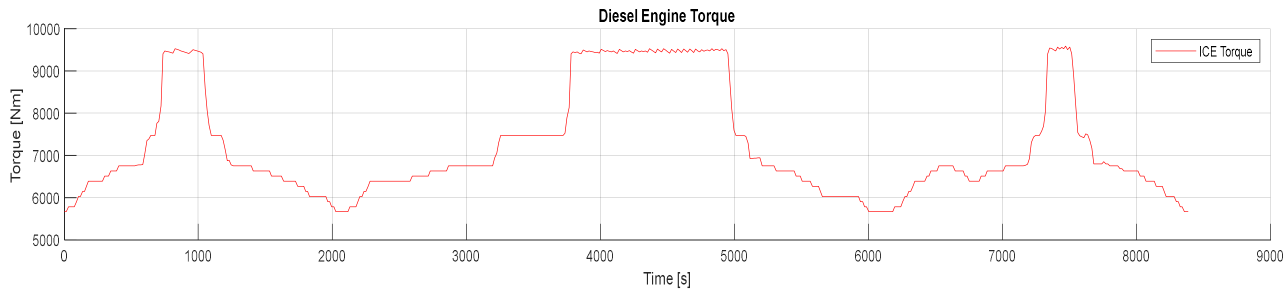


Figure 71: Diesel Engine Torque for combination No. (4.1)

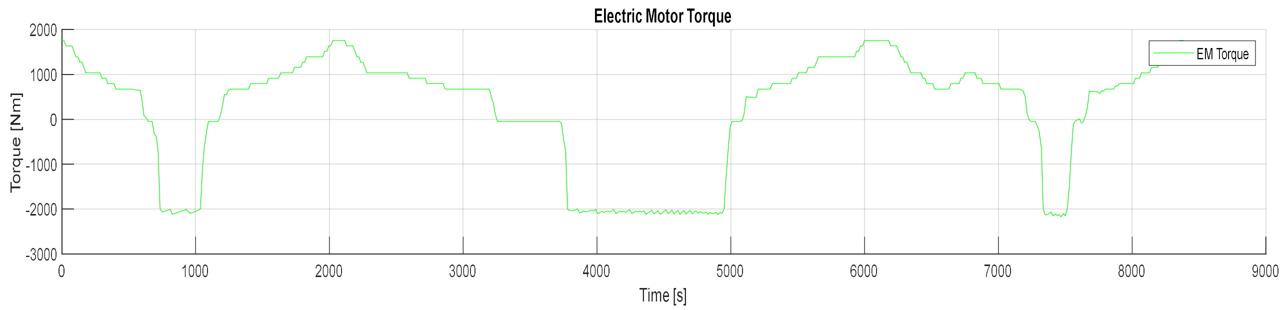


Figure 72: Electric Motor Torque for combination No. (4.1)

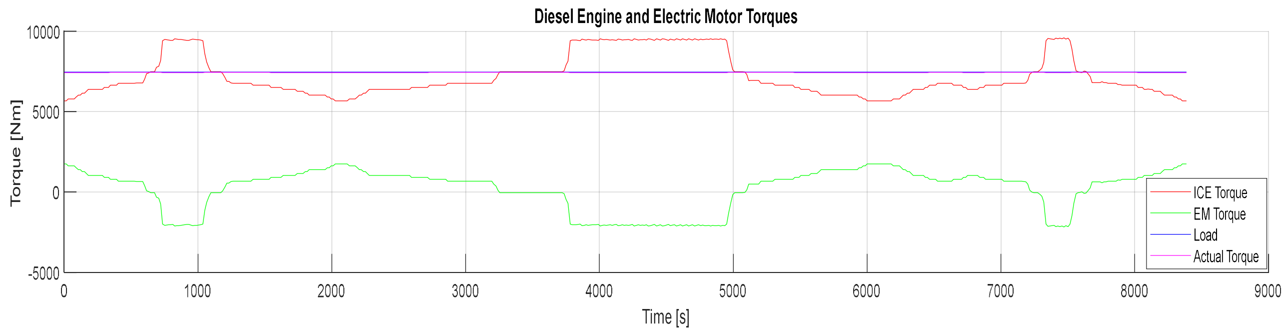


Figure 73: ICE Torque, EM Torque, Load and Actual Torque for combination No.(4.1)

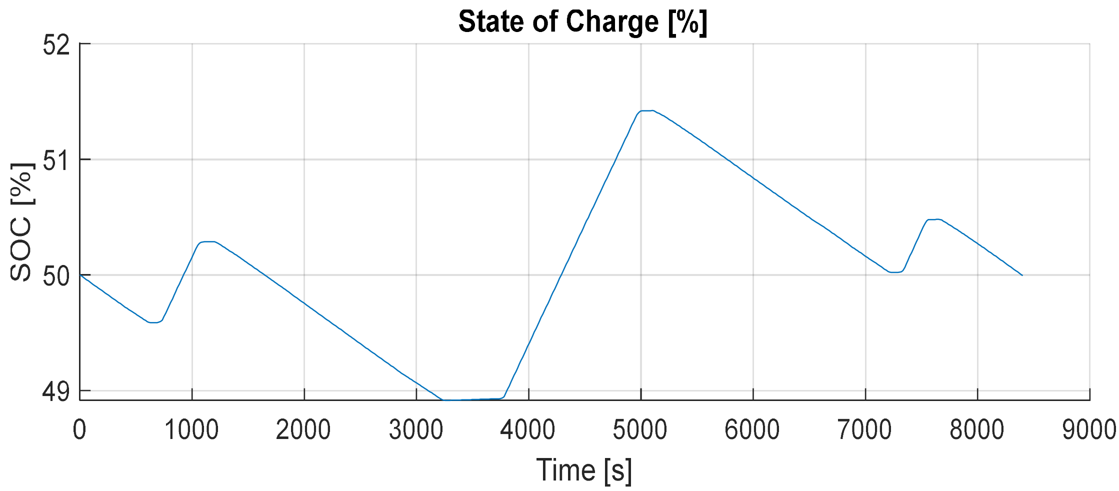


Figure 74: State of charge alteration over time for combination No. (4.1)

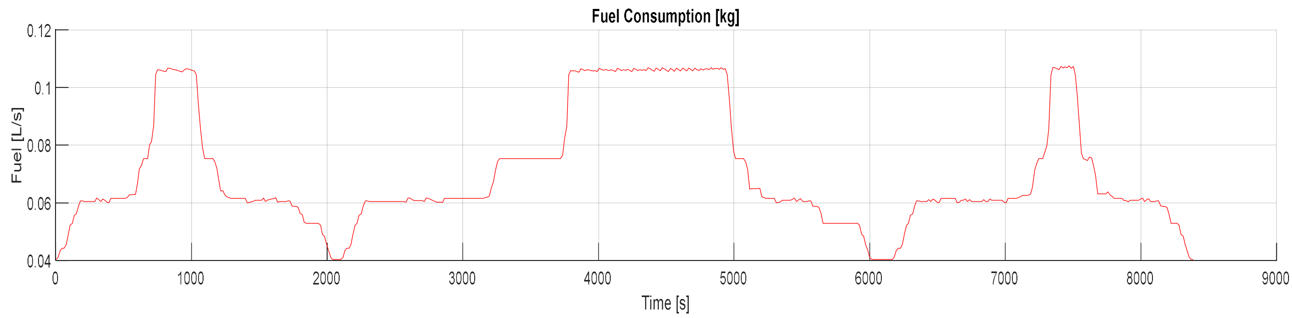


Figure 75: Fuel consumption for combination No. (4.1)

The integral of the above diagram gives 590 L. By multiplying the liters with the density of the marine diesel, which is 0.9 $\frac{kg}{L}$, the result that occurs is 531 kg. This results to total fuel consumption for this certain itinerary for the yacht's propulsion system configuration No. (4.1) is calculated at 531 kg.

Combination 4.2

Below, there are the diagrams for the combination No. (4.2) which has the following propulsion system parts data:

Diesel Engine – MCR (kW)	El. Motor – Max Power (kW)	Battery Capacity (Ah)
2000	800	2500

Table 13: Combination No. (4.2) data

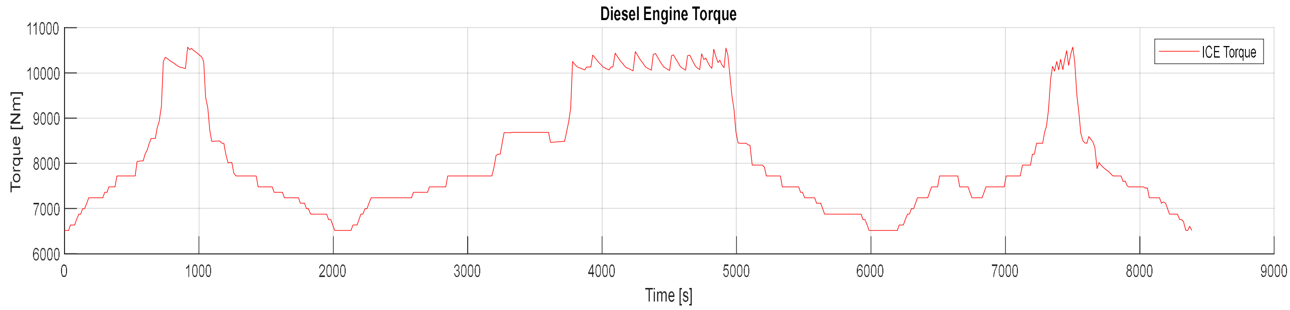


Figure 76: Diesel Engine Torque for combination No. (4.2)

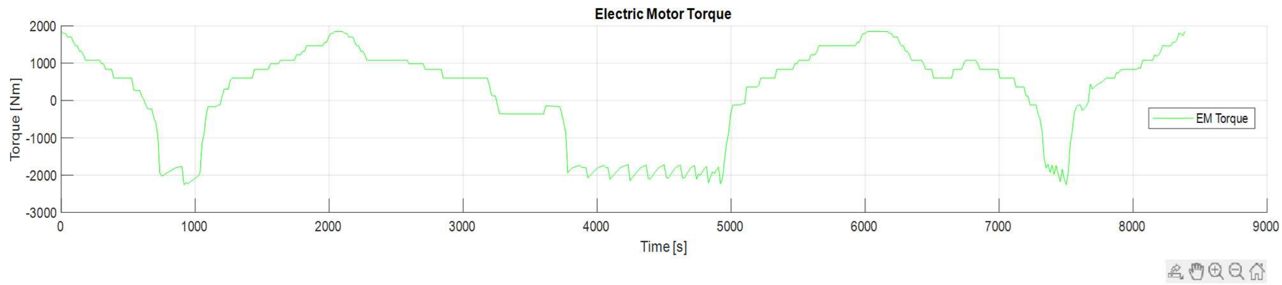


Figure 77: Electric Motor Torque for combination No. (4.2)

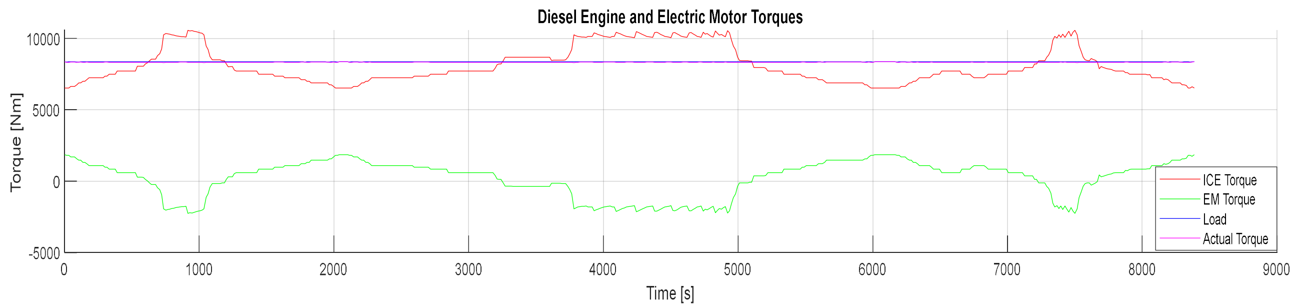


Figure 78: ICE Torque, EM Torque, Load and Actual Torque for combination No.(4.2)

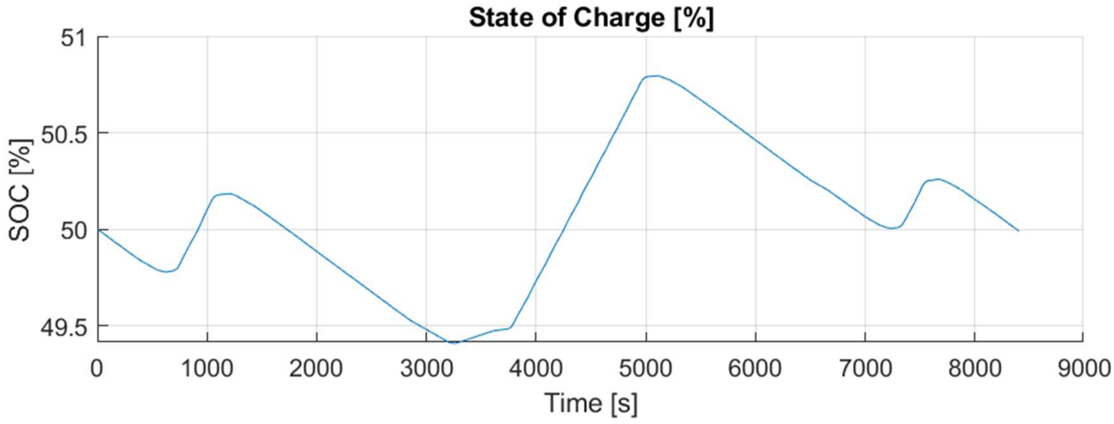


Figure 79: State of charge alteration over time for combination No. (4.2)

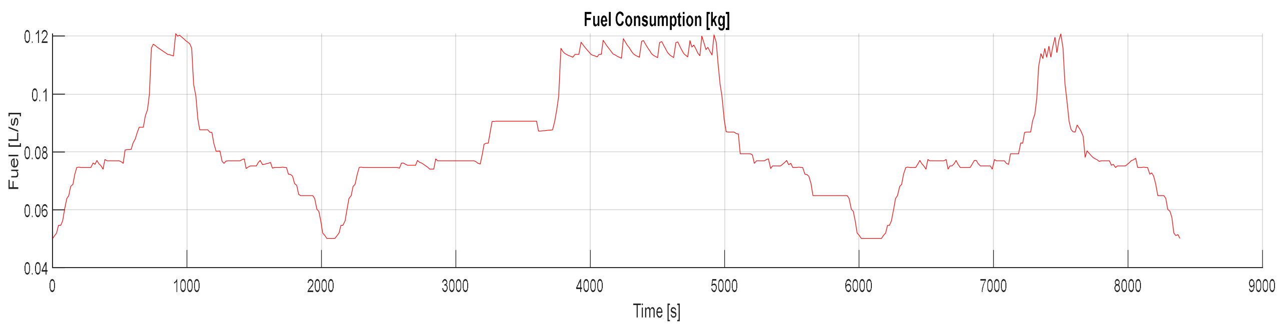


Figure 80: Fuel consumption for combination No. (4.2)

The integral of the above diagram gives 698 L. By multiplying the liters with the density of the marine diesel, which is 0.9 $\frac{kg}{L}$, the result that occurs is 628.2 kg. This results to total fuel consumption for this certain itinerary for the yacht's propulsion system configuration No. (4.2) is calculated at 628.2 kg.

Pivot Tables

To summarize all the necessary data, the following Pivot Tables are created:

No.	Total Power (kW)	Battery (Ah)	Total Fuel Consumption (kg)
1.1	4600	500	439.2
1.2	5000	1000	456.3
1.3	5200	1400	464.4
1.4	5400	1500	472.5
1.5	5800	2200	488.7
1.6	6200	2500	504
2.1	4000	500	470.7
2.2	4200	1000	485.1
3.1	5120	1500	603
4.1	5000	1500	531
4.2	5600	2500	628.2

Table 14: Final data of total power, battery capacity and total fuel consumption.

Moreover, Table 15 depicts the data from the combination with the lowest total power to the one with the highest one:

No.	*Total Power (kW)*	Battery (Ah)	Total Fuel Consumption (kg)
2.1	4000	500	470.7
2.2	4200	1000	485.1
1.1	4600	500	439.2
1.2	5000	1000	456.3
4.1	5000	1500	531
3.1	5120	1500	603
1.3	5200	1400	464.4
1.4	5400	1500	472.5
4.2	5600	2500	628.2
1.5	5800	2200	488.7
1.6	6200	2500	504

Table 15: Final data of total power, battery capacity and total fuel consumption, classified from the lowest total power to the highest one.

Furthermore, Table 16 depicts the data from combination with the lowest total fuel consumption the one with the highest one:

No.	Total Power (kW)	Battery (Ah)	*Total Fuel Consumption (kg)*
1.1	4600	500	439.2
1.2	5000	1000	456.3
1.3	5200	1400	464.4
2.1	4000	500	470.7
1.4	5400	1500	472.5
2.2	4200	1000	485.1
1.5	5800	2200	488.7
1.6	6200	2500	504
4.1	5000	1500	531
3.1	5120	1500	603
4.2	5600	2500	628.2

Table 16: Final data of total power, battery capacity and total fuel consumption, classified from the lowest total fuel consumption to the highest one.

In Fig. 81, a comparison based on the combinations' total power and total fuel consumption and is depicted. In this figure the differences between combinations with similar total power and big difference in the total fuel consumption are shown.

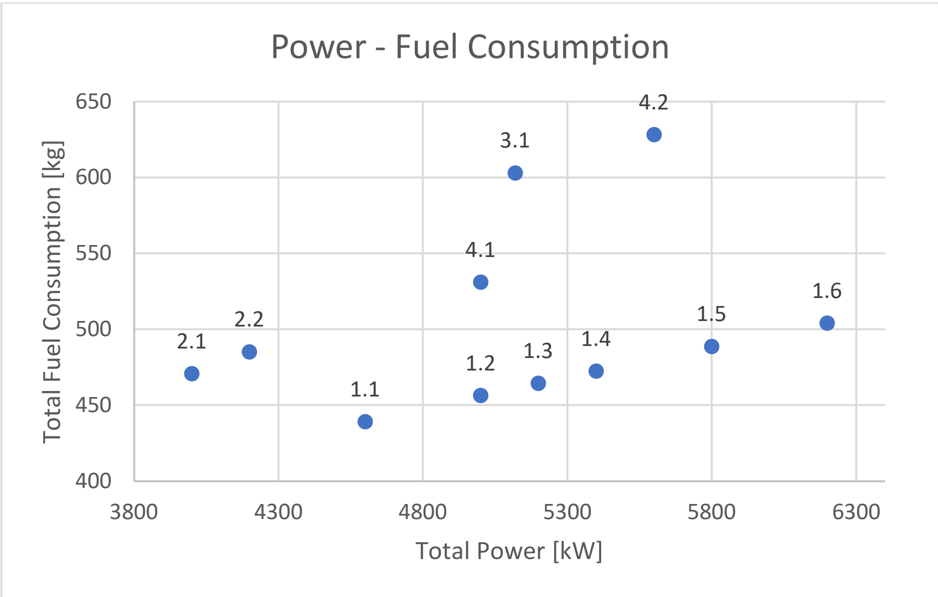


Figure 81: Total power – Total fuel consumption for all combinations.

CHAPTER 7: Conclusions and Future Work

Conclusions

In the present work, many combinations of different diesel engines, electric motors/generators and battery capacity created. It’s clear that the data gathered are very interesting concerning the fact that all the diesel engines are from the same construction company. But the results depict that the impact on the total fuel consumption for a certain itinerary is bigger than the expected as the total power outputs are kind of similar as magnitude. For example, having in mind the combination (4.1) with total power equal to 5000 kW and the combination (1.2), with the same quantity of total power delivered, the fuel consumed in a two and a half operation time is 16.4% higher. Even bigger difference results from the combinations (1.4), (1.5) and (4.2),which have similar total power, where the (4.2) consumed 33% more fuel than the (1.4) and 28.5% more fuel than the (1.5). Similar differences there are between the combinations (3.1), (1.2) and (1.3), where the (3.1) consumes 32.15% more fuel than (1.2) and 29.85% more fuel than (1.3). Taking the above into consideration, it seems that the tool operated in a sufficient way and leaves room for even more interesting and complete information and data gathered about the present work’s subject in the future.

Future work

As mentioned above, there is room for deeper and more thorough research concerning this important subject called: reduction of fossil fuels, protection for the sea environment, cost minimization for the yacht owners and one step forward to the zero carbonized vessel fuels. There is space for attaining even bigger accuracy to the results produced from the dynamic programming tool, by developing the code in order to reach even deeper results and analyzing the output data gathered from up-to-date scenarios over time. Finally, it will be an interesting field to explore, if an economic analysis takes place in order to decide whether it’s less expensive to put in the yachts larger amounts of battery cells and if the outcome of this movement will save more money than given in the near future by minimizing the fuel rate.

APPENDIX

In this part of the thesis, are listed some values of important parameters used during the work in order to create the above results. To start with, in Tables 17,18,19 and 20 there are the values of the constants of the fuel consumption polynomial for each diesel engine.

Reminding the form of the polynomial:

$$\text{Fuel Rate} = p_{03} * (P_{DIESEL})^3 + p_{21} * P_{DIESEL} * (N_{DIESEL})^2 + p_{12} * (P_{DIESEL})^2 * N_{DIESEL} + p_{30} * (N_{DIESEL})^3 + p_{02} * (P_{DIESEL})^2 + p_{20} * (N_{DIESEL})^2 + p_{11} * P_{DIESEL} * N_{DIESEL} + p_{01} * P_{DIESEL} + p_{10} * N_{DIESEL} + p_{00}$$

Constant	Value
p00	-22.13
p10	0.02035
p01	0.3079
p20	$-1.228*10^{-6}$
p11	$-1.584*10^{-5}$
p02	$-7.69*10^{-5}$
p30	$6.191*10^{-9}$
p21	$-2.901*10^{-8}$
p12	$5.719*10^{-8}$
p03	$-3.202*10^{-9}$

Table 17: Fuel consumption polynomial constants for CAT 3516C-HD

Constant	Value
p00	188.4
p10	-1.483
p01	1.68
p20	0.003126
p11	-0.004483
p02	0.0004973
p30	$-1.869*10^{-6}$
p21	$3.088*10^{-6}$
p12	$-3.443*10^{-7}$
p03	$-8.111*10^{-8}$

Table 18: Fuel consumption polynomial constants for CAT C280-6.

Constant	Value
p00	402
p10	-2.791
p01	2.328
p20	0.005253
p11	-0.005984
p02	0.0006475
p30	$-2.879*10^{-6}$
p21	$3.892*10^{-6}$
p12	$-5.596*10^{-7}$
p03	$-3.582*10^{-8}$

Table 19: Fuel consumption polynomial constants for CAT C280-8.

Constant	Value
p00	-218.8
p10	0.2325
p01	1.757
p20	0.0001998
p11	-0.003232
p02	0.001099
p30	$-1.86*10^{-7}$
p21	$1.54*10^{-6}$
p12	$-8.157*10^{-7}$
p03	$4.446*10^{-8}$

Table 20: Fuel consumption polynomial constants for CAT C175-16 DITA.

Moreover, in Table 21 there are the data for the quasi-static battery model:

Parameter	Value
c_1	652
c_2	40.9091
R_i	1.024

Table 21: Quasi-static battery model parameters

Another point of the present work that should be mentioned is the method used in order to introduce the necessary differentiations between the electric motors and their influence on the results. In particular, it is decided that the constant value at the Equation (2.H) is a result for the principal power and vessel maximum speed as following: $P_{SHAFT} = 5200\ kn$ and $V_S = 15\ kn$. This constant constitutes a certain relation between the vessel's hull and the sea environment. As a result, the constant of this equation is equal to 15.7. In order to calculate the maximum speed that this certain hull can reach for a certain maximum total power delivered from the two diesel engines and the two electric motors, the Equation (2.H) takes the following form:

$$V_S = \left(\frac{P_{SHAFT}}{constant}\right)^{\left(\frac{1.4}{3}\right)}$$

This equation's result for each combination are used in the programming tool.

No.	Vessel's Maximum Speed (kn)
1.1	14.17
1.2	14.73
1.3	15.00
1.4	15.27
1.5	15.78
1.6	16.28
2.1	13.27
2.2	13.57
3.1	14.89
4.1	14.73
4.2	15.53

Table 22: Vessel's Maximum speed depending on total power.

CITATIONS

[1] Lino Guzzella, Antonio Sciarretta , "Vehicle Propulsion Systems - Introduction to Modeling and Optimization", Springer, Third Edition, 2013.

[2] Simona Onori, Lorenzo Serrao, Giorgio Rizzoni , "Hybrid Electric Vehicles – Energy Management Strategies", Springer, 2016.

[3] "Making the case for Lithium-Ion Batteries", Making the case for Lithium-Ion Batteries (visionmarinetechnologies.com) , Vision Marine Technologies, March 2022.

[4] "The Complete Guide to Lithium vs Lead Acid Batteries", The Complete Guide to Lithium vs Lead Acid Batteries - Power Sonic (power- sonic.com) , Power Sonic.

[5] "Lab8: Faraday's Law, generators, and motors" Lab8.pdf (yorku.ca)

York University, Toronto, Canada.

[6] " What Are The Different Types Of Marine Batteries", What Are The Different Types Of Marine Batteries? LithiumHub , Lithium Hub.

[7] Michele Maggi, Capt. Steve, e- Motion, BoatTest.com, "e-Motion Hybrid System - Video by BoatTEST.com", (240) e-Motion Hybrid System - Video by BoatTEST.com - YouTube, YouTube, February 2022.

[8] " Serial or parallel hybrid marine propulsion – how do they work?" Serial or parallel hybrid marine propulsion – how do they work? | Volvo Penta, Volvo Penta, May 2021.

[9] "Marine diesel engines - A bluffer's guide", https://www.gard.no/web/updates/content/20736191/marine-diesel-engines-a-bluffers-guide#:~:text=Diesel engines were first introduced,are now powered by them. ,Gard , July 2013.

[10] basic-principles-of-ship-propulsion_web_links.pdf (man-es.com) , "Basic principles of ship propulsion" , MAN Energy Solutions, October 2018.

[11] Vasileios Karystinos, " Nonlinear Model Predictive Control of a Hybrid Diesel-Electric Marine Propulsion Plant" , Diploma Thesis, July 2019.

[12] Nikolaos Planakis, "Power-Split Strategies for Hybrid Marine Propulsion Plants in Transient Loading Conditions for Optimal Energy Management and Emissions Reduction", PhD Thesis, April 2021.

[13] Nikolaos P. Planakis, "Predictive Control of a Hybrid Diesel-Electric Marine Propulsion Plant", Diploma Thesis, October 2016.

[14] "User FAQ – DPM Function" , ETH Zürich, Institute for Dynamic Systems and Controls, June 2013.

[15] Bengt Sundén, "Hydrogen, Batteries and Fuel Cells", 2019.

[16] G.B. Gharehpetian , S. Mohammad Mousavi Agah, "Distributed Generation Systems - Design, Operation and Grid Integration", 2017.

[17] Generic battery model - Simulink (mathworks.com) , MathWorks.

[18] Olle Sundström, Lino Guzzella, "A Generic Dynamic Programming Matlab Function" , July 2009.