PROPULSION CONFIGURATIONS FOR MEGA-YACHTS: AN ENERGY, ECONOMIC, AND ENVIRONMENTAL ANALYSIS

by

Rafail Kamaras

Supervisor

George Dimopoulos

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Acknowledgments

Θυμάμαι ακόμα, σαν να ήταν χτες, την πρώτη φορά που βρέθηκα στο πολυτεχνείο. Ένας χώρος τελείως διαφορετικός με χιλιάδες άγνωστα πρόσωπα, εικόνες και έννοιες. Για καλή μου τύχη, ο Αναστάσης και εγώ, φίλοι απο το φροντηστίριο, διαλέξαμε την ίδια σχολή και πλέον ήμασταν καταδικασμένοι να υποστούμε ο ένας τον άλλον για τα επόμενα 5 χρόνια. Εδώ θέλω να σε ευχαριστήσω, λοιπόν, που από την πρώτη μέρα, με βοηθάς με όποιο τρόπο περνάει απο το χέρι σου.

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Abstract

This thesis presents a comprehensive analysis of different propulsion configurations within the megayacht industry, focusing on the evaluation of energy efficiency, economic viability, and environmental impact. Through the detailed modeling of five distinct propulsion configurations across two operational scenarios, employing real-world data and the simulation capabilities of PSE gPROMS framework, this research delves into mechanical, hybrid, and diesel-electric systems. Each configuration is evaluated based on thermal efficiency, fuel consumption, operational costs, and CO2 emissions, providing a comprehensive understanding of their performance.

Key to this research is the utilization of propulsion-velocity curves, electrical consumption profiles, and a carefully constructed operational timetable that mirrors potential voyages of a megayacht during the peak summer season. This approach allows for a precise assessment of propulsion demands and the environmental footprint associated with each voyage.

Despite exploring the advantages of alternative propulsion solutions, the findings reveal a compelling narrative: the mechanical (traditional) propulsion configuration not only competes favorably with its modern counterparts but also emerges as the most thermally efficient option. This outcome challenges prevailing assumptions about propulsion technologies, suggesting a reevaluation of traditional systems' role in future maritime operations. Moreover, the research identifies the potential of battery-equipped configurations to reducing shore power costs, underscoring the value of sophisticated power management strategies.

The thesis also engages with prevailing market trends, highlighting the increasing preference for eco-friendly and technologically advanced maritime solutions. This market orientation suggests a potential for higher resale values for vessels incorporating sustainable technologies, aligning with broader environmental objectives.

Concluding, this study prompts a reevaluation of propulsion choices in the megayacht industry, highlighting the efficiency of mechanical systems equipped with modern diesel engines alongside newer technologies. It suggests that achieving sustainability and operational efficiency does not only rely on cutting-edge innovations but also on optimizing existing solutions. This thesis contributes to the sustainable maritime operations dialogue, advocating for deeper research into how traditional propulsion can meet modern efficiency and environmental standards.

1. Introduction

This thesis delves into the comparative analysis of five distinct propulsion configurations in the mega-yacht industry: mechanical, hybrid, hybrid with batteries, diesel-electric, and diesel-electric with batteries. It seeks to evaluate their performance across three main criteria: energy efficiency, cost implications, and environmental impact, in the context of the maritime industry's shift towards more sustainable operations.

To ground this analysis in reality, the study employs a methodology based on actual data, including speed-power requirement curves and power management strategies, to simulate scenarios reflective of a mega-yacht's summer season operations. A significant part of this method involved securing technical performance data directly from engine manufacturers and suppliers, enhancing the accuracy of our simulations. Utilizing the gPROMS software for simulation, this research provides a detailed evaluation of each propulsion system's operational efficiency.

The research is guided by several questions aimed at uncovering which propulsion solution stands as the most efficient and identifying the determinants of this efficiency. Among the focal points are the economic and environmental benefits of incorporating batteries into propulsion systems, how these benefits are influenced by factors like voyage specifics, battery specifications, and management strategies, and the implications for machinery maintenance and lifespan.

The thesis is carefully structured to guide readers through a comprehensive examination of propulsion technologies within the mega-yacht industry. Initially, we present the primary specifications and requirements of our reference vessel, setting the stage for the subsequent analysis. Following this introduction, we detail the five propulsion configurations under consideration, alongside their components, selected with valuable input from suppliers. Next, we focus into the technical specifications and performance curves that underpin these configurations, laying the foundation for our simulations.

Further, the study outlines the operational scenarios and assumptions that form the basis of our simulations. This is followed by a detailed description of our approach to modeling these configurations within the gPROMS software, illustrating the methodology that enables our evaluation.

The thesis then moves into a thorough presentation of the results, followed by a comparative analysis between the different configurations. This part of the thesis highlights key performance differences among the propulsion configurations and elaborates on their implications regarding efficiency, environmental impact and operational costs. This structured approach ensures that the thesis comprehensively covers the assessment of propulsion technologies for mega-yachts, providing stakeholders in the maritime industry with valuable insights based on real data and analysis.

2. The mega-yachts ship segment

2.1. What is a mega-yacht

The term 'mega-yacht' conjures images of luxury, size, and exclusivity, but what precisely defines this class of vessel? A mega-yacht is generally characterized by its substantial length, typically over 80 meters, and is often custom-built to accommodate the lavish preferences of its owners. These vessels stand out for their scale, sophistication, and the degree of customization, offering amenities that rival five-star hotels.

In terms of design and construction, mega-yachts represent the pinnacle of naval architecture and maritime engineering. They frequently employ cutting-edge technology and high-quality materials, with a focus on performance, stability, and luxury. The interiors are usually custom-made, tailored to individual tastes, featuring everything from designer living spaces to bespoke entertainment systems and state-of-the-art navigational aids.

These vessels often house multiple decks with luxurious cabins, spas, cinemas, swimming pools, and fully equipped gyms. Advanced communication and navigation systems are standard, ensuring safety and connectivity no matter the location.

From an operational standpoint, mega-yachts are built for impressive performance. They boast long-range capabilities, allowing for extensive voyages, and are equipped with powerful engines that ensure efficient cruising speeds. The operational profile of these yachts is a testament to the sophistication of their propulsion and power management systems.

Historically, the concept of luxury yachting dates back to the early 20th century, with wealthy individuals commissioning custom-built vessels for private leisure. Over the decades, the scale and opulence of these vessels have grown, transforming them into the mega-yachts we see today. This evolution reflects not only advancements in maritime technology but also a change in the aspirations and status symbols of the marine industry.

Mega-yachts are typically owned by a select group of wealthy individuals and are used for private leisure, corporate events, or as charter vessels. The ownership and operation of these yachts contribute significantly to the maritime industry, both economically and in terms of technological development.

However, with great luxury comes great responsibility. The environmental impact of mega-yachts is an area of increasing focus, particularly in terms of emissions and energy use. This has prompted a growing interest in more sustainable practices and technologies in the mega-yacht industry, a theme that is central to this thesis.

2.2. Main features

Mega-yachts are a unique class of luxury vessels that stand out due to their exceptional size and intricate engineering [1]. Mega-yachts exceed traditional yachts' overall length, with LOAs commonly ranging from around 80 meters up to 150 meters [2] [3].

Propulsion systems, the heart of any vessel's functionality, undergo heightened engineering planning within the context of mega-yachts. Given their size and multifaceted operational requirements, these yachts often incorporate hybrid or advanced propulsion configurations, such as azimuth thrusters, pod drives, or even emerging technologies like fuel cells or electric propulsion. The selection process for these propulsion technologies is influenced by a comprehensive array of criteria, encompassing fuel efficiency, power generation capacity, agility, preferred navigation routes, and environmental impact considerations. This intricate decision-making framework underscores the efforts to optimize performance while adhering to sustainability and efficiency standards in the design and operation of mega-yachts. [1].

The engineering prowess within mega-yachts extends to the incorporation of cutting-edge technologies, seamlessly blending luxury with innovation. Advanced stabilization systems mitigate the impact of the sea, ensuring a comfortable experience for passengers even in rough weather. Integrated automation systems manage various onboard functions, from navigation to entertainment, enhancing both operational efficiency and guest experience. Moreover, materials selection is a critical engineering aspect, with lightweight composites and advanced materials enabling the construction of robust yet agile structures, enhancing comfort, performance and luxury all together.

2.3. Machinery requirements and operational needs

Addressing the operational needs of a mega-yacht is a complex task that revolves around the vessel's advanced engineering features, ensuring both its seamless functionality and the satisfaction of its high-end clientele. The intricate design of engineering considerations includes propulsion systems, power generation, navigation, and onboard systems, all of which are pivotal to sustaining the vessel's operations and enhancing the guest experience [2].

Key to a mega-yacht's operation is the propulsion system. The choice of propulsion configuration such as conventional diesel engines, hybrid systems, or emerging electric technologies, significantly influences the yacht's performance, fuel efficiency, and environmental impact. Continuous monitoring and maintenance of propulsion components are paramount to guaranteeing optimal functionality, as the reliable operation of these systems underpins the vessel's operational integrity.

Power generation is another critical aspect for the mega-yacht's operation. These vessels boast an array of power-demanding amenities, from lighting and climate control to entertainment systems and advanced navigation equipment. The integration of robust power generation solutions, which may include generators, batteries, and solar panels, is essential to ensure a stable and continuous power supply. Furthermore, the synchronization of power generation with consumption patterns requires sophisticated energy management systems that enhance efficiency and minimize waste.

Navigation and onboard systems constitute further engineering considerations in mega-yacht operations. Advanced navigation technology, including satellite communication, GPS, and radar systems, facilitate safe and accurate voyages, especially in remote or challenging maritime environments. Additionally, onboard systems, encompassing environmental control, water treatment, and waste management, contribute to the vessel's self-sufficiency and the comfort of its occupants. The integration and automation of these systems streamline operations, ensuring a smooth and luxurious guest experience.

Maintenance of engineering systems is crucial to the mega-yacht’s operations. Regular inspections, predictive maintenance practices, and rapid response protocols minimize the risk of unforeseen disruptions. Collaborations with specialized engineering service providers ensure that the machinery and systems remain in optimal working condition, supporting both operational reliability and guest satisfaction.

In summary, the operational and machinery requirements of mega-yachts depend on a sophisticated interplay of engineering aspects such as propulsion systems, power generation, navigation technology, and onboard systems. These engineering considerations constitute the foundation upon which the vessel's flawless functionality and its capacity to offer an unparalleled experience to its discerning passengers are built. By combining innovation and prevention, mega-yacht operations embody the blending of luxury and technology, where the complexity of engineering design ensures not only the vessel's reliable operation but also the fulfillment of its promise for an unforgettable experience onboard.

2.4. Upcoming trends and concerns

The mega-yacht industry is currently undergoing a significant transformation, driven by an increasing focus on sustainability, the introduction of strict regulations, and a growing commitment to eco-friendly practices. These factors are collectively forging a new trajectory for the industry, steering it towards a paradigm that prioritizes environmental responsibility and forward-thinking approaches.

Sustainability has emerged as a paramount consideration within the mega-yacht sector. The environmental footprint of these luxury vessels has attracted intensified examination, prompting a significant shift toward environmentally conscious practices. Mega-yacht builders and operators are increasingly investing in research and development to incorporate sustainable materials, energy-efficient propulsion systems, and waste reduction technologies. Moreover, the integration of renewable energy sources like solar and wind power is gaining momentum, underscoring the industry's commitment to reducing its carbon footprint.

Simultaneously, the regulatory landscape is evolving with a focus on environmental protection and safety. Stricter emissions standards, waste management protocols, and navigational regulations are driving the industry to adopt comprehensive compliance strategies. The International Maritime Organization (IMO) has been a catalyst in setting guidelines for reducing greenhouse gas emissions from ships, compelling mega-yachts to explore cleaner propulsion alternatives, such as hybrid systems [4] [5]. Compliance with these regulations is steering yacht design and operation towards a more sustainable future.

The shift towards sustainability and eco-friendliness is not only a response to external pressures but also a reflection of evolving consumer preferences. Today's yacht enthusiasts are increasingly environmentally conscious and seek experiences that harmonize with their values. Charter clients are showing a growing interest in eco-friendly itineraries that prioritize marine life conservation and sustainable cultural engagement. The mega-yacht industry's responsiveness to these preferences underscores its commitment to aligning luxury with environmental responsibility.

In conclusion, the direction of the mega-yacht industry is fundamentally being redefined by the convergence of sustainability mandates, regulatory frameworks, and a strong drive towards eco-friendly trends. The industry's engagement with these evolving dynamics, through their incorporation into vessel architecture, operational paradigms, and promotional endeavors, not only underscores a dedicated commitment to preserving marine environments and natural resources but also secures its relevance and sustainability in a swiftly evolving global context.

3. Energy efficiency and environmental performance

3.1. Current Regulations and Environmental Requirements for Mega-Yachts

In recent years, the mega-yacht industry has undergone a notable shift towards heightened environmental consciousness, driven by growing global awareness of the need for sustainable maritime practices. This transition has been catalyzed by a series of international regulations and standards that underscore the necessity to reduce the environmental impact of maritime operations. This section delves into the current regulatory landscape governing mega-yachts, highlighting the framework of requirements that shape the industry's approach to energy efficiency and environmental performance.

- International Maritime Organization (IMO) Guidelines

At the forefront of international regulations is the International Maritime Organization (IMO), a United Nations agency that plays a central role in setting global standards for maritime safety, security, and environmental protection. The IMO's regulatory framework exerts a significant influence on mega-yachts' environmental performance. Notably, the International Maritime Organization's MARPOL Annex VI, which focuses to the prevention of air pollution from ships, mandates stringent limits on sulfur oxide (SOx) and nitrogen oxide (NOx) emissions from vessels [4] [6] [7].

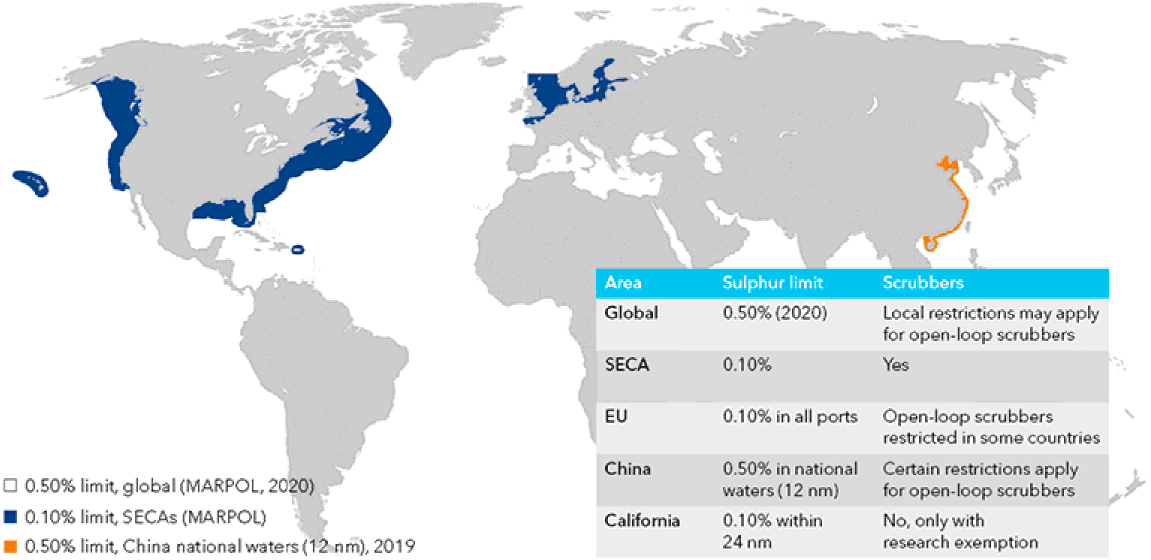
Moreover, the IMO's Energy Efficiency Existing Ship Index (EEXI) [4] [7] and Carbon Intensity Indicator (CII) are shaping the industry's approach to enhancing energy efficiency. The EEXI sets benchmarks for energy efficiency based on a vessel's design and operational characteristics, while the CII assesses a ship's carbon emissions per ton-mile traveled. Complying with these standards necessitates either operational adjustments or retrofitting, pushing mega-yacht operators to invest in energy-efficient technologies and operational practices [6].

While the International Maritime Organization (IMO) regulations do not presently encompass yachts, including mega-yachts, aligning with contemporary environmental trends has emerged as a salient consideration. Charter clients, in particular, are demonstrating an escalating interest in eco-friendly practices within the mega-yacht industry [4] [7]. This growing emphasis on environmental responsibility reflects a broader shift towards sustainability, where passengers are increasingly seeking experiences that harmonize luxury with conscientious practices. As a result, the industry is experiencing a proactive engagement with energy-efficient technologies, reduced emissions strategies, and ecologically mindful itineraries that cater to the evolving preferences of environmentally conscious clientele.

- Emission Control Areas (ECAs) and Local Regulations

In addition to the IMO's overarching regulations, certain regions have established Emission Control Areas (ECAs) with even stricter emission limits [8]. The North American ECA, for instance, encompasses waters along the coasts of the United States and Canada and enforces reduced emission limits for nitrogen oxides, sulfur oxides, and particulate matter. Mega-yacht operators traversing these areas must adhere to these stringent standards or risk incurring penalties and reputational damage [8].

Furthermore, local regulations imposed by individual countries and regions further underscore the industry's commitment to environmental responsibility. Coastal states are increasingly adopting regulations that restrict the discharge of untreated sewage, implement waste management procedures, and control ballast water exchange to prevent the introduction of invasive species.



Area	Sulphur limit	Scrubbers
Global	0.50% (2020)	Local restrictions may apply for open-loop scrubbers
SECA	0.10%	Yes
EU	0.10% in all ports	Open-loop scrubbers restricted in some countries
China	0.50% in national waters (12 nm)	Certain restrictions apply for open-loop scrubbers
California	0.10% within 24 nm	No, only with research exemption

Figure 1. Map of Emission Control Areas (ECAs) [9]

3.2. Design Considerations for Energy Efficiency and Environmental Compliance

Responding to the urgency of energy efficiency and environmental adherence, the mega-yacht industry is undergoing a fundamental transformation in its approach to design. This section investigates key design elements, focusing on engineering and propulsion, that mega-yacht architects, naval engineers, and designers are prioritizing. The goal is to ensure that these vessels not only meet but surpass expectations in terms of energy efficiency and environmental responsibility.

- Optimized Hull Design and Lightweight Materials

The hull design significantly impacts energy efficiency by reducing water resistance. Hydrodynamic efficiency is a central concern, leading to the integration of streamlined hull shapes and appendages that decrease drag. Computational Fluid Dynamics (CFD) simulations play a crucial role in fine-tuning hull designs for optimal fuel consumption. The selection of lightweight yet durable materials, including advanced composites, not only reduces vessel weight but also diminishes fuel usage and emissions [10].

- Innovative Propulsion Technologies

Mega-yacht designers are increasingly turning to innovative propulsion technologies to enhance efficiency and reduce environmental impact. Hybrid propulsion systems, which integrate traditional internal combustion engines with electric motors or other alternative power sources, offer the flexibility to operate on cleaner energy modes during specific voyage phases [11]. This dynamic approach not only conserves fuel but also reduces emissions, aligning with both regulatory demands and environmental consciousness.

Electric propulsion systems have also emerged as a promising avenue. By harnessing electricity as the primary power source, these systems eliminate direct emissions and significantly reduce noise levels, thereby contributing to a quieter and more environmentally considerate operation. Electric propulsion, when combined with energy storage solutions like advanced batteries, enables extended silent cruising, catering to eco-conscious passengers seeking serene seafaring experiences.

- Energy Waste Reduction

Beyond propulsion configurations, energy recovery systems are garnering attention for their ability to extract and reuse otherwise wasted energy from various onboard processes. A noteworthy strategy for reducing energy waste within the mega-yacht context involves the utilization of rechargeable batteries in conjunction with Power Take-Off (PTO) and Power Take-In (PTI) motors. This innovative approach harnesses excess kinetic energy generated by the yacht's movement, converting it into electricity through PTO motors [12]. This electricity is then used to recharge onboard batteries, which can subsequently power the vessel's systems during low-speed operations or when docked, effectively reducing the demand on the main engines. This integrated system optimizes energy utilization and also aligns with the industry's commitment to innovative solutions that line up with energy efficiency and environmental preservation.

4. Mega-yacht machinery and propulsion alternatives.

4.1. Machinery Configurations

The mega-yacht industry's propulsion systems range from traditional to innovative technologies. This section examines the variety of options available, showcasing their evolution from standard methods to advanced alternatives. Each system is evaluated based on energy efficiency, environmental impact, and operational performance, illustrating the industry's shift towards more sustainable and effective solutions.

- Conventional Propulsion Systems

Conventional propulsion systems, deeply rooted in maritime tradition, represent the historical backbone of vessel propulsion, including that of mega-yachts. These systems, characterized by their proven reliability and familiar operational mechanics, have been pivotal in guiding the development and functional dynamics of yacht design and operation over the years. [13].

The origins of conventional propulsion systems can be traced back to the early days of maritime exploration when sail-driven ships transitioned to steam-powered vessels. This transformation marked a turning point in maritime history, revolutionizing trade, travel, and warfare. In the context of yachts, the transition from sail to steam marked the emergence of luxury leisure cruising, where engines replaced wind as the primary means of propulsion. This historic progression laid the groundwork for the conventional propulsion systems that continue to influence mega-yacht design.

Conventional propulsion systems in mega-yachts typically consist of two internal combustion diesel engines coupled with shaft-driven fixed-pitch propellers. Diesel engines, renowned for their efficiency and durability, are the workhorses responsible for converting fuel energy into mechanical power. This power is then transmitted to the propellers through shafts and reduction gears, propelling the vessel through water. While these systems offer stability and simplicity, they are associated with higher fuel consumption and emissions compared to modern alternatives.

- Advanced Propulsion Alternatives

Advancements in propulsion technologies have introduced cutting-edge configurations, merging tradition with innovation. Driven by the quest for superior energy efficiency and environmental sustainability, these developments have led to the creation of advanced propulsion solutions that mark a new era in maritime engineering.

At the forefront of advanced propulsion alternatives are the innovative hybrid propulsion systems. Combining conventional internal combustion engines with electric motors and energy storage systems, hybrid configurations facilitate seamless transitions between power sources based on operational demands. The integration of Power Take-Off

(PTO) and Power Take-In (PTI) motors within advanced propulsion systems represents an robust approach to energy conservation. PTO motors harness energy generated by the yacht's motion, converting it into electricity that can be stored in batteries or used to power onboard systems. Conversely, PTI motors can operate as generators, replenishing the battery reserves while the yacht is stationary, capitalizing on opportunities to recharge without expending additional fuel [7] [13].

Electric propulsion stands as a pinnacle of innovation, powering yachts through electric motors and energy storage systems, such as battery packs. This approach eliminates direct emissions, reduces noise pollution, and enables extended silent cruising. The integration of renewable energy sources, such as solar panels and wind turbines, further advances the concept of energy autonomy and carbon neutrality. Notably, rechargeable batteries assume a pivotal role in storing surplus energy generated during cruising or braking phases. This stored energy can subsequently be utilized to power the vessel during low-speed maneuvers or while docked, resulting in reduced engine usage, emissions, and noise pollution.

4.2. Main Components

- Diesel engine

This is the primary power source for the conventional propulsion system, and it converts the chemical energy stored in diesel fuel into mechanical energy. The engine may be a single unit or it may consist of multiple units, depending on the size and power requirements of the yacht.

- Gearbox

A marine gearbox is a mechanical device used to transmit power and torque from the engine of a marine vessel to the propeller or other propulsion system. It consists of a housing that encloses a set of gears, used to reduce the engine speed and increase the propulsion system's torque output.

A marine gearbox with two inputs and one output is a type of mechanical device that is used to transmit power and torque from two separate sources to a single output. This type of gearbox is commonly used in the marine industry to transmit power from multiple engines or generators to a single propulsion system or load. It can be used to increase the system's power and reliability or to allow the use of different types of engines or power sources. This type of gearboxes is commonly used for hybrid propulsion systems.

- Shaft

Shafts form the critical link between propulsion systems and propellers, transmitting power with precision. In conventional setups, shafts connect engines to fixed-pitch propellers, ensuring consistent energy transfer. In advanced configurations, such as hybrid or electric, shafts accommodate varying power sources, demanding adaptability and meticulous engineering. The shaft is typically supported by bearings at each end, which allow it to rotate smoothly and reduce friction, vibrations and noise.

- Propeller

The propeller may be a fixed-pitch propeller or a controllable-pitch propeller, depending on the design of the propulsion system. Propellers are the workhorses of propulsion systems, converting energy into forward movement while influencing efficiency and maneuverability in mega-yachts. Across propulsion configurations, propeller design factors such as diameter, blade pitch, and material choice impact performance. In advanced setups like hybrids and electrics, precision design accommodates varying power sources. Materials like lightweight composites align with efficiency goals.

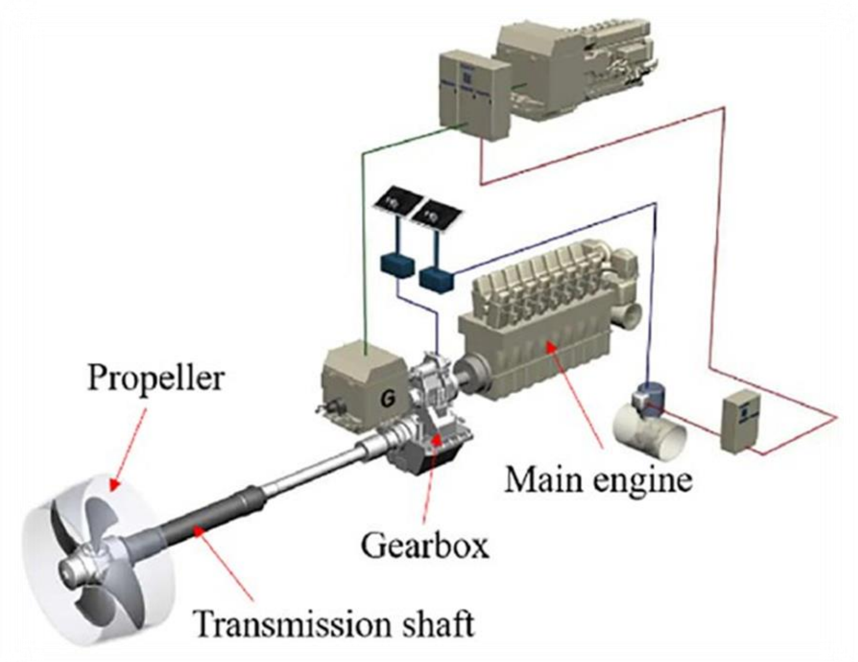


Figure 2. Schematic diagram of a mechanical marine propulsion system. [13]

- Engine controls

These are the electronic and mechanical systems that are used to control the operation of the diesel engine, such as the throttle, fuel system and cooling system. The engine controls may be operated manually or automated, depending on the propulsion system's design.

- Generator sets

The primary goal of a generator on board a ship is to generate electrical power to meet the ship's energy needs. This includes powering the ship's systems and equipment, such as propulsion, navigation, communications, lighting and climate control. Generators are an essential part of a ship's power system, as they provide a reliable source of electrical energy when the ship is at sea and not connected to shore-side power. Diesel generators are the most common type of generator used in the marine industry, as they are reliable, efficient, and relatively inexpensive. They use diesel fuel to power an internal combustion engine, which drives an alternator to generate AC power.

- Frequency Converters

Frequency converters are commonly used in the marine industry to power and control electric motors that drive various shipboard systems, such as propulsion, ballast pumps, cargo handling, and auxiliary power. They can be used to adjust the speed of motors to optimize their efficiency and performance, and to ensure that they run smoothly and reliably. Frequency converters can also be used to interface with shore-side power supplies or to generate and control alternating current (AC) power on board the ship.

- Electric Motors

Electric motors are a common type of propulsion system used in the marine industry. They can be powered by a variety of energy sources, including batteries, fuel cells, and generators, and they offer several advantages over traditional fossil fuel-powered propulsion systems, such as lower emissions, improved efficiency, and reduced maintenance requirements. There are several types of electric motors that are used for marine propulsion, including direct current (DC) motors, alternating current (AC) motors, and synchronous motors. DC motors are simple and reliable, but they are not as efficient as AC motors. AC motors, on the other hand, can be more efficient and offer better performance, but they require more complex control systems. Synchronous motors are typically used for large, slow-moving ships, such as cargo vessels and tankers. They offer high efficiency and excellent power factor, but they are more expensive and complex than other types of electric motors.

The synchronous speed of an electric motor is the speed at which the motor's rotor rotates when it is driven by a sinusoidal AC power supply at a constant frequency. The synchronous speed of an electric motor is determined by the number of poles it has and the frequency of the AC power supply.

The synchronous speed of a motor is:

$$ns = (120 \times f) / p$$

Equation 1. Synchronous speed of an electric motor.

Where,

ns = synchronous (rotational) speed [RPM]

f = the frequency of the AC-supply [Hz]

p = the number of poles of the electric motor

The most common frequencies used in marine applications are 50 and 60 Hz so the synchronous speeds are 3000, 1500, 1000, 750, 600 RPM and 3600, 1800, 1200, 900, 720 respectively for 2, 4, 6, 8 and 10 poles.

Electric propulsion motors offer numerous advantages beyond energy efficiency. Their near-instantaneous torque delivery results in rapid acceleration and precise maneuverability, enhancing overall vessel control. Furthermore, their modular design enables easy scalability, accommodating a wide range of vessel sizes and types. In advanced configurations, electric motors integrate seamlessly with Power Take-Off (PTO) and Power Take-In (PTI) systems, maximizing energy recovery during deceleration or stationary periods.

In many hybrid propulsion systems, the PTI electric motor drives the vessel's propeller directly or with the main diesel engine. The PTI motor is generally smaller than the main diesel engine and usually operates at a constant speed, allowing for improved efficiency and reduced emissions. When the PTI motor is used in conjunction with the main engine, the main engine can operate at its most efficient speed, while the PTI motor provides additional power when needed.

The PTO electric motor, on the other hand, is used to generate electricity from the rotation of the vessel's propeller shaft. This electricity is then used to charge the vessel's batteries, power the PTI motor, or other onboard systems. The PTO motor allows for the recovery of energy that would otherwise be lost as heat through the vessel's propeller shaft, improving the overall efficiency of the propulsion system.

One of the main benefits of using PTI and PTO electric motors in hybrid propulsion systems is that they allow for improved efficiency and reduced emissions compared to traditional fossil-fuel powered engines. By using electric motors in combination with fossil-fuel powered engines, it is possible to optimize the operation of the propulsion system to provide the desired performance while minimizing its environmental impact. Moreover, by equipping such electric motors there is a significant reduction of CAPEX, as the power plant is optimized with smaller or even fewer auxiliary engines.

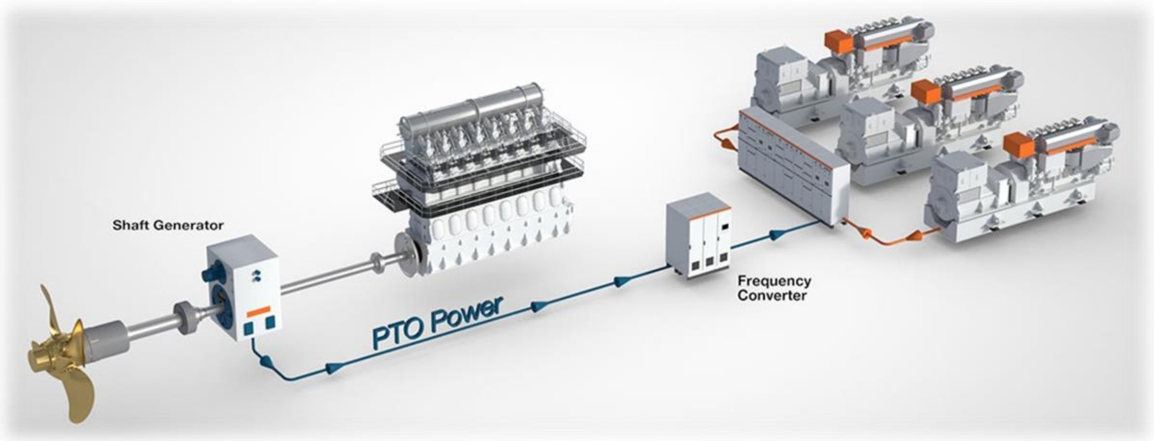


Figure 3. Schematic diagram of a marine propulsion system with a PTO generator. [14]

- DC to AC Inverters

An electric inverter is a device that converts direct current (DC) electrical energy into alternating current (AC) electrical energy. It consists of an electronic circuit that uses transistors or other switching devices to generate an AC voltage from a DC voltage. Electric inverters are used in a wide range of applications, including power generation, distribution, and utilization. They are commonly used to convert the DC power produced by batteries, solar panels, and fuel cells into AC power, which is used to power AC devices and systems. Electric inverters are also used in hybrid and full electric propulsion systems in the marine industry to convert the DC power stored in the battery packs into AC power to drive the electric motors.

- Battery Packs

Battery packs stand as the backbone of modern propulsion configurations, embodying the industry's commitment to energy efficiency and environmental consciousness. These compact reservoirs of stored energy play a pivotal role in advanced setups, such as hybrid and electric propulsion, where they enable the seamless conversion of power from various sources into sustainable propulsion.

Batteries are used to store electrical energy that can be used to power the vessel's systems and equipment, including the electric motors that drive the propeller or other propulsion system. There are several types of batteries that can be used for marine applications, including lead-acid batteries, lithium-ion batteries, and nickel-metal hydride batteries. Each type of battery has its own set of characteristics, such as energy density, capacity, discharge rate, and lifespan, which make it suitable for different types of vessels and applications. Battery packs for marine vessels need to be designed and constructed to withstand the harsh marine environment, and they must be able to operate reliably under a variety of conditions. Battery packs for yachts need to be designed and constructed to withstand the harsh marine environment, and they must be able to operate reliably under a variety of conditions.

Battery packs can be used to store either direct current (DC) or alternating current (AC) electrical energy, depending on the application and the type of battery. Most battery packs used in marine propulsion systems are designed to store DC electrical energy, as they are used to power DC electric motors or to charge DC battery-powered devices. These battery packs are typically made up of individual cells that are connected in series and parallel to form a single battery pack. The cells can be made of a variety of materials, including lead-acid, lithium-ion, and nickel-metal hydride.

There are also battery packs that are designed to store AC electrical energy, such as those used in hybrid or full electric propulsion systems. These battery packs are typically made up of many cells that are connected in series and parallel to form a single battery pack. The cells can be made of a variety of materials, including lithium-ion, nickel-metal hydride, and flow batteries

Charging the battery pack on a yacht is an important task that is necessary to maintain the vessel's electrical systems and equipment. There are several ways to charge the battery pack on a yacht, depending on the type of battery and the charging system that is being used. Some common methods of charging yacht battery packs include:

1. Alternator charging: This is the most common method of charging the battery pack on a yacht. It uses the yacht's main engine or a separate generator to power an alternator, which generates electricity to charge the battery pack.
2. Shore power charging: This method involves connecting the yacht's battery pack to an external power source, such as a shore-side electrical outlet, to charge the batteries.
3. Solar panel charging: This method uses solar panels to convert sunlight into electricity, which is used to charge the battery pack.
4. Wind turbine charging: This method uses a wind turbine to generate electricity, which is used to charge the battery pack.

Lithium-ion battery technology dominates in the marine industry due to its high energy density, efficiency, and relative lightness. These batteries offer a balance between energy storage capacity and weight, enabling yacht designers to optimize vessel performance without sacrificing efficiency.

The task of choosing the right size of battery packs within propulsion systems is an intricate endeavor that underscores the mega-yacht industry's commitment to precision and performance. Balancing power requirements with energy efficiency is paramount in this decision-making process. Oversizing battery packs offers extended cruising ranges and prolonged silent operations, ensuring ample power reserves. However, it comes at the cost of increased weight, impacting vessel dynamics and energy consumption during recharging.

Some of the most important factors that should be considered in order to select a well-suited battery pack for a mega-yacht are:

- Vessel Size and Usage: Determine the battery capacity to match the yacht's size and intended operational patterns, ensuring adequate power for different cruising scenarios.

- Propulsion Configuration: Determine the power requirements of the chosen propulsion system – hybrid, electric, or other – to size the battery pack accordingly.
- Charging Infrastructure: Evaluate available charging sources, such as renewable energy inputs and onboard generators, to gauge the required battery capacity.
- Operational Flexibility: Balance power reserves with the ability to operate silently, accounting for longer cruising ranges and quiet periods without compromising performance.

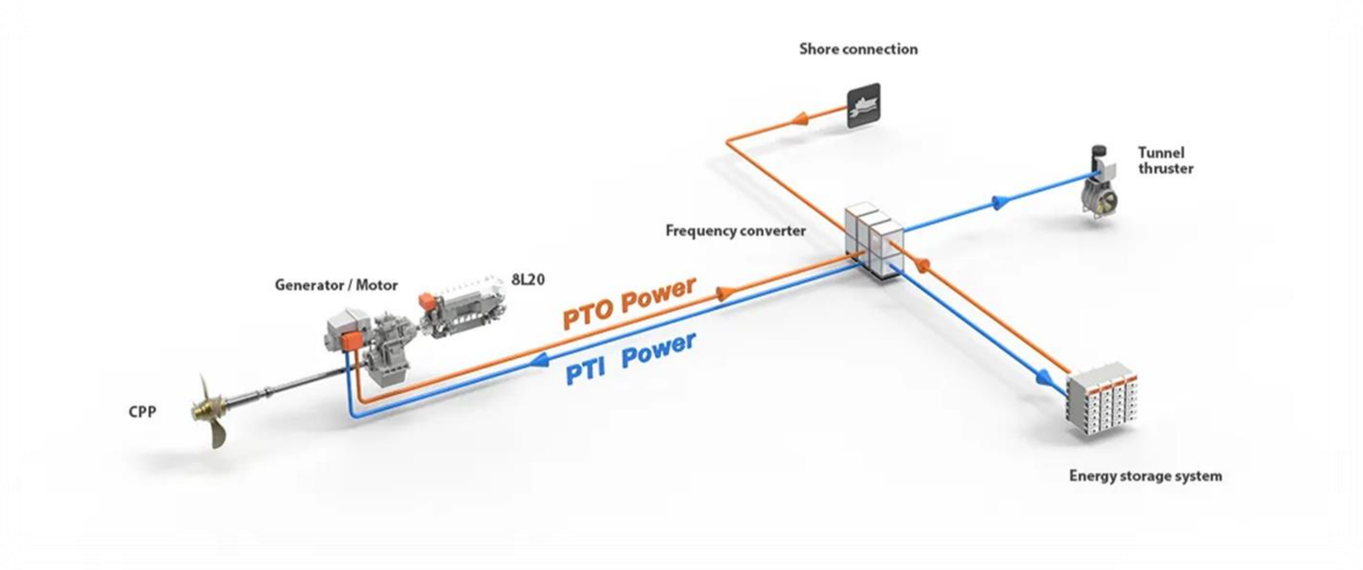


Figure 4. Schematic diagram of a marine propulsion system with a PTO/PTI motor and batteries. [15]

5. Application Study

5.1. Case Study Vessel

The vessel considered in this study is a mega-yacht with the main characteristics shown in Table [Number]. The reference mega-yacht was initially designed with a traditional diesel propulsion configuration. However, during its most recent refit, four additional propulsion configurations were considered as possible. The goal of these configurations is to provide the same propulsion power as the original traditional configuration while being more efficient and eco-friendlier.

Table 1. Main characteristics of the reference vessel

Quantity	Symbol	Value	Unit
Length overall	Loa	84.89	m
Beam	B	12.8	m
Draught	T	4.53	m
Displacement	Δ	2290	ton
Propulsion Power	P	4340	kW
Hotel Load	H	350	kW
Maximum Speed	Vmax	18.2	kn

5.2. Reason for Vessel Selection: Practical Considerations and Challenges

The choice of our case study vessel, an 85-meter mega-yacht built in 1990, stems from several pragmatic factors that align with the goals of this application study.

- Appropriate Size and Historical Context

The vessel's size of 85 meters strikes a balance between spaciousness and navigational efficiency, making it an ideal candidate for our examination. Its construction in 1990, an era when maritime engineering emphasized sturdiness, is significant. The heavier construction of this vintage yacht demands more power compared to modern vessels of similar size, providing a valuable perspective on how propulsion systems have evolved over time.

- Rich Technical Information from Refitting

The recent refit of the chosen vessel has provided a wealth of technical specifications. This abundance of technical data is essential for our study, as it enables us to thoroughly analyze the yacht's machinery and propulsion configurations. The insights gained from the refit allow us to delve deep into the vessel's propulsion intricacies, providing essential information for assessing its energy efficiency and environmental impact.

- Challenges regarding the age of the vessel

The age of the vessel, now over 30 years old, introduces an intriguing challenge. The need to modernize the propulsion system within the framework of an older vessel presents an opportunity to explore the compatibility of modern propulsion technologies with a legacy structure. This aspect serves as a significant facet of our study – an examination of whether contemporary propulsion systems can seamlessly integrate with an aging vessel. The historical context of the yacht's age adds a layer of complexity and practicality to our investigation.

- Diverse Propulsion System Scenarios

The vessel's notable hotel loads, a consequence of its size, introduces an intriguing dimension. The utilization of batteries or transitioning to a fully electric propulsion system offers a practical case study to evaluate energy efficiency. The potential to alleviate hotel load energy demands by integrating batteries or electric propulsion presents an opportunity to demonstrate the efficacy of these technologies in real-world, high-load scenarios.

5.3. Configuration 1 – Mechanical: Current propulsion configuration

The conventional mechanical propulsion configuration, the most common amongst similar type of vessels, is defined by its mechanical simplicity. The main feature, an internal combustion engine that generates mechanical power. This power is transmitted to a propeller shaft via a series of mechanical components, such as reduction gears and shaft couplings. The propeller then transforms this mechanical power into thrust, propelling the vessel through water.

The mechanical setup of the conventional propulsion system is characterized by its robustness and reliability. While it may lack the sophisticated energy efficiency features of modern alternatives, it offers a direct and dependable power transfer mechanism. The coupling of internal combustion engines with mechanical components results in a propulsion system well-suited for vessels with substantial hotel loads and traditional operational profiles.

The reference mega-yacht’s configuration mainly consists of the following:

- Two (2) Main Engines
- Two (2) Gearboxes
- Two (2) Diesel Generator sets
- Two (2) fixed-pitch Propellers

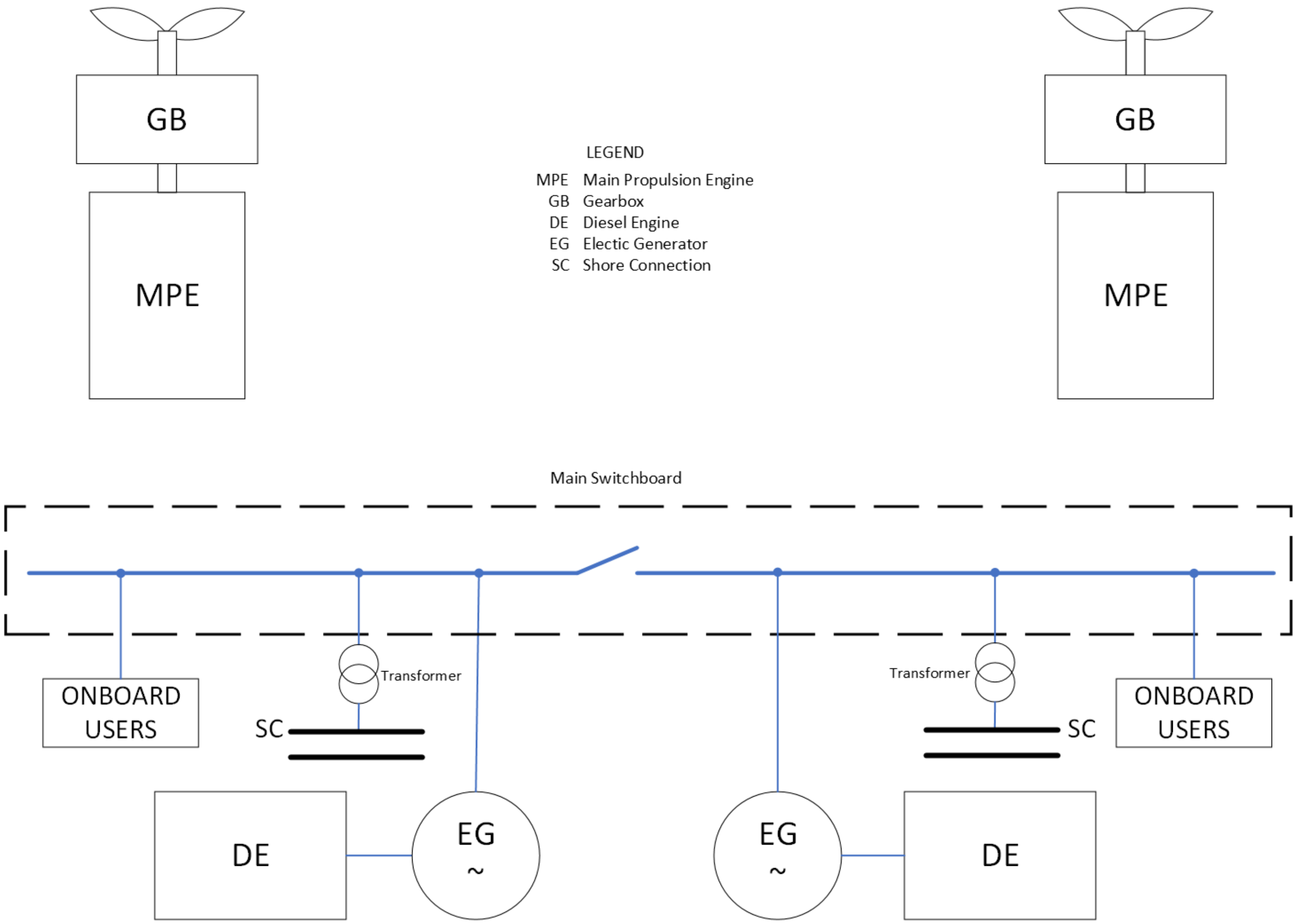


Figure 5. Simplified scheme of the mechanical propulsion configuration (Configuration 1).

However, the conventional mechanical propulsion system carries its share of drawbacks. Energy efficiency can be compromised due to inherent energy losses in the mechanical components. Additionally, emissions, including greenhouse gases, are a concern as internal combustion engines burn fossil fuels. Noise and vibrations associated with mechanical linkages are further challenges, detracting from the onboard experience and environmental harmony.

5.4. Alternative propulsion configurations

Transitioning from conventional mechanical propulsion, our focus now shifts to propulsion alternatives. These configurations merge traditional engineering and modern technology. Here, we encounter methods that balance power, reliability, and environmental concerns in maritime propulsion. This shift takes us from the conventional to the innovative, as we examine how these alternatives optimize energy and enhance performance. This exploration paves the way for potential solutions in efficient maritime propulsion.

5.4.1. Configuration 2: Mechanical propulsion with electric assist (Hybrid)

Hybrid diesel electric propulsion systems are a type of hybrid propulsion system that combine diesel engines with one or more electric motors to drive a marine vessel. Those systems are being increasingly used on yachts to improve fuel efficiency and reduce emissions. In a hybrid diesel electric propulsion system, a diesel engine is used to generate electricity, which is then used to power one or more electric motors that drive the yacht's propeller or other propulsion system.

The hybrid propulsion system is fundamentally characterized by the strategic integration of Power Take-In (PTI) and Power Take-Off (PTO) motors in conjunction with the primary diesel engines. PTI motors, as highlighted earlier, function as generators by capturing surplus power from the main engine during high-load conditions. On the other hand, PTO motors are designed to transform mechanical power from the main engine into electrical energy, which can be used to charge batteries when present or to power auxiliary systems during periods of reduced propulsion demand.

In our case the hybrid configuration mainly consists of the following:

- Two (2) Main Engines
- Two (2) Dual-input gearboxes
- Two (2) Diesel Generator sets
- Two (2) PTI/PTO Propulsion motor drives

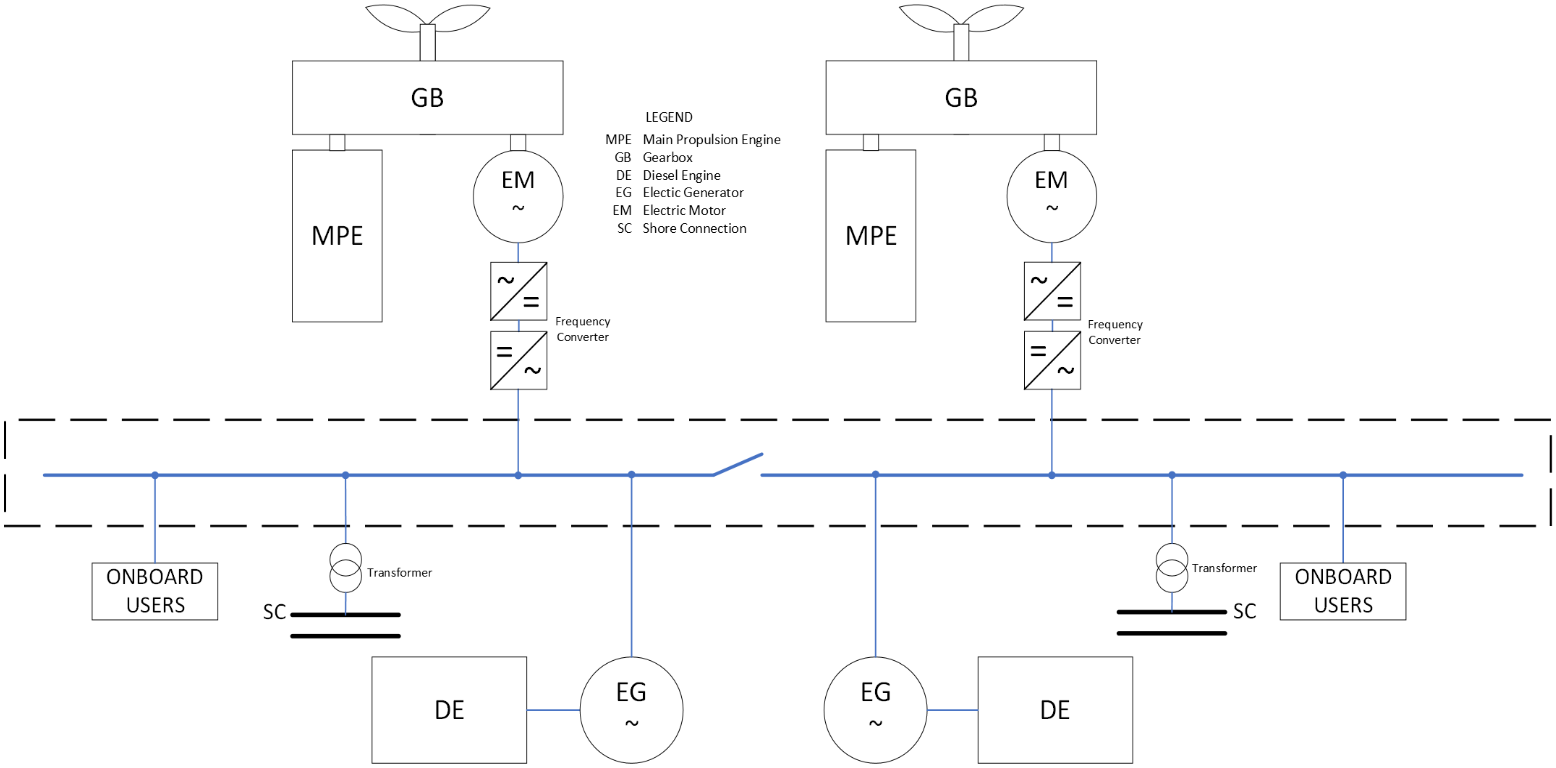


Figure 6. Simplified scheme of the hybrid propulsion configuration (Configuration 2).

5.4.2. Configuration 3: Hybrid propulsion with onboard battery pack

The integration of batteries within hybrid propulsion systems brings forth a host of advantages that underscore the transformative potential of this configuration. Batteries serve as dynamic energy reservoirs, enabling efficient energy storage and distribution. This stored energy can be strategically deployed during high-demand periods, such as rapid acceleration or navigating challenging waters, augmenting the power output of the main engine.

During phases of lower propulsion demand, excess energy can be harnessed by auxiliary systems. This results in reduced fuel consumption and emissions, as the battery system optimizes power allocation based on real-time requirements. Moreover, batteries enable silent, emissions-free operation during low-load scenarios, enhancing the onboard experience and environmental stewardship. The integration of batteries into hybrid propulsion embodies the industry's response to the imperatives of efficiency, sustainability, and operational adaptability, presenting a compelling model for advancing maritime propulsion into a more responsible and resource-efficient future.

The arrangement of this configuration is the same as the previous configuration with the addition of:

- Properly sized battery pack
- Battery Management System (BMS)
- DC to AC Inverters

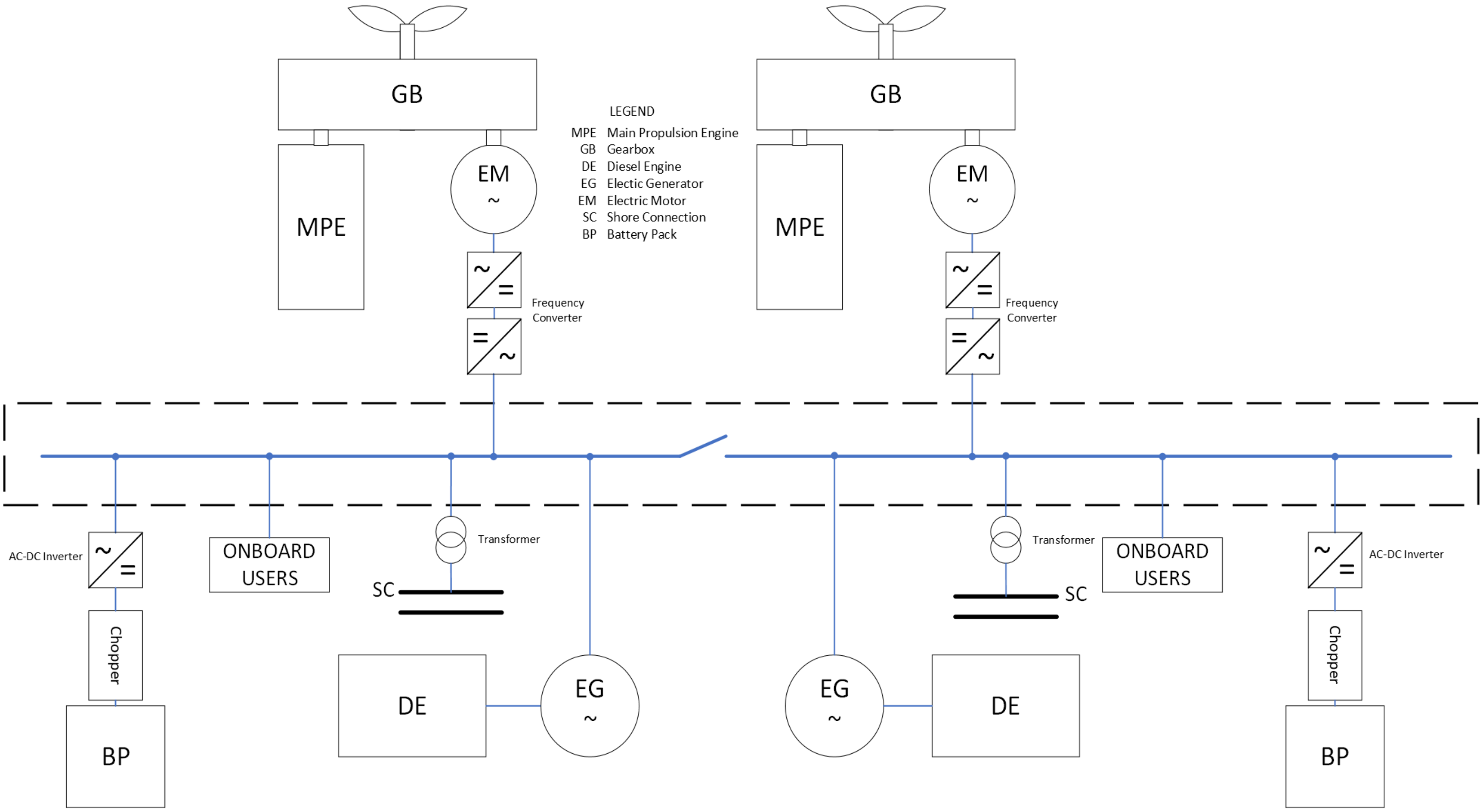


Figure 7. Simplified scheme of the hybrid with batteries propulsion configuration (Configuration 3).

5.4.3. Configuration 4: Diesel-Electric

Diesel-electric propulsion offers a different approach in energy utilization. By employing generators to produce electrical power, the engines can be operated at their most fuel-efficient speeds, irrespective of propulsion demands. This optimization is expected to reduce fuel consumption and emissions, resulting in a substantial reduction of the vessel's carbon footprint. Moreover, the flexibility in power allocation enhances operational efficiency by adapting to varying load conditions.

Key features of Diesel-Electric propulsion configurations:

- Diesel generators form the primary power source in diesel-electric propulsion systems. They convert diesel fuel into mechanical energy, which is subsequently transformed into electrical energy. Diesel generators provide all the necessary power for various onboard systems, including propulsion, electrical load, and auxiliary equipment.

- Electric motors play a critical role in diesel-electric propulsion systems, converting electrical energy into mechanical energy to drive the propellers. These motors offer advantages such as high torque, precise control, and quiet operation.

- The power management system coordinates the distribution of electrical power generated by the diesel generators to the electric motors and other onboard electrical loads. It ensures an optimal allocation of power based on the vessel's operational requirements, load demand, and energy storage capabilities.

The diesel-electric configuration aligns seamlessly with the maritime industry's pursuit of eco-friendly solutions. By minimizing fuel consumption and emissions, this system contributes to a more sustainable maritime ecosystem. Furthermore, the technological progress in power electronics and control systems has enhanced the performance and reliability of diesel-electric propulsion, making it a viable choice for vessels seeking to strike a balance between power, efficiency, and environmental considerations.

In order to properly select the diesel generator sets for the full electric configuration, it is important to ensure that all electric needs, including hotel loads, can be covered by the chosen gensets.

In the case study vessel, the diesel-electric configuration includes:

- Two (2) Primary Diesel Generator sets
- Two (2) Secondary Diesel Generator sets
- Two (2) Propulsion motor drives

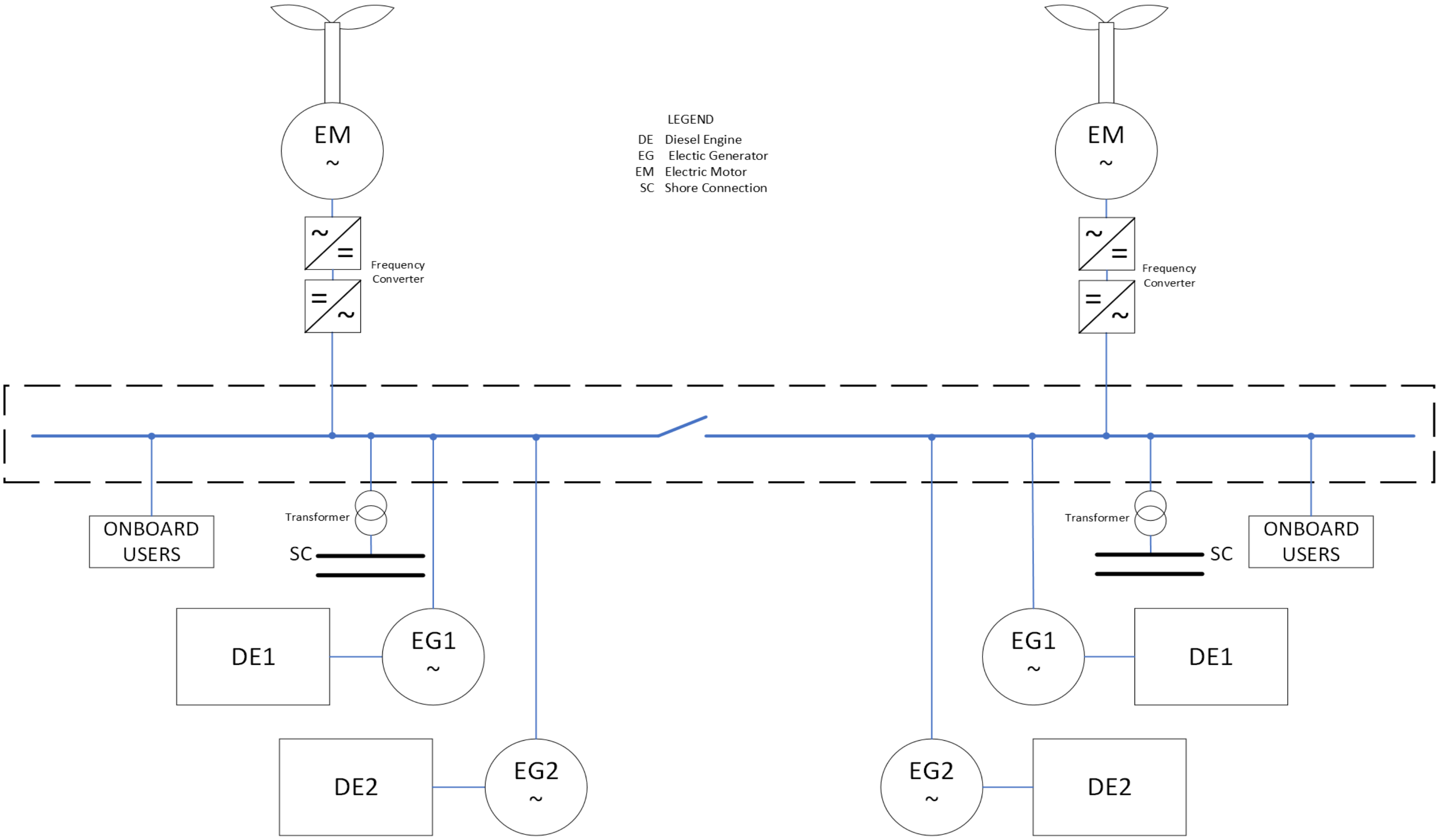


Figure 8. Simplified scheme of the diesel-electric propulsion configuration (Configuration 4).

5.4.4. Configuration 5: Diesel-Electric with battery pack

This section illuminates the perfect example where the potent combination of diesel engines, electric generators, and batteries harmonize to amplify energy efficiency, operational flexibility, and environmental responsibility.

Batteries serve as reservoirs for surplus electrical energy generated by the diesel engines. This stored energy can be tapped into during periods of high propulsion demand, augmenting the power output and providing a temporary boost of acceleration or maneuvering capabilities. Consequently, the engines can be operated at optimal, fuel-efficient speeds, enhancing overall energy efficiency.

This type of propulsion configuration for mega-yachts uses electric motors powered mainly by batteries as the source of propulsion instead of traditional diesel engines. The system includes electric motors to drive the propellers, a battery bank to store the electrical energy, a power management system to control the flow of electrical power and a shore power connection to charge the battery and cover the vessel’s needs when moored.

The inclusion of battery packs, as also mentioned in Configuration 3, significantly contributes to the objective of silent, emissions-free operation during low-load scenarios. The vessel can switch to battery power, enabling noiseless cruising in environmentally sensitive areas or during quiet hours. By reducing the reliance on diesel engines during these periods, emissions are minimized, resulting in a more ecologically harmonious maritime presence.

The ability to seamlessly transition between different power sources optimizes energy usage and reduces carbon footprint. This configuration aligns with the maritime industry's aspirations for sustainable practices, and its evolution signifies a milestone in the pursuit of a harmonious coexistence between maritime operations and the environment.

However, there are also some limitations, such as limited range and longer charging times. As battery technology improves and charging infrastructure expands, full electric propulsion systems are expected to become more common on mega-yachts and other vessels in the future.

In our case this configuration includes:

- Two (2) Primary Diesel Generator sets
- Two (2) Secondary Diesel Generator sets
- Two (2) PTI/PTO Propulsion motor drives
- Properly sized battery pack
- Battery Management System

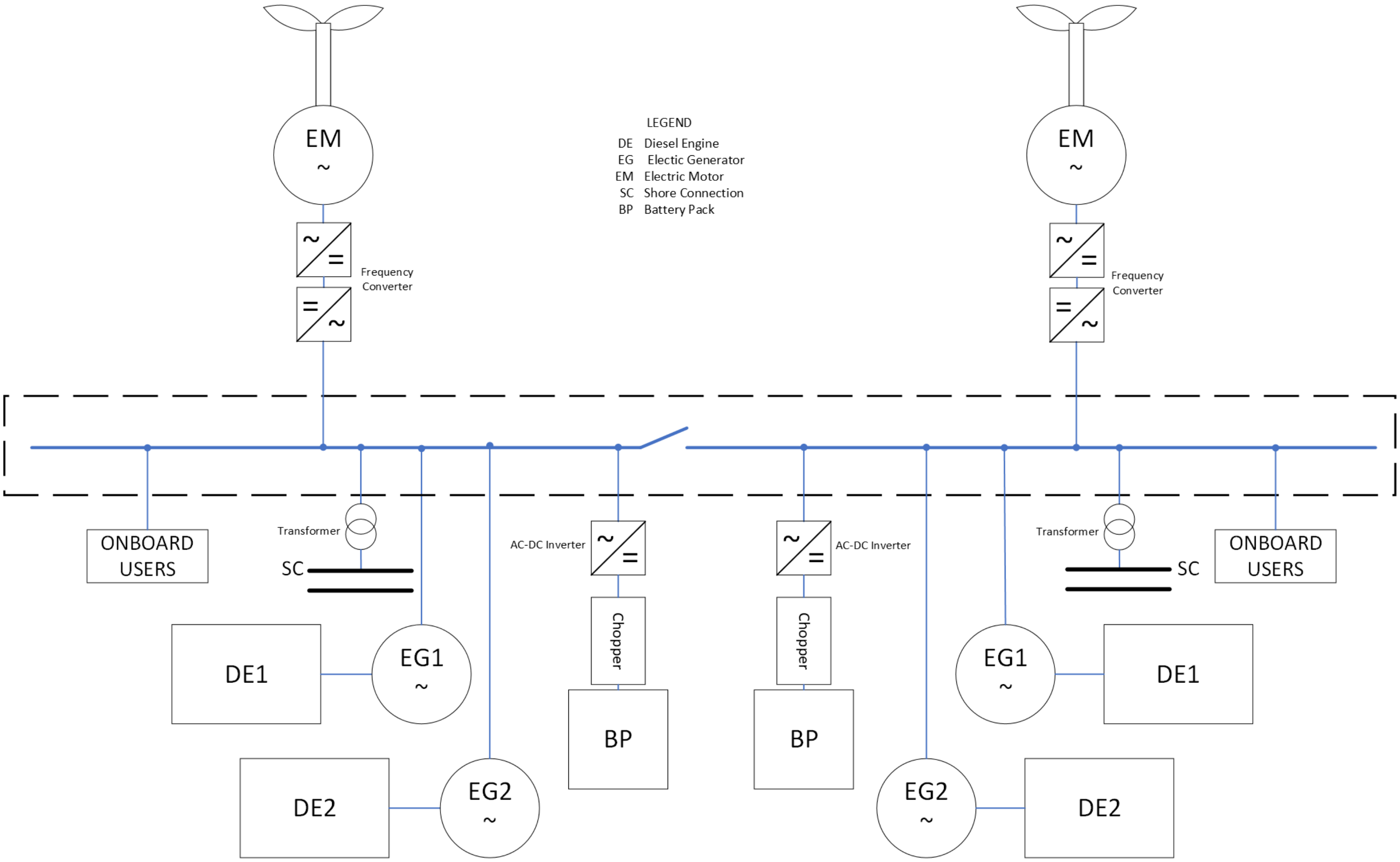


Figure 9. Simplified scheme of the diesel-electric with batteries propulsion configuration (Configuration 5).

5.5. Selection of configuration components

The next section is dedicated to dissecting the technical aspects that drive propulsion systems. We will closely examine the detailed technical data for the configurations previously discussed.

Following private communication with diesel marine engine manufacturers, a careful selection of components was conducted. Factors such as engine type, power output, engine speed, fuel efficiency, emissions, and compatibility with the vessel's requirements such as space requirements and weights were considered. The aim was to ensure that the chosen components meet the necessary technical specifications and contribute to the overall effectiveness and reliability of the propulsion configurations.

To appropriately discern the machinery best suited for all five (5) propulsion configurations, a comprehensive understanding of the vessel's requirements was essential. The selection process commenced with a meticulous analysis of the mega-yacht's needs. Primarily, our focus was directed towards satisfying the propulsion power demands of 4340 kW, imperative for maintaining the vessel's desired cruise and maximum speeds. Furthermore, in configurations based in the synergy of electric motors and diesel engines, such as the hybrid setups (Configuration 2 and 3), attention was devoted to ensure that the combined power output effectively covers the power requirements. This ensured that the propulsion configurations delivered the desired performance metrics while attaining the desired efficiency goals.

Considerations extended beyond propulsion, encompassing auxiliary power prerequisites necessary to support the yacht's operational functions. Additionally, catering to the energy needs of the passengers and providing onboard amenities became paramount. As elaborated in greater detail in Chapter 6, the calculated hotel load that the generator sets are tasked with accommodating stands at 350 kW. Moreover, the decision regarding the frequency of the chosen generator was driven by practical considerations. A frequency of 50 Hz was chosen, aligning with the most common standard for shore connections in European marinas. This choice ensures compatibility with existing infrastructure.

The selection of the main engines and generator sets was supervised by the technical department of ΕΛΤΡΑΚ Α.Ε. [14], and focused on choosing the most recent and eco-friendly solutions available that suited our needs

Choosing the batteries for the propulsion configurations was determined by several key factors. We carefully evaluated the size of the batteries to ensure their compatibility with the vessel's available space, while also considering the weight to prevent undue strain on the yacht's structure. The capacity of the chosen battery packs was a crucial consideration, directly impacting the operational range and endurance. Additionally, we selected batteries with manageable recharging times to maintain efficient vessel scheduling during layovers. Ensuring compatibility with the propulsion systems and other components was also a significant priority in our decision-making process. Collectively, these factors guided our machinery selection, leading us to battery solutions that should effectively balance efficiency, performance, and operational viability.

The machinery specifications for the selected propulsion configurations are presented in Table 2.

Table 2. Main components' specifications for each selected propulsion configuration.

Configuration	Quantity	Machinery	Type	Specifications
Traditional	2	Diesel Engine	Caterpillar 3516C	2240bkW
	2	Diesel Genset	Caterpillar C9.3	195 ekW @50Hz
	2	Gearbox		6:1 reduction ratio
Hybrid	2	Diesel Engine	Caterpillar 3516E	2100 bkW
	2	Diesel Genset	Caterpillar C18	465 ekW @50Hz
	2	Dual-input Gearbox		6:1 reduction ratio
	2	Propulsion motor drive		465 kW
Hybrid w/ Batteries	2	Diesel Engine	Caterpillar 3516E	2100 bkW
	2	Diesel Genset	Caterpillar C18	465 ekW @50Hz
	2	Dual-input Gearbox		6:1 reduction ratio
	2	Propulsion motor drive		465 kW
	1	Battery Pack		4000kWh
Diesel-Electric	2	Primary Diesel Genset	Caterpillar 3516E	1840 ekW @50Hz
	2	Secondary Diesel Genset	Caterpillar C18	465 ekW @50Hz
	2	Propulsion motor drive		2300 kW
Diesel-Electric w/ Batteries	2	Primary Diesel Genset	Caterpillar 3516E	1840 ekW @50Hz
	2	Secondary Diesel Genset	Caterpillar C18	465 ekW @50Hz
	2	Propulsion motor drive		2300 kW
	1	Battery Pack		4000kWh

5.6. Operational Profiles

In the forthcoming section, we delve into the operational profiles that define the diverse states of the vessel. These operational scenarios include a variety of maritime activities, each having specific propulsion demands.

5.6.1. Modes of Operation

The vessel's operation can be classified into the following states [15]:

1. **Maneuvering**: This profile involves complex navigational maneuvers, including docking, departing from ports, or performing tight turns, necessitating meticulous control over propulsion and power distribution to guarantee precise and secure movement.
2. **Cruising**: During this phase, the vessel operates at a consistent speed while traversing open waters. This profile involves steady propulsion and energy management to sustain cruising efficiency over prolonged distances.
3. **Cruising at Max Speed**: This state involves operating the vessel at its maximum attainable speed, often required to meet strict timelines or navigate through challenging conditions. It demands optimized power output and fuel efficiency to sustain elevated speeds.
4. **Anchor Stationed**: When the vessel is stationary but afloat, it assumes an anchor-stationed state. In this scenario, the propulsion system is inactive, and energy management focuses on supporting onboard systems and accommodation while maintaining vessel stability.
5. **Berthed/Moored**: This profile pertains to when the vessel is docked or berthed at a port/marina. Propulsion is inactive, and energy is directed towards auxiliary systems, passenger accommodations, and vessel services.

Each of these operational profiles introduces unique propulsion requirements, emphasizing the need for propulsion configurations that adapt seamlessly to the varying demands. Through a comprehensive examination of these profiles, we establish a foundation for evaluating propulsion efficiency and making informed decisions that align with operational realities.

5.6.2 Operational Scenarios

To take full advantage of the potential of the modelling software used in this thesis, a real-time operational profile approach was developed. More specifically, based on the data presented in the tables above, two time-based schedules were created that a mega-yacht similar to the reference vessel would follow during chartering season in the summer months.

Scenario 1. Round Trip: Flisvos Marina, Mykonos, Naxos, Santorini

Key Characteristics:

- Short cruising intervals (island hopping) at various speeds.
- Plenty of time spent anchored and maneuvering.
- Frequent and long stops at marinas/ports (moored).
- Marinas equipped with facilities that support shore connection while mooring.

Table 3. Schedule for Scenario 1.

Number	Starting Location	Destination	Duration	Status
1	Flisvos Marina	-	3hrs	Berthed
2	Flisvos Marina	-	15mins	Maneuvering
3	Flisvos Marina	Mykonos Port	5.5hrs	Cruising Speed
4	Mykonos Port	-	30mins	Maneuvering
5	Mykonos Port	-	15hrs	Berthed
6	Mykonos Port	-	15mins	Maneuvering
7	Mykonos Port	Mykonos Beach 1	30mins	Cruising at 12 knots
8	Mykonos Beach 1	-	4hrs	Anchored
9	Mykonos Beach 1	Mykonos Port	30mins	Cruising at 12 knots
10	Mykonos Port	-	25mins	Maneuvering
11	Mykonos Port	-	24hrs	Berthed
12	Mykonos Port	-	15mins	Maneuvering
13	Mykonos Port	Naxos Port	1hr	Max Speed
14	Naxos Port	-	10mins	Maneuvering
15	Naxos Port	-	5hrs	Berthed
16	Naxos Port	-	10mins	Maneuvering
17	Naxos Port	Naxos Beach1	1hr	Cruising at 7 knots
18	Naxos Beach1	-	3hrs	Anchored
19	Naxos Beach1	NW of Santorini	3hrs	Cruising at 14 knots
20	NW of Santorini	Santorini Port	40mins	Cruising at 8.5 knots
21	Santorini Port	-	25mins	Maneuvering
22	Santorini Port	-	15hrs	Berthed
23	Santorini Port	-	15mins	Maneuvering
24	Santorini Port	Santorini Beach 1	40mins	Cruising at 12 knots
25	Santorini Beach 1	-	1.5hrs	Anchored
26	Santorini Beach 1	Santorini Beach 2	35mins	Cruising at 12 knots
27	Santorini Beach 2	-	1.5hrs	Anchored
28	Santorini Beach 2	Santorini Port	75mins	Cruising at 12 knots
29	Santorini Port	-	20mins	Maneuvering
30	Santorini Port	-	20hrs	Berthed

31	Santorini Port	-	15mins	Maneuvering
32	Santorini Port	Flisvos Marina	8hrs	Cruising Speed
33	Flisvos Marina	-	30mins	Maneuvering

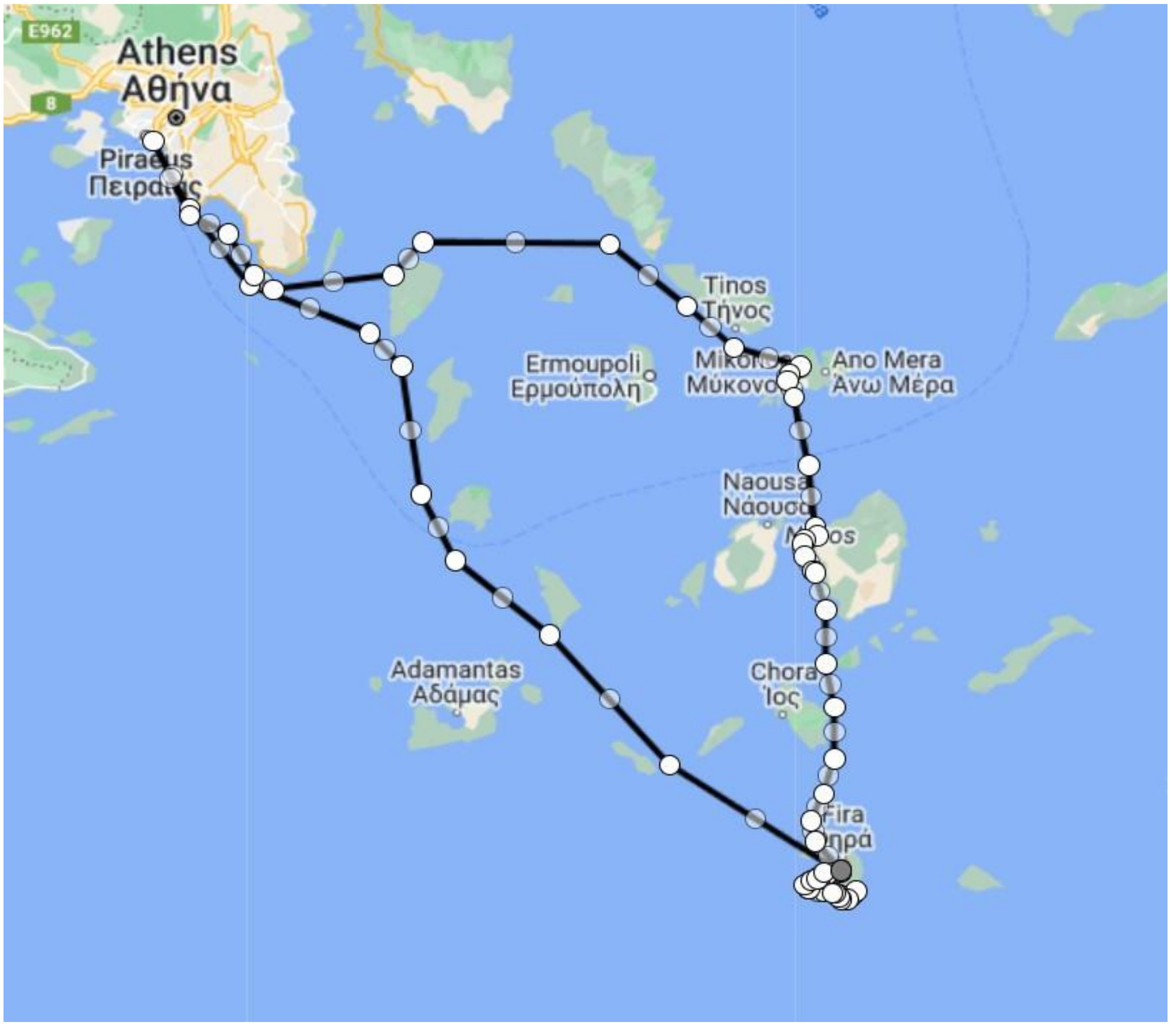


Figure 10. Visual representation of Scenario 1. Screenshot taken from Google Maps.

Goals and expectations:

- Examine if zero emissions mode is feasible at marinas/ports.
- Examine if zero emissions mode is feasible when anchored.
- Examine if zero emissions mode is feasible during short voyages (ex. Port to Beach)
- Determine if time during stops is enough to charge batteries.
- Test if the batteries' capacity is sufficient to maintain the max speed.

Scenario 2. One-way trip: Ag. Kosmas Marina ► Fiskardo, Kefalonia ► Isole Eolie, Italy ► Capri, Italy

Key Characteristics:

- Longer voyages and fewer stops than Scenario 1.
- Mooring in smaller marinas, where shore connection is not always available.
- Limit time spent anchored.
- Passing through speed limited zones, such as Corinth Canal and Strait of Messina.

Table 4. Schedule for Scenario 2.

#	Starting Location	Destination	Duration	Status
1	Ag. Kosmas	-	3hrs	Berthed
2	Ag. Kosmas	-	15mins	Maneuvering
3	Ag. Kosmas	Corinth Canal	2hrs	Cruising Speed
4	Corinth Canal	-	2hrs	Anchored
5	Corinth Canal	-	45mins	Maneuvering at 5knots
6	Corinth Canal	Fiskardo, Kefalonia	8.5hrs	Cruising at 15knots
7	Fiskardo, Kefalonia	-	20mins	Maneuvering
8	Fiskardo, Kefalonia	-	24hrs	Berthed
9	Fiskardo, Kefalonia	-	15mins	Maneuvering
10	Fiskardo, Kefalonia	Messina, Italy	16hrs	Cruising Speed
11	Messina, Italy	-	1hr	Anchored
12	Messina, Italy	-	100mins	Cruising at 8 knots
13	Messina, Italy	Liparo, Isole Eolie	2hrs	Cruising Speed
14	Liparo, Isole Eolie	-	20mins	Maneuvering
15	Liparo, Isole Eolie	-	36hrs	Berthed
16	Liparo, Isole Eolie	-	10mins	Maneuvering
17	Liparo, Isole Eolie	Positano, Italy	8.5hrs	Cruising Speed
18	Positano, Italy	-	16hrs	Anchored
19	Positano, Italy	Capri, Italy	45mins	Max Speed
20	Capri, Italy	-	20mins	Maneuvering

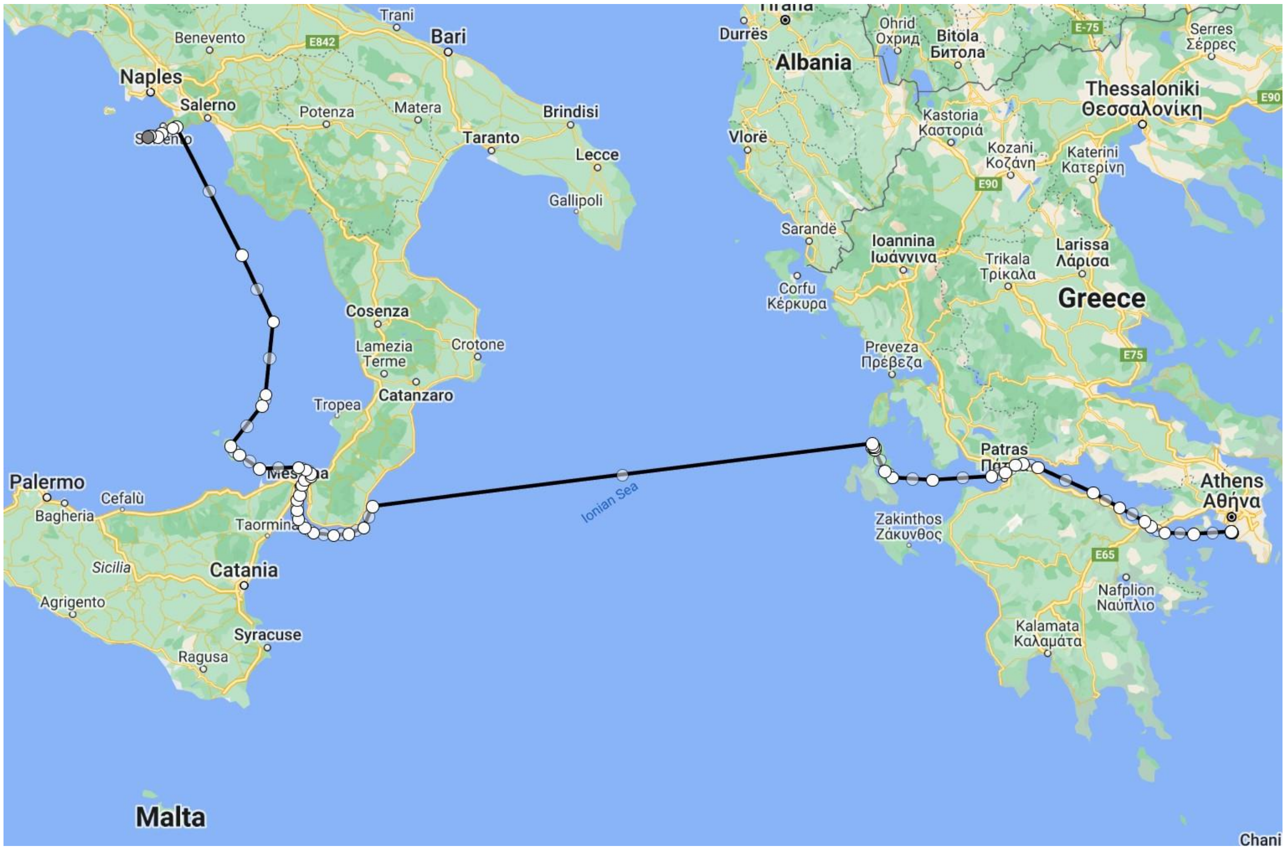


Figure 11. Visual representation of Scenario 2. Screenshot taken from Google Maps.

Goals and expectations:

- Examine if zero emissions mode is feasible while passing through canals and straits, such as the Corinth Canal and Strait of Messina.
- Compare the performance of the propulsion configurations in long voyages.

6. Analysis method and data

6.1. Data gathering

Obtaining precise results required the acquisition of genuine performance data covering all machinery within the selected propulsion configurations. Our findings' credibility depended on accessing direct insights into how these systems operate. This was accomplished through discreet communication with marine diesel engine manufacturers and their official partners. By leveraging these expert sources, a comprehensive collection of operational data was secured.

A Note of Appreciation

At this point, we would like to express our gratitude towards to ΕΛΤΡΑΚ Α.Ε. [14] for sharing invaluable data for our research. This collaborative spirit forms the essence of our analysis, adding a realistic approach to this thesis.

The following tables present an extract from the technical data which was provided. The assessment of the propulsion configurations will be based on the following:

1. Brake-specific fuel consumption
2. Exhaust gas temperatures
3. Exhaust gas mass flow rates

In the following tables, all the above are presented as a function of load for each engine that will be used in the selected propulsion configurations.

Table 5. Technical data for CAT 3516C.

ENGINE SPEED RPM	ENGINE POWER BKW	ISO BSFC G/BKW-HR	EXH MFLD TEMP DEG C	WET EXH. GAS MASS FLOW RATE KG/HR
1800	2240	195.5	582	14204.4
1700	2240	192.2	588.3	13537.7
1600	2020	187.8	561.3	12190.1
1500	1826	184	549	10602.7
1400	1680	183.2	556.8	9231.1
1300	1645	184.2	602.9	8325.3
1200	1166	191.9	643	5478.1
1100	836	198.9	644.3	3918.2
1000	589	199.8	578.4	2929.7
900	488	200.2	553.6	2431.5
800	424	201.7	550.7	2045.6
700	348	202.6	522.1	1687.3

Table 6. Technical data for CAT 3516E at 2100bkW.

ENGINE SPEED RPM	ENGINE POWER BKW	ISO BSFC G/BKW-HR	EXH MFLD TEMP DEG C	WET EXH. GAS MASS FLOW RATE KG/HR
1600	2100	195.5	582	14204.4
1500	2100	192.2	588.3	13537.7
1400	2046	187.8	561.3	12190.1
1300	1952	184	549	10602.7
1200	1814	183.2	556.8	9231.1
1100	1487	184.2	602.9	8325.3
1000	677	191.9	643	5478.1
900	522	198.9	644.3	3918.2
800	478	199.8	578.4	2929.7
700	370	200.2	553.6	2431.5
650	303	201.7	550.7	2045.6

Table 7. Technical data for CAT 3516E at 1840ekW/50Hz.

LOAD PERCENT %/100	GEN SET POWER EKW	BSFC G/BKW-HR	EXH MFLD TEMP DEG C	WET EXH. GAS MASS FLOW RATE KG/HR
1.1	2024	197.1	578.2	13161.3
1	1840	197.1	543.6	12826.5
0.9	1656	197.7	511.9	12352.9
0.8	1472	198.3	487.8	11533.9
0.75	1380	198.9	480.2	10957.4
0.7	1288	199.5	473.8	10344.0
0.6	1104	201.3	463.4	9050.5
0.5	920	205.6	451.9	7792.0
0.4	736	212.3	435	6649.7
0.3	552	223.8	404.9	5647.5
0.25	460	233.6	384.8	5229.1
0.2	368	248.8	359.6	4858.3
0.1	184	323.6	291	4158.5

Table 8. Technical data for CAT C9.3 195ekW/50Hz.

LOAD PERCENT %/100	GEN SET POWER EKW	ISO BSFC G/BKW-HR	EXH MFLD TEMP DEG C	WET EXH. GAS MASS FLOW RATE KG/HR
1.1	214.5	204.4	630.4	1036.6
1	195	205.0	604	990.7
0.9	175.5	207.4	585.4	940.3
0.8	156	211.7	567.8	885.1
0.75	146.2	212.9	556.7	855.3
0.7	136.5	214.1	541.6	822.7
0.6	117	215.3	506.9	756.6
0.5	97.5	217.8	466	692.3
0.4	78	224.5	422.4	638.7
0.3	58.5	236.6	370	587.9
0.25	48.8	245.7	340.7	563.4
0.2	39	259.7	304.7	538.8
0.1	19.5	326.0	218.6	490.2

Table 9. Technical data for CAT C18 465ekW/50Hz.

LOAD PERCENT %/100	GEN SET POWER EKW	BSFC G/BKW-HR	EXH MFLD TEMP DEG C	WET EXH. GAS MASS FLOW RATE KG/HR
1.1	511.5	209.9	625.7	2652.8
1	465	208.6	592	2582.3
0.9	418.5	208.6	557	2494.1
0.8	372	209.2	522	2378.5
0.75	348.8	209.2	505	2310.1
0.7	325.5	209.9	490.3	2210.0
0.6	279	211.1	461.3	2008.8
0.5	232.5	213.5	431.7	1806.0
0.4	186	220.2	399.4	1596.9
0.3	139.5	231.8	362.9	1391.4
0.25	116.2	240.9	343	1291.7
0.2	93	253.7	312.4	1196.2
0.1	36.5	312.7	238	1012.8

6.2. Assumptions

In academic research, it is common to encounter situations where data may be incomplete. To keep our analysis on track, we need to make some educated guesses. In this section, the assumptions we've made during this study will be explained. These assumptions are helping us continue our analysis ensuring that our findings are still trustworthy, even when we don't have all the required data.

6.2.1. P-V Curve

One fundamental element in our analysis involves calculating the total propulsion power required at various vessel speeds. Ideally, this would entail a detailed power-velocity (kW-knots) curve specific to our vessel and configurations. However, as this data was not available, we resorted to a well-established formula known as the "Law of Propeller." This formula delineates the relationship between the power required by the propeller (P) and the vessel's velocity (V) [16].

$$P = c * V^n$$

Equation 2. Law of Propeller

Where c is a constant and n is an index that is dependent on the vessel’s dimensions and operation velocity.

More specifically, regarding the index number n:

Table 10. Values of index number n for different type of vessels.

n=4.5	High speed vessels
n=4.0	Medium size and speed vessels
n=3.5	Low speed vessels

While we acknowledge that this approach is a workaround in the absence of an actual curve, we have based our assumptions on the credibility of this formula within the maritime industry. It is important to underscore that this assumption is a pivotal element in our calculations and analysis.

The determination of the index (n) of the formula is a critical step in our analysis. This index essentially characterizes the relationship between propulsion power (P) and vessel velocity (V). To pinpoint the most accurate value for "n", we relied on available data points where power and velocity were known.

The first data point hinged on the reference vessel's maximum speed of 18.2 knots, achieved at a power output of 4152 kW. This power value corresponded to approximately 95% of the total installed engine power.

The second data point was sourced from the MTU Hybrid Propulsion Configurator [17]. By inputting the vessel's dimensions, weight, maximum speed, and hotel load, the configurator calculated the requisite propulsion power for the vessel to maintain a speed of 6 knots, which amounted to approximately 90 kW.

By employing these two data points, we systematically experimented with various values for the index 'n'. This process allowed us to discern the most fitting value. Ultimately, after careful evaluation, we settled on n=3.45. The resultant P-V curve is graphically represented in the figure following this explanation.

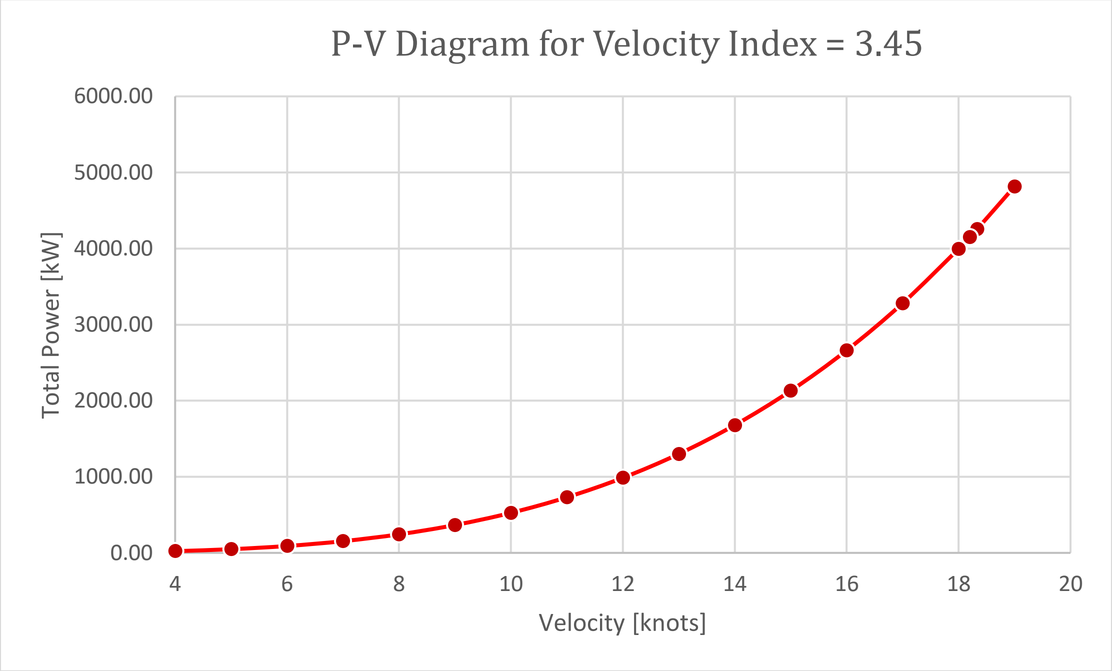


Figure 12. Propulsion Requirement [kW] – Velocity [kn] Diagram for Velocity Index equal to 3.45.

6.2.2. Electric consumption per operational mode

Accurately determining the precise electrical power needed for different operational modes, including maneuvering, cruising, anchoring, and berthing, typically relies on comprehensive electrical balance documents that delineate the electricity consumption of each onboard component and device. Regrettably, this detailed technical paper was unavailable for our reference vessel. However, we were able to access a comparable document from a smaller yacht with known main dimensions and propulsion power, as described in the accompanying table.

Table 11. Main dimensions and propulsion power of the vessel that electric balance was provided.

L	43	m
B	9	m
T	2.6	m
P	2500	kW

By examining this smaller vessel's electrical balance document, we were able to estimate the specific consumption levels for each operational mode. This estimation was achieved by applying specific ratio factors (λ) that take into account the proportionality of dimensions and power between our reference vessel and the smaller yacht. It's important to note that this assumption is underpinned by the assumption that the electricity consumption patterns are reasonably consistent between these two vessels.

Within the context of electrical power distribution, as also shown in the table below, it is important to distinguish between "Bus A" and "Bus B". "Bus A" primarily powers the auxiliary machinery, while "Bus B" includes all the yacht’s amenities like lighting, galley equipment and even the jacuzzi.

Table 12. Conversion of electric consumption per operational mode.

Electric Consumers / Operational Mode										
-/-	DATA PROVIDED					REFERENCE VESSEL				
	BUS A	BUS B	BUS A+B	BOW THR.	TOTAL	BUS A	BUS B	**BUS A+B**	BOW THR.	**TOTAL**
Man.	38.2	22.9	61.1	42.1	103.2	71.8	43.1	**114.9**	71.5	**186.4**
Cruis.	50	40.4	90.4	0.00	90.4	94.0	76.0	**170.0**	0.0	**170.0**
Anch.	46.6	48.8	95.4	0.00	95.4	78.1	81.8	**159.9**	0.0	**159.9**
Berth.	39.1	35.4	74.5	0.00	74.5	65.5	59.3	**124.8**	0.0	**124.8**

The determination of ratio factors (λ) for each operational mode was based in specific analogies comparing the reference vessel's dimensions to those of the smaller vessel. For the maneuvering and cruising modes, the ratio factors were established using an analogy between the *Length x Power (LxP)* of the reference vessel and the smaller vessel. This analogy reflects the relationship between the vessel's length and its power requirements during these operational phases.

In contrast, for the anchoring and berthing modes, the ratio factors were based on an analogy between the *Length x Beam (LxB)* of the reference vessel and the smaller vessel. This choice was made by the assumption that these modes are significantly influenced by both the vessel's length and its beam, as the yacht is stationary and most of its electric consumption does not have to do with propulsion.

Furthermore, the bow thruster ratio factor was calculated through an analogy between the *Length x Beam x Draft (LxBxT)* of the reference vessel and the smaller vessel. This compound analogy acknowledges the combined influence of length, beam, and draft in dictating the power needs during the bow thruster’s operation.

6.2.3. Transitions between modes of operation

In the context of our computational models, we've introduced the assumption of instantaneous transitions between various operational modes. This simplification was implemented primarily to enhance the efficiency and manageability of the coding that underlies our real-time model schedules. By assuming instantaneous transitions, we diminish the need to factor in time delays or transitional periods within the models.

However, it is essential to acknowledge that in practical maritime operations, transitions between operational modes typically involve finite time intervals for adjustments and adaptations. Such transitions encompass the shift from cruising to maneuvering, berthing to cruising, and so forth.

6.2.4. Weather Conditions and power requirement randomization

Within the analytical framework designed to evaluate the power requirements of mega-yachts, recognizing the inherent variability in these demands is crucial. Such variability is shaped by external influences like weather conditions and internal load changes, including variations in passenger numbers and fuel levels. The assumption of constant power requirements (both mechanical and electrical) across various operational modes is overly simplistic and does not accurately reflect the realities of maritime operations.

To address this, our methodology involves establishing a range of power requirements for each operational mode by identifying minimum and maximum power thresholds. This process is informed by an understanding that external conditions, particularly weather, can substantially alter navigational resistance and, consequently, propulsion power needs. Similarly, variations in onboard weight affect not only fuel efficiency but also the electrical load requirements.

Building upon the operational scenarios delineated in section 5.6.2., we concluded to a different modeling approach. This involves segmenting operational timelines into discrete 5-minute intervals, within which power requirements are randomized, adhering to the previously established minimum and maximum values. This randomization introduces a level of variability that more accurately mirrors the fluctuating power demands encountered in real-world maritime contexts.

The resulting model is not only more reflective of the fluctuating nature of power requirements but also serves as a robust tool for evaluating the efficacy of various power management strategies under a spectrum of operational conditions. Consequently, this approach enriches our analytical capacity, enabling a more accurate assessment of power management strategies, and underscores the importance of adaptive systems in managing the dynamic operational environment of mega-yachts.

This timeline will be exported to a data file, which serves as a critical input for the subsequent phase of our analysis. This data file will be imported into our chosen modeling platform, where it will form the basis of the simulation process.

Table 13. Detailed timetable for Schedule 1.

Number	Starting Location	Destination	Duration	Status	El. Consumption	Propulsion Power	Time Start (sec)	Time End (sec)	Electricity min	Electricity max	Propulsion min	Propulsion max
1	Flisvos Marina	-	3hrs	Berthed	125.0	-	0	10800	105	145	0	0
2	Flisvos Marina	-	15mins	Maneuvering	186.0	22.3	11100	11700	156	216	20	40
3	Flisvos Marina	Mykonos Port	5.5hrs	Cruising Speed	170.0	3281.0	12000	31500	140	200	2700	4000
4	Mykonos Port	-	30mins	Maneuvering	186.0	22.3	31800	33300	156	216	20	40
5	Mykonos Port	-	15hrs	Berthed	125.0	-	33600	87300	105	145	0	0
6	Mykonos Port	-	15mins	Maneuvering	186.0	22.3	87600	88200	156	216	20	40
7	Mykonos Port	Mykonos Beach 1	30mins	Cruising at 12 knots	170.0	986.58	88500	90000	140	200	850	1200
8	Mykonos Beach 1	-	4hrs	Anchored	160.0	-	90300	104400	140	180	0	0
9	Mykonos Beach 1	Mykonos Port	30mins	Cruising at 12 knots	170.0	986.58	104700	106200	140	200	850	1200
10	Mykonos Port	-	25mins	Maneuvering	186.0	22.3	106500	107700	156	216	20	40
11	Mykonos Port	-	24hrs	Berthed	125.0	-	108000	194100	105	145	0	0
12	Mykonos Port	-	15mins	Maneuvering	186.0	22.3	194400	195000	156	216	20	40
13	Mykonos Port	Naxos Port	1hr	Max Speed	170.0	4256.00	195300	198600	110	155	4000	4400
14	Naxos Port	-	10mins	Maneuvering	186.0	22.3	198900	199200	156	216	20	40
15	Naxos Port	-	5hrs	Berthed	125.0	-	199500	217200	105	145	0	0
16	Naxos Port	-	10mins	Maneuvering	186.0	22.3	217500	217800	156	216	20	40
17	Naxos Port	Naxos Beach1	1hr	Cruising at 7 knots	170.0	153.66	218100	221400	140	200	90	250
18	Naxos Beach1	-	3hrs	Anchored	160.0	-	221700	232200	140	180	0	0
19	Naxos Beach1	NW of Santorini	3hrs	Cruising at 14 knots	170.0	1679.19	232500	243000	140	200	1450	1900

20	NW of Santorini	Santorini Port	40mins	Cruising at 9 knots	170.0	365.68	243300	245400	140	200	250	460
21	Santorini Port	-	25mins	Maneuvering	186.0	22.3	245700	246900	156	216	20	40
22	Santorini Port	-	15hrs	Berthed	125.0	-	247200	300900	105	145	0	0
23	Santorini Port	-	15mins	Maneuvering	186.0	22.3	301200	301800	156	216	20	40
24	Santorini Port	Santorini Beach 1	40mins	Cruising at 12 knots	170.0	986.58	302100	304200	140	200	850	1200
25	Santorini Beach 1	-	1.5hrs	Anchored	160.0	-	304500	309600	140	180	0	0
26	Santorini Beach 1	Santorini Beach 2	35mins	Cruising at 12 knots	170.0	986.58	309900	311700	140	200	850	1200
27	Santorini Beach 2	-	1.5hrs	Anchored	160.0	-	312000	317100	140	180	0	0
28	Santorini Beach 2	Santorini Port	75mins	Cruising at 12 knots	170.0	986.58	317400	321600	140	200	850	1200
29	Santorini Port	-	20mins	Maneuvering	186.0	22.3	321900	322800	156	216	20	40
30	Santorini Port	-	20hrs	Berthed	125.0	-	323100	394800	105	145	0	0
31	Santorini Port	-	15mins	Maneuvering	186.0	22.3	395100	395700	156	216	20	40
32	Santorini Port	Flisvos Marina	8hrs	Cruising Speed	170.0	3281.0	396000	424500	140	200	2700	4000
33	Flisvos Marina	-	30mins	Maneuvering	186.0	22.3	424800	426300	156	216	20	40

Table 14. Detailed timetable for Schedule 2.

Number	Starting Location	Destination	Duration	Status	El. Consumption	Propulsion Power	Time Start (sec)	Time End (sec)	Electricity min	Electricity max	Propulsion min	Propulsion max
1	Ag. Kosmas	-	3hrs	Berthed	125.00	0.00	0	10800	105	145	0	0
2	Ag. Kosmas	-	15mins	Maneuvering	186.00	22.29	11100	11700	156	216	20	40
3	Ag. Kosmas	Korinth Canal	2hrs	Cruising Speed	170.00	3281.01	12000	18900	140	200	2700	4000
4	Korinth Canal	-	2hrs	Anchored	160.00	0.00	19200	26100	140	180	0	0
5	Korinth Canal	-	45mins	Maneuvering at 5knots	186.00	48.13	26400	28800	156	216	45	70
6	Korinth Canal	Fiskardo, Kefalonia	8.5hrs	Cruising at 15knots	170.00	2130.46	29100	59400	140	200	1950	2700
7	Fiskardo, Kefalonia	-	20mins	Maneuvering	186.00	22.29	59700	60600	156	216	20	40
8	Fiskardo, Kefalonia	-	24hrs	Berthed	125.00	0.00	60900	147000	105	145	0	0
9	Fiskardo, Kefalonia	-	15mins	Maneuvering	186.00	22.29	147300	147900	156	216	20	40
10	Fiskardo, Kefalonia	Messina, Italy	16hrs	Cruising Speed	170.00	3281.01	148200	205500	140	200	2700	4000
11	Messina, Italy	-	1hr	Anchored	160.00	0.00	205800	209100	140	180	0	0
12	Messina, Italy	-	100mins	Cruising at 8 knots	170.00	243.57	209400	215100	140	200	180	360
13	Messina, Italy	Liparo, Isole Eolie	2hrs	Cruising Speed	170.00	3281.01	215400	222300	140	200	2700	4000
14	Liparo, Isole Eolie	-	20mins	Maneuvering	186.00	22.29	222600	223500	156	216	20	40
15	Liparo, Isole Eolie	-	36hrs	Berthed	125.00	0.00	223800	353100	105	145	0	0
16	Liparo, Isole Eolie	-	10mins	Maneuvering	186.00	22.29	353400	353700	156	216	20	40
17	Liparo, Isole Eolie	Positano, Italy	8.5hrs	Cruising Speed	170.00	3281.01	354000	384300	140	200	2700	4000
18	Positano, Italy	-	16hrs	Anchored	160.00	0.00	384600	441900	140	180	0	0

19	Positano, Italy	Capri, Italy	45mins	Max Speed	170.00	4256.00	442200	444600	145	210	4000	4400
20	Capri, Italy	-	20mins	Maneuvering	186.00	22.29	444900	445800	156	216	20	40

6.2.5. Load Management Plan

Achieving optimal efficiency depends on the strategic selection of power-generating and distributing components for different operational modes. Our focus is to establish a clear and effective strategy for identifying the most efficient mix of components, such as the main engine, generator sets, and auxiliary systems, to meet the unique demands of each operational mode. Our goal is to develop a power balance approach that enhances performance while prioritizing environmental sustainability and economic viability. This strategy is essential for steering mega-yacht operations towards greater efficiency and reduced environmental footprint.

Each propulsion configuration demands a distinct approach in terms of the machinery's operation synergy. This necessity stems from the varying power requirements and operational characteristics unique to each configuration. Therefore, understanding the interplay between machinery in operation in different propulsion configurations is critical in achieving an efficient, sustainable, and economically viable power balance.

To fully understand the goal of the Power Balance Plan it is important to summarize the power required in each operational mode. This overview must encompass a detailed assessment of not only the propulsion requirements but also the power needs of auxiliary machinery and accommodation facilities.

- **Mechanical Propulsion Configuration**

Operational Modes

Given the presence of two propellers, each necessitating an equal share of power for optimal operation, it becomes prudent to evenly distribute the torque requirements between the two main engines.

In the following paragraph we focus on the electric power requirements in different operational modes.

(a) **Berthed** and **Anchored** Mode:

In scenarios where the yacht is either berthed or anchored, the demand for electric power is comparatively low. During these periods, it is sufficient to have just one of the two generator sets active. This single generator set efficiently fulfills the electrical needs of the yacht, encompassing both the auxiliary machinery and accommodation facilities, while also ensuring fuel economy and reduced operational wear.

(b) **Maneuvering** Mode:

The maneuvering mode presents a scenario with increased electric power requirements. In such situations, both generator sets are brought into operation. This is crucial to accommodate the heightened power demand, ensuring that all systems, particularly those critical for navigation and safety, receive adequate power without any compromise on performance or safety.

(c) **Cruising** Mode:

While cruising, the strategy is to primarily rely on a single generator set to cover the electrical needs of the auxiliary machinery and accommodation areas. This approach is in line with efficient power management, optimizing fuel usage and minimizing unnecessary operational strain on the machinery. However, in instances where the total power requirement exceeds the capacity of a single generator set, the second generator, maintained on stand-by, is activated to provide additional power. This not only ensures a continuous and reliable power supply but also allows for flexible power management in response to varying demands.

Table 15. Simplified power balance distribution for the Mechanical Propulsion Configuration.

Traditional				
Mechanical	*Electrical*			
	#	*Mode*	*Range [kW]*	*Active*
Equal Split	1	Berthed	[105,145]	1
	2	Anchored	[140,180]	1
	3	Maneuvering	[156,216]	2
	4	Cruising	[140,200]	Depends

Calculation of optimal load distribution between generator sets

In the context of optimizing propulsion configurations, a critical aspect is finding the most efficient allocation of load between generator sets. This section introduces a computational approach used to determine the most efficient load split, a crucial aspect for energy conservation and operational effectiveness in maritime applications. Understanding and optimizing the load distribution is not just about maximizing power output; it's also about aligning with the yacht's varying power needs and the limitations imposed by the generators' capacities.

In Configuration 1 (Mechanical Propulsion Configuration) the nominal power of each the generator set is 195 kW. However, for safety reason the maximum load allowed is 95%.

$$Pmax = 0.95 \times 195\ kW = 185.25\ kW\ \approx 180\ kW$$

As also mentioned in section 6.3., the efficiency of the generator sets is described by the following equation:

$$y = Efficiency = -0.0975077x^2 + 0.1720843x + 0.8650989$$

Equation 3. Propulsion configuration 1 generator set efficiency equation.

The combined efficiency of the two (2) generators working as a pair can be calculated by the following equation:

$$Combined\ Efficiency = \frac{Efficiency\ \times P1 + Efficiency\ \times P2}{Prequired}$$

Equation 4. Combined efficiency of a pair of generator sets for a specific power requirement.

Where,

$P_{required}$ is the total required power by the generator sets at a given point of time and

P1, P2 the power generated by generator set 1 and 2 accordingly.

In order to achieve the best combined efficiency possible, a simple Python script was developed. Its goal, to simulate different load scenarios for two generator sets. The script varies the load assigned to each generator, calculating efficiencies based on a specific efficiency curve. This algorithmic approach allows for an extended search by testing possible load combinations, identifying the one that yields the highest overall efficiency. A screenshot of this script and its explanation will follow, illustrating how this methodical computation plays a pivotal role in determining the optimal load split.

```
def calculate_efficiency(power):
    x = power / 195
    return -0.0975077 * x**2 + 0.17208425997 * x + 0.865098968

max_power = 185  # kW
total_power = 210  # kW
best_efficiency = 0
best_split = (0, 0)

for P1 in range(max_power + 1):
    P2 = total_power - P1
    if P2 > max_power:
        continue

    Efficiency1 = calculate_efficiency(P1)
    Efficiency2 = calculate_efficiency(P2)
    combined_efficiency = (Efficiency1 * P1 + Efficiency2 * P2) /
total_power

    if combined_efficiency > best_efficiency:
        best_efficiency = combined_efficiency
        best_split = (P1, P2)

print("Best Split:", best_split)
```

Figure 13. Python script for calculating optimal load distribution between generator sets of Configuration 1. For example, this code calculated the optimal load distribution for a total required power of 210 kW.

The output of the variable "best_split" from the Python script directly indicates the most efficient load distribution between the two generator sets. This pair of values represents the optimal allocation of power, ensuring maximum efficiency under the defined conditions and constraints.

As an example, the execution of the code above, gives us the following distribution:

Best Split: (185,25)

Subsequent to conducting a series of tests with various power values, a significant conclusion was reached regarding the optimal operation of two generator sets. It was determined that when the power requirement necessitates the use of both generators, the most efficient strategy is to operate the first generator set at its maximum allowable power, which is 95% of its nominal capacity. The remaining power needed to meet the total requirement is then produced by the second generator. This approach maximizes the overall efficiency of the system by utilizing the full potential of one generator while balancing the load with the capacity of the second, thereby optimizing the power generation process under the given operational constraints.

However, in order to avoid simulation crashes due to unexpected fluctuations of the required power, we have decided to use a safety threshold which puts the second generator in use when the required power is equal to 90% of the maximum power of the primary one. Thus, when the value of 167 kW is exceeded the second generator will automatically turn on (see section 7.4).

Mechanical with Electrical Assist (Hybrid) Configuration

Hybrid propulsion configuration of mega-yachts combines mechanical propulsion with electrical assistance. This hybrid system, distinct in its ability to seamlessly transition between power sources, offers a versatile approach to meeting the diverse power demands of a mega-yacht across various operational modes. This section delves into how the hybrid configuration optimally manages these demands, leveraging both generator sets and main engines in a manner that prioritizes efficiency and environmental consciousness.

(a) **Berthed** and **Anchored**:

While berthed or anchored, the power requirements are minimal. In this mode, only one generator set is active to supply all the energy needs for the yacht, including auxiliary systems and accommodations. The main engines are turned off to conserve fuel and minimize emissions.

(b) **Maneuvering**:

During maneuvering, precision is key, and power efficiency is prioritized. Here, a single generator set is operational to handle the yacht's electrical needs. The main engines are on standby, ready to engage if necessary but not actively generating torque. This approach enhances efficiency during delicate maneuvering.

(c) **Cruising** Mode:

In cruising mode, the yacht relies on its main engines for propulsion. Simultaneously, a generator set is running to cover the electrical demands of auxiliary machinery and accommodation areas. This mode highlights the hybrid system's capability to combine mechanical propulsion with electrical power support.

(d) **Max Speed**:

To achieve maximum speed, the yacht fully utilizes its hybrid propulsion system. Both generator sets are operational, providing additional electrical power to assist the main engines. This setup maximizes the available torque and demonstrates the effectiveness of the hybrid configuration in high-demand scenarios.

(e) Special Route - **Corinth Passage**:

While navigating through the Corinth Passage at a speed of 5 knots, the yacht operates in a manner similar to the maneuvering mode. One generator set is active, supplying power for both propulsion and the vessel's various systems, demonstrating the efficiency and precision of the hybrid system in constrained navigation areas.

(f) Special Route - **Messina Strait**:

In the Messina Strait, the yacht aims to cruise at 8 knots using electric power only, with the main engines turned off. Both generator sets are operational in this mode, providing all necessary power for the yacht's propulsion and onboard systems. This mode showcases the vessel's ability to function efficiently under electric power, highlighting the flexibility of the hybrid configuration.

This hybrid configuration underscores the adaptability of the yacht to various operational requirements, seamlessly transitioning between mechanical and electrical power sources to optimize efficiency and reduce environmental impact.

Table 16. Simplified power balance distribution for the Hybrid Propulsion Configuration.

Mechanical with Hybrid Assist				
Operation		*Mechanical*	*Electrical*	
#	*Mode*	Main Engines Status	*Range [kW]*	*Active Gen Sets*
1	Berthed	OFF	[105,145]	1
2	Anchored	OFF	[140,180]	1
3	Manoeuvring	OFF	[156,216]	1
3*	Corinth Canal	OFF	[201,326]	1
4	Cruising	ON	[140,200]	1
5	Max Speed	ON	[145,Max]	2

- **Full-Electric Configuration**

Transitioning to the full-electric propulsion configuration, we encounter a fundamentally different approach to power distribution. In this setup, the core principle revolves around the centralization of power generation and distribution:

1. Centralized Power Distribution:

All the power generated in a full-electric propulsion system is directed to a central switchboard. This switchboard acts as the hub for power management, efficiently allocating electrical power to various consumers aboard the yacht. This includes propulsion systems, auxiliary machinery, and accommodation facilities.

2. Electric Power for Propulsion:

A key aspect of this configuration is the reliance on electric power for propulsion. Electric motors, responsible for generating torque, are a significant consumer of this power. This is a departure from traditional mechanical propulsion systems, where the main engines directly drive the propellers.

3. Power Requirements in Different Operational Modes:

(a) In the **Berthed** and **Anchored** modes, the power requirements are minimal. The propulsion system, being one of the major power consumers, is not in use, leading to a significantly reduced power demand. Only one secondary generator set is active, which is sufficient to cover all energy needs, including auxiliary machinery and accommodation facilities.

(b) In the **Maneuvering** mode, there is a noticeable increase in electric power requirements. The electric propulsion system requires substantial power for precise and controlled movements of the yacht, necessitating a higher power output from the generation system. In this scenario, only one secondary generator set is typically in operation. However, there is also another secondary generator set on stand-by, ready to be engaged if the power needs exceed the capabilities of the first secondary generator set.

(c) The **Cruising** mode demands the highest level of power. In this mode, the propulsion system's requirement for electric power is at its peak due to the need for sustained high-speed operation. This significantly elevates the total power requirement, surpassing the demands of other operational modes. In cruising mode, the two primary generator sets are engaged. If the power needs exceed 3500 kW, which constitutes approximately 95% of the load capacity of both primary generator sets, a single secondary generator set is also activated to supplement the power supply. In situations where the power demand exceeds 3940 kW, all four generators – the two primary and two secondary sets – are activated to meet the yacht's power requirements.

The full-electric propulsion configuration thus presents a scenario where power management is dynamically adjusted according to operational modes. The switchboard's role becomes critical in ensuring that the power supply is efficiently allocated, particularly given the significant variations in power demand between the different modes of operation.

Table 17. Simplified power balance distribution for the Diesel-Electric Propulsion Configuration.

Full-Electric			
Electrical			
#	*Mode*	*Range [kW]*	*Active*
1	Berthed	[105,145]	1xSecondary
2	Anchored	[140,180]	1xSecondary
3	Maneuvering	[176,256]	1xSecondary
4	Cruising	[2090,4200]	Depends
5	Max Speed	[4145,4610]	ALL, Equal Split

- **Battery-equipped configurations**

To accurately examine the functionality of propulsion configurations integrated with battery packs (specifically Configuration 3 and Configuration 5), a thorough examination of the operational modes of the battery packs is requisite. This analysis is conducted in Section 7.2.5, where these modes are elaborated. Subsequently, Section 7.4 explains the power distribution mechanisms inherent to Configurations 3 and 5.

6.3. Machinery technical data pre-processing

In the process of data preparation, a significant step involved refining raw information into a more user-friendly and informative format. The use of trendlines facilitated the capture of essential data dynamics, generating equations that best represented observed trends. This transformation simplified data points into formulas, contributing to enhanced interpretability and usability.

Within Microsoft Excel's analytical toolkit, the creation of trendlines involves a systematic process that empowers users to extract meaningful insights from datasets. One commonly employed method is polynomial fitting, which serves as an effective means to capture underlying trends in data points.

When applying a polynomial trendline to a dataset, with the use of Excel we can evaluate various polynomial equations (e.g., quadratic, cubic) and identify the one that best fits the data distribution. This process involves minimizing the deviations between the data points and the curve described by the polynomial equation. The result is a curve that smoothly navigates through the data points, highlighting the overall trend.

The accuracy of these trendlines is checked by using the coefficient of determination, often denoted as R-squared (R^2). The R^2 value ranges from 0 to 1, indicating how well the trendline fits the data. A value closer to 1 signifies a strong fit, implying that the trendline closely approximates the data points. Conversely, an R^2 value closer to 0 suggests a weaker fit, indicating that the trendline may not adequately capture the data's variations.

In the context of this analysis, Excel's R^2 values for each trendline allowed us to evaluate the accuracy of trendlines applied to our data points. This approach facilitated a data-driven assessment of how well the trendlines aligned with the observed patterns, enabling us to discern meaningful trends and correlations within the machinery's performance metrics across diverse operational scenarios.

While Excel's trendline analysis offers a powerful approach to distilling insights from datasets, it's important to recognize that not all data can be encapsulated by a single polynomial trendline. The dynamics of real-world data are often intricate and diverse, encompassing a range of behaviors that may resist simple curve fitting. In cases where data points exhibit multiple trends, irregular fluctuations, or complex interactions, attempting to force a single polynomial trendline can lead to inaccuracies and oversimplifications. Acknowledging these limitations, we approach the data by recognizing that certain scenarios may necessitate more sophisticated analytical techniques or the consideration of multiple trendlines to adequately capture the diverse patterns and behaviors present in the data.

In the following pages, the figures showing the collected data are presented with trendlines constructed to depict the underlying patterns within the datasets. These trendline equations will be later used in this thesis to assess the efficiency of the selected configurations under realistic operational scenarios.

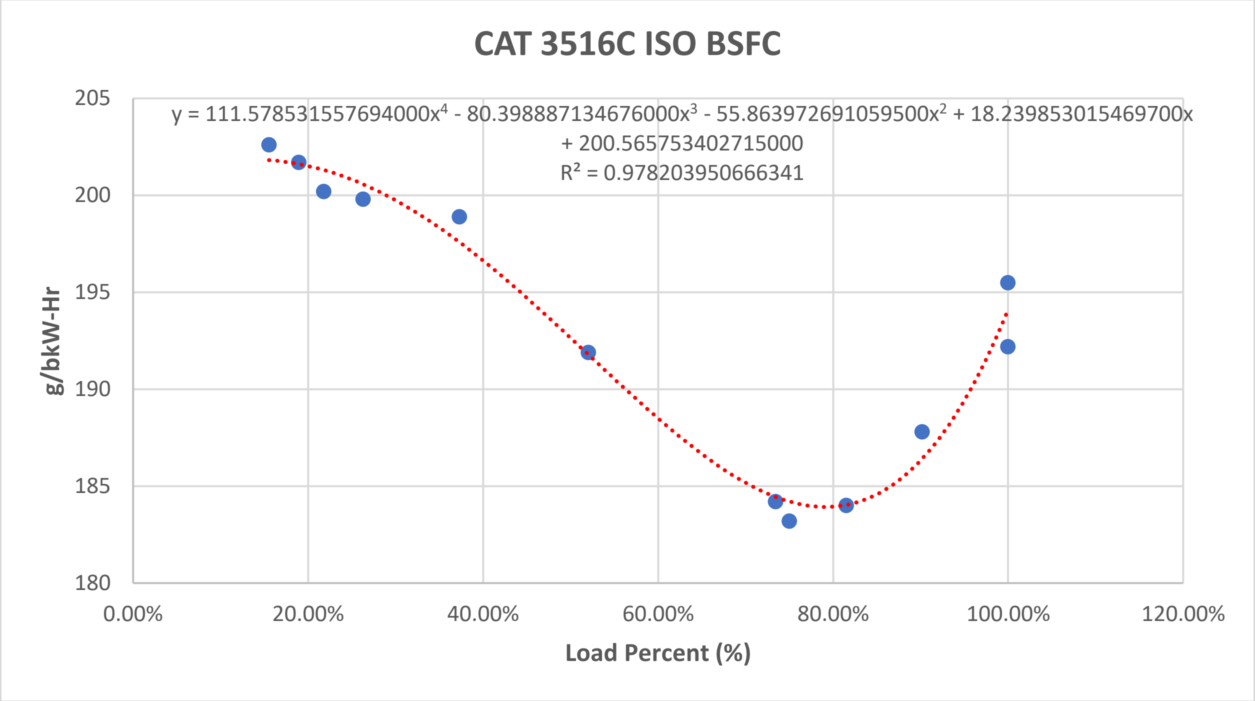


Figure 14. ISO BSFC [g/bkW-Hr] as a function of Load for CAT 3516C Main Engine.

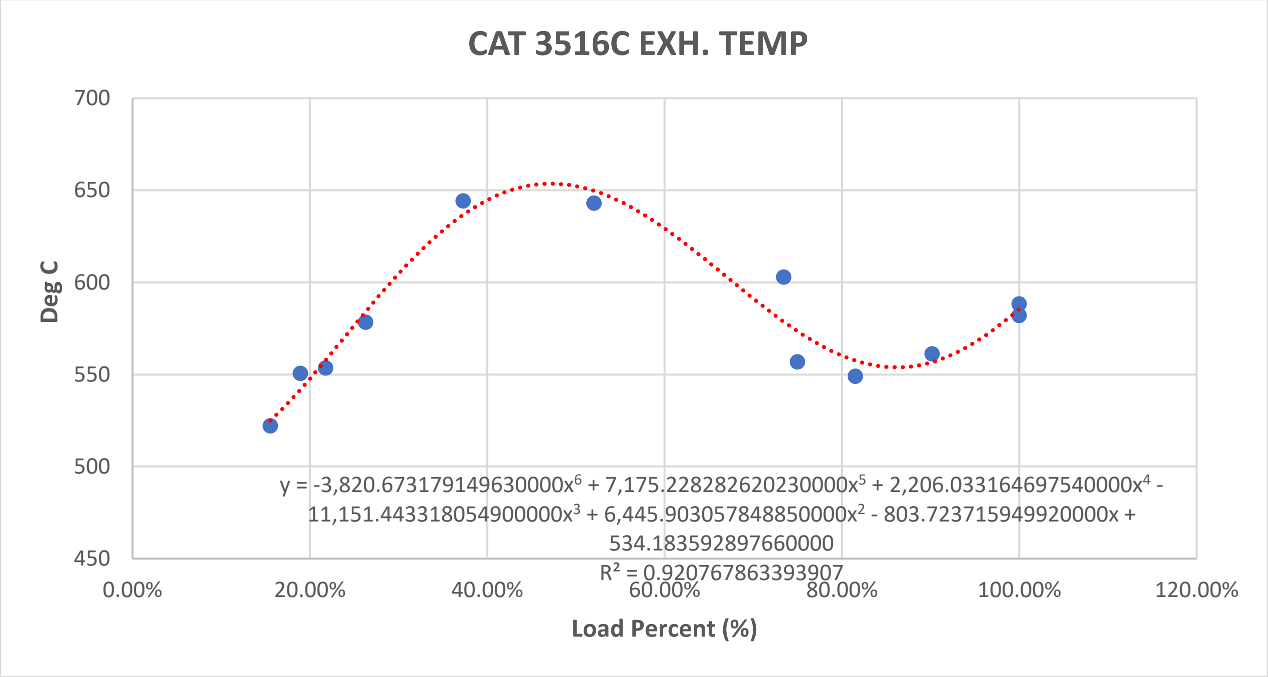


Figure 15. Exhaust Gas Temperature [Celsius Degrees] as a function of Load for CAT 3516C Main Engine.

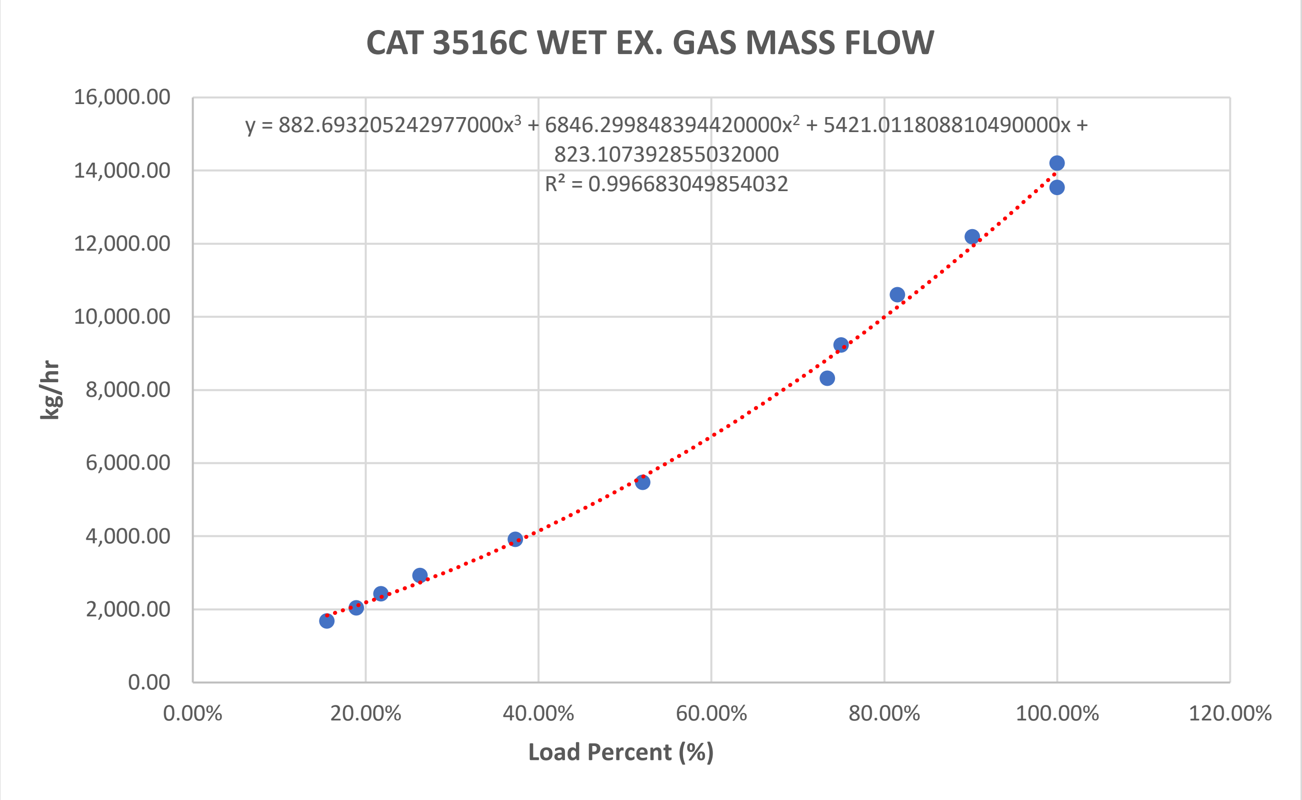


Figure 16. Wet Exhaust Gas Mass Flow [kg/Hr] as a function of Load for CAT 3516C Main Engine.

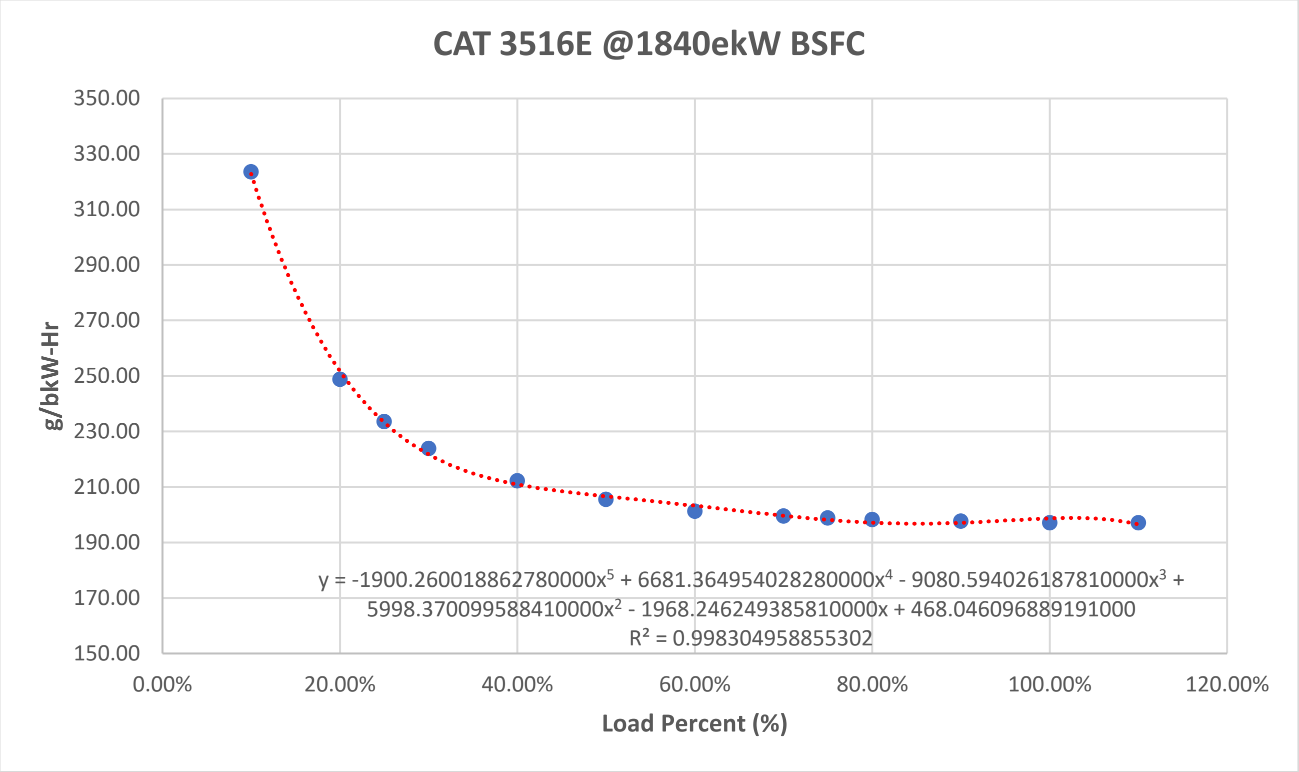


Figure 17. ISO BSFC [g/bkW-Hr] as a function of Load for CAT 3516E @1840ekW.

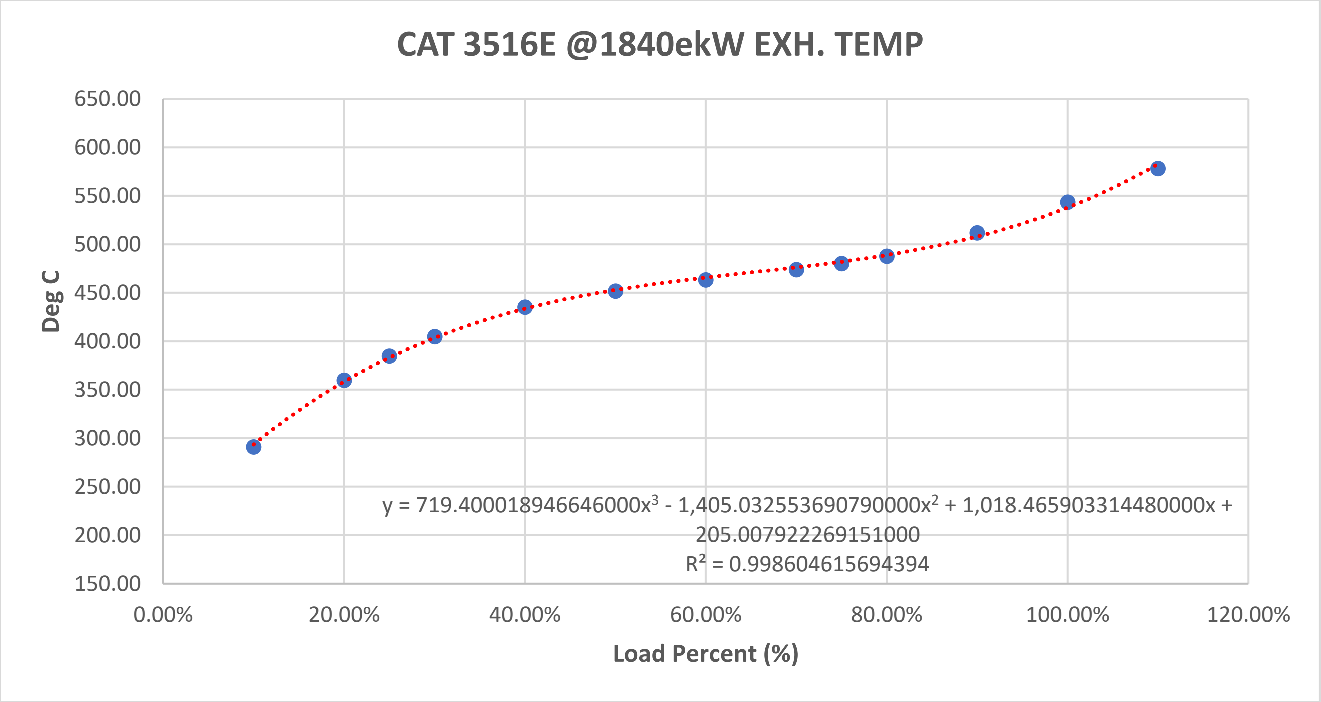


Figure 18. Exhaust Gas Temperature [Celsius Degrees] as a function of Load for CAT 3516E @1840ekW.

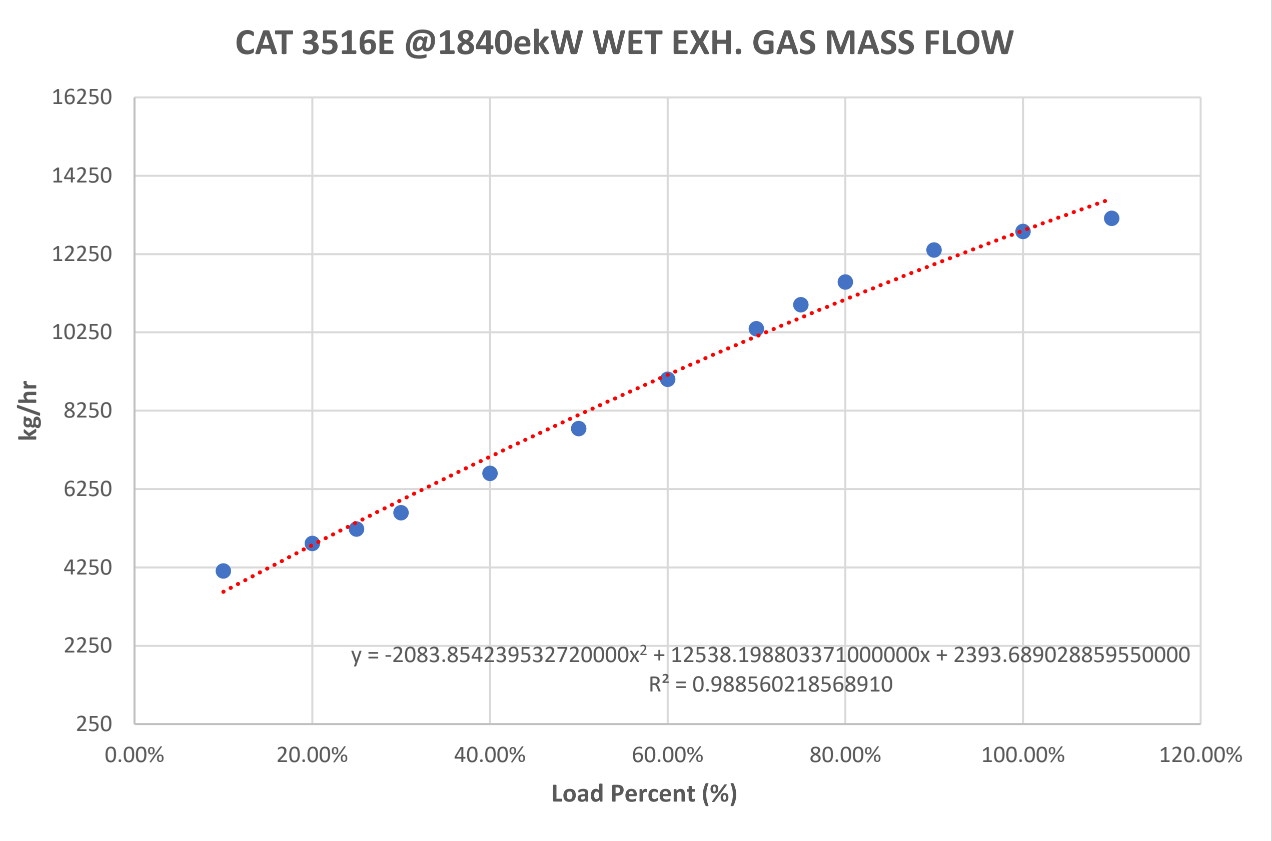


Figure 19. Wet Exhaust Gas Mass Flow [kg/Hr] as a function of Load for CAT 3516E @1840ekW.

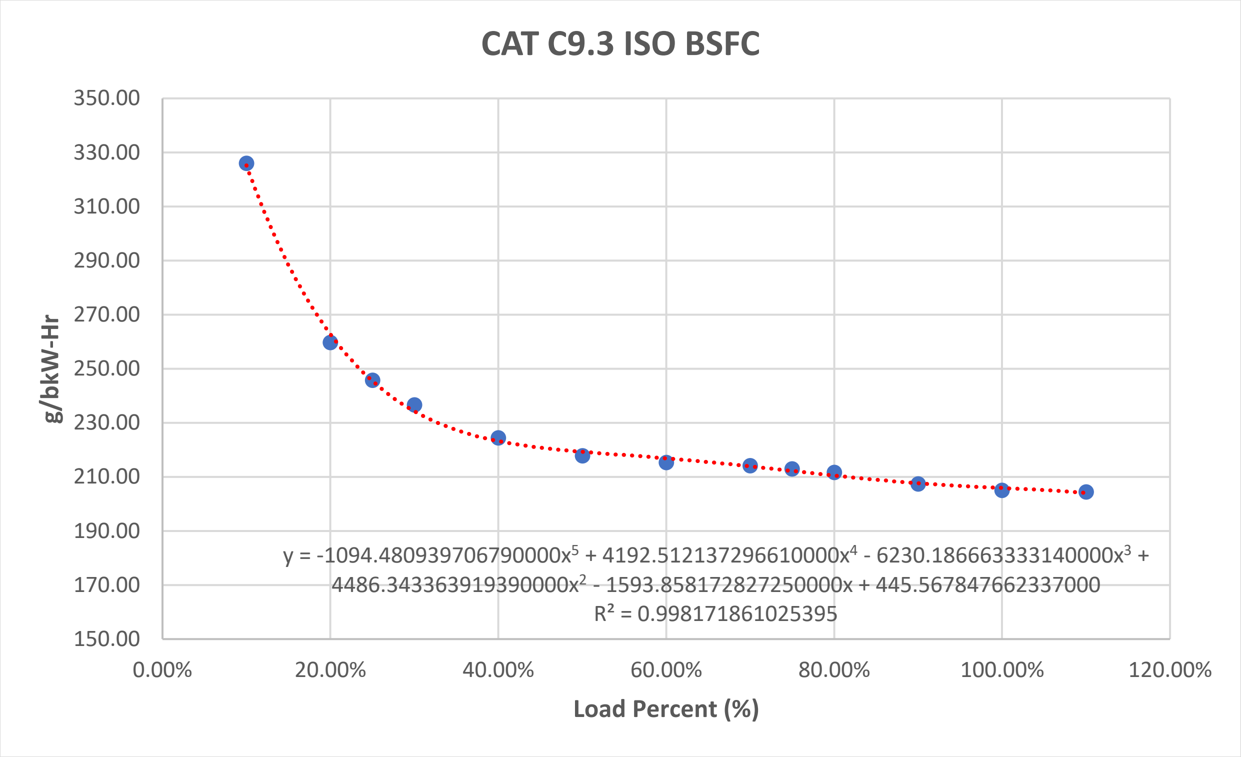


Figure 20. ISO BSFC [g/bkW-Hr] as a function of Load for CAT C9.3

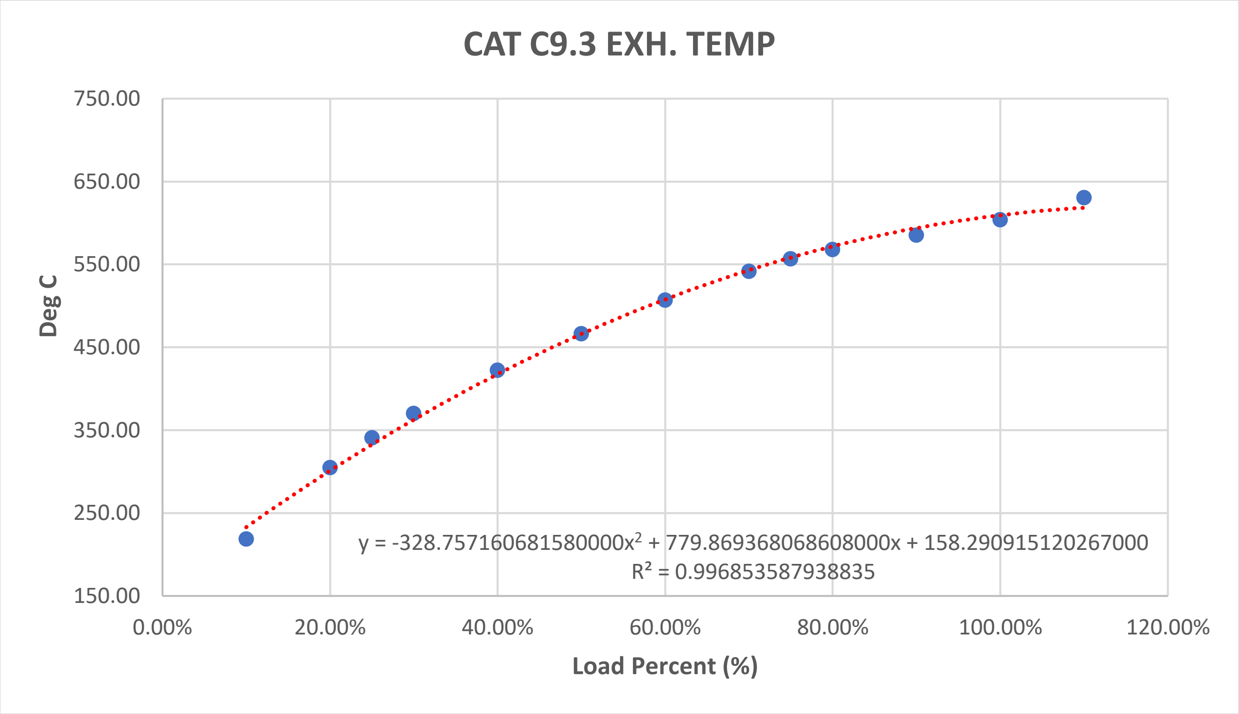


Figure 21. Exhaust Gas Temperature [Celsius Degrees] as a function of Load for CAT C9.3

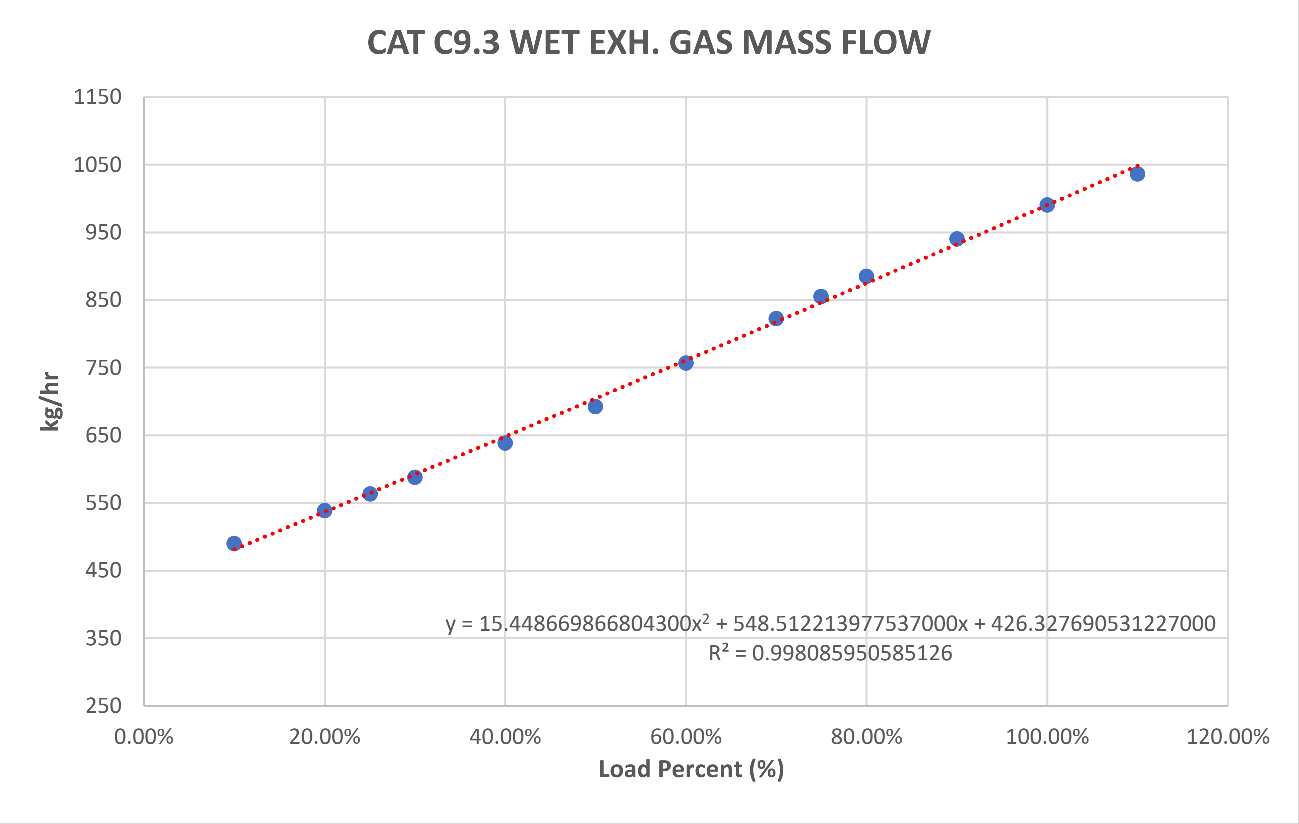


Figure 22. Wet Exhaust Gas Mass Flow [kg/Hr] as a function of Load for CAT C9.3

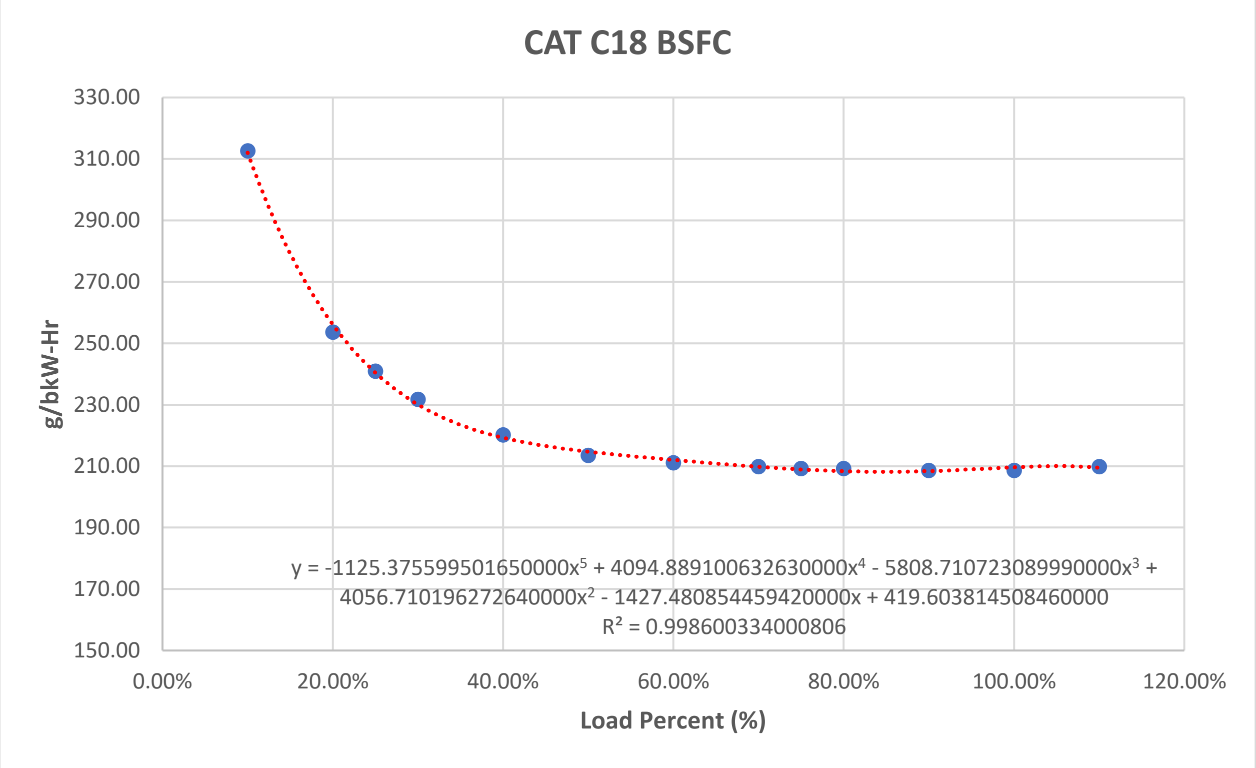


Figure 23. ISO BSFC [g/bkW-Hr] as a function of Load for CAT C18.

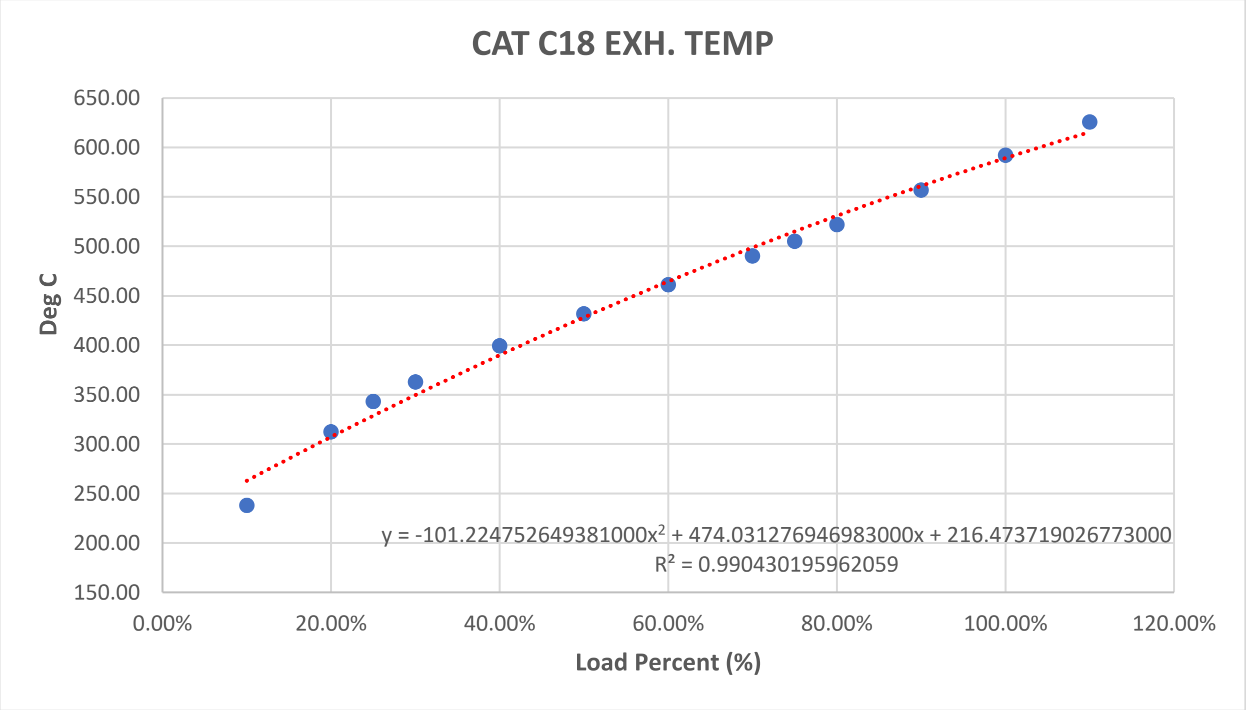


Figure 24. Exhaust Gas Temperature [Celsius Degrees] as a function of Load for CAT C18.

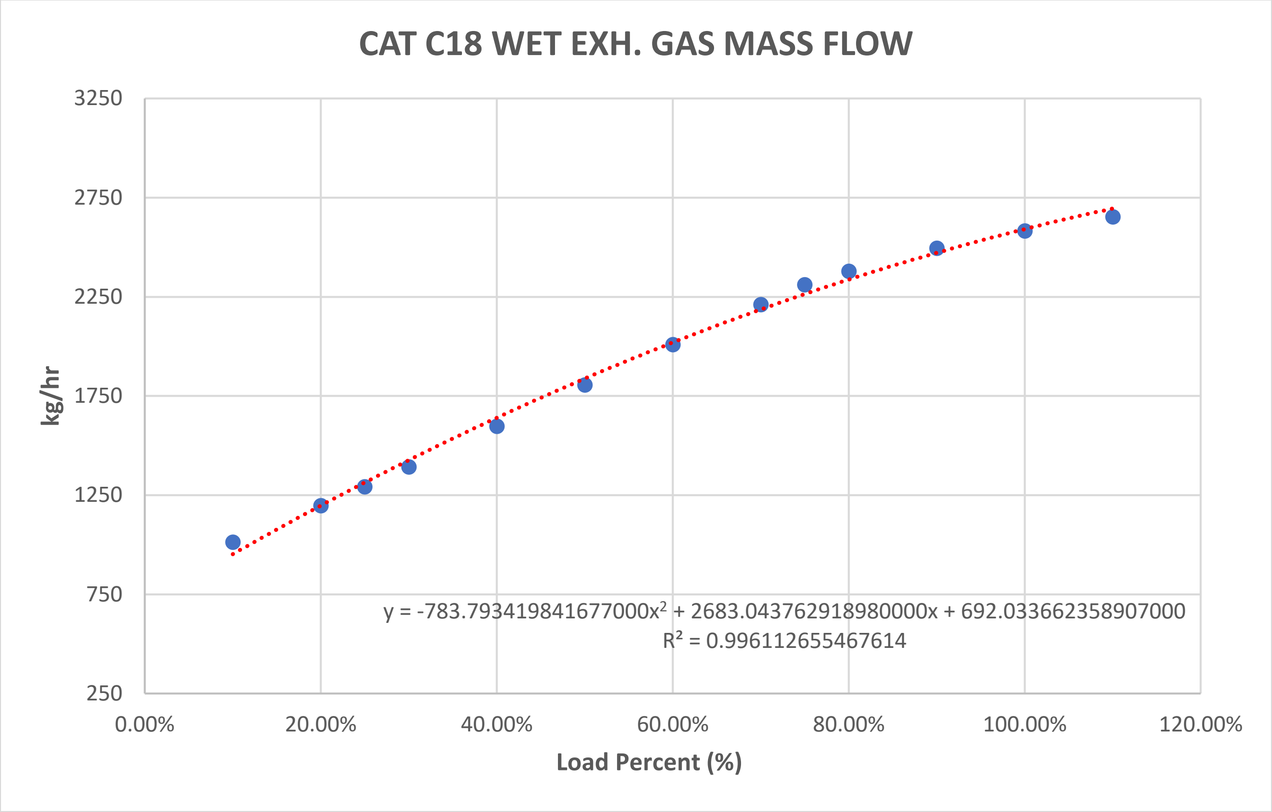


Figure 25. Wet Exhaust Gas Mass Flow [kg/Hr] as a function of Load for CAT C18.

7. Computer modeling

7.1. Brief description of PSE gPROMS modeling platform

7.1.1. gPROMS framework

PSE gPROMS stands as a modeling platform designed to transcend the boundaries of process systems engineering. Mainly, it operates as a comprehensive toolset that empowers engineers and researchers to predict, analyze, and optimize complex processes across diverse industries. This platform is characterized by its ability to seamlessly integrate complex mathematical modeling and advanced simulation capabilities [18].

PSE gPROMS is a powerful process modeling language, adept at representing complex systems' behaviors through mathematical equations, allowing users to encapsulate the interplay of variables, interactions, and constraints within a unified framework. PSE gPROMS enables dynamic simulation, predictive analysis, and optimization to ascertain optimal operating conditions, uncover inefficiencies, and accelerate process innovation.

In the maritime industry, PSE gPROMS finds its relevance in the world of propulsion systems. By simulating the complex dynamics of propulsion configurations, this modeling platform facilitates an examination of system performance across various operational scenarios. This, in turn, aids in evaluating the feasibility of new propulsion technologies, optimizing existing systems, and predicting the environmental impact of different configurations, while using realistic operational profiles.

In an era where environmental concerns and operational efficiency drive maritime advancements, modeling propulsion systems takes on heightened importance. PSE gPROMS enables us to test and refine these systems virtually, reducing the reliance on costly physical prototypes and minimizing the ecological footprint of experimentation. By facilitating comprehensive analysis of propulsion configurations, PSE gPROMS lays the groundwork for informed decision-making, propelling the maritime industry towards greener, more efficient, and sustainable propulsion solutions [18].

7.1.2. The concept of constructing the propulsion configuration models

Developing a propulsion configuration model within the PSE gPROMS framework is a structured endeavor that utilizes existing libraries, mathematical formulations, and operational profiles to produce detailed simulations.

Key to this modeling endeavor are the premade libraries, designed to encapsulate the intrinsic characteristics of the machinery featured in the chosen propulsion configurations. These libraries include models that serve as “digital twins” of the actual components of the propulsion configuration. By integrating these libraries, the simulation models within PSE gPROMS gain the ability to emulate the interactions, responses, and energy transfers inherent to real-world propulsion systems.

Moreover, the mathematical equations extracted from Excel's trendlines play a pivotal role in the modeling process. These equations, generated by the data that the manufacturers provided, serve as foundations to recreate the relationships between variables within the propulsion systems. By embedding these equations within the models, PSE gPROMS accurately simulates the machinery responses, facilitating the prediction of system behaviors across a spectrum of conditions.

The creation of realistic operational profiles further enhances the accuracy of these models. By integrating the operational profiles – representing various states such as maneuvering, cruising, and anchoring – the simulations gain the context of real-world scenarios.

7.1.3. The objective of simulation models

The models crafted within the PSE gPROMS framework are poised to yield a range of valuable outcomes, enriching our understanding of propulsion configurations and their intricate dynamics. Through simulations and analyses, the following results are anticipated:

- **Performance Insights**: The models will offer detailed insights into the performance of each propulsion configuration across various operational states. This includes metrics such as efficiency, power consumption, emissions, and response to changing load conditions. These insights will enable us to gauge the viability of different propulsion choices under real-world scenarios.
- **Optimization Opportunities**: By manipulating the model's variables and parameters, we can identify optimization opportunities that enhance efficiency, reduce energy consumption, and minimize environmental impact. The models can serve as a testing ground for refining operational strategies and fine-tuning system settings.
- **Environmental Impact Assessment**: Through the simulations, we will be able to quantify the environmental footprint of each propulsion configuration. This assessment includes the estimation of emissions, fuel consumption, and overall ecological implications. Such insights are pivotal in making informed decisions aligned with sustainability goals.
- **Comparative Analysis**: The models will facilitate a direct comparison between different propulsion configurations. By assessing key performance indicators side by side, we can discern which configuration aligns best with the operational needs, economic considerations, and environmental objectives.

7.2. Description of models and components

This section provides a detailed exposition of the construction process, offering a comprehensive walkthrough of how the capabilities of gPROMS were utilized to craft models that mirror real-world propulsion systems.

Pre-made models of the main components of our propulsion configurations, such as four-stroke engines, generators etc., were provided and served as the fundamental tools to encapsulate the operation of the vessel. By integrating these models into our simulations, we gain the capability to replicate the dynamic interplay of engine components, fuel systems, and operational responses.

7.2.1. Four-stroke engine

In order to better describe the process of generating a complex propulsion model-system we will examine the configuration of each component individually.

Below, a comprehensive model of a four-stroke engine, imported from SENSE_library_v2, is depicted. This "model-set" includes not only the engine itself but also vital components such as the air intake pipeline, sea water pipeline for cooling, and an exhaust sink for exhaust gas management. These components are configured with parameters, such as pressures, temperatures and gas compositions of the intake and exhaust sinks, to align with the needs of our modeling endeavors. Moreover, the model-engine itself is configurable so the simulation is as accurate as possible to a real-life configuration.

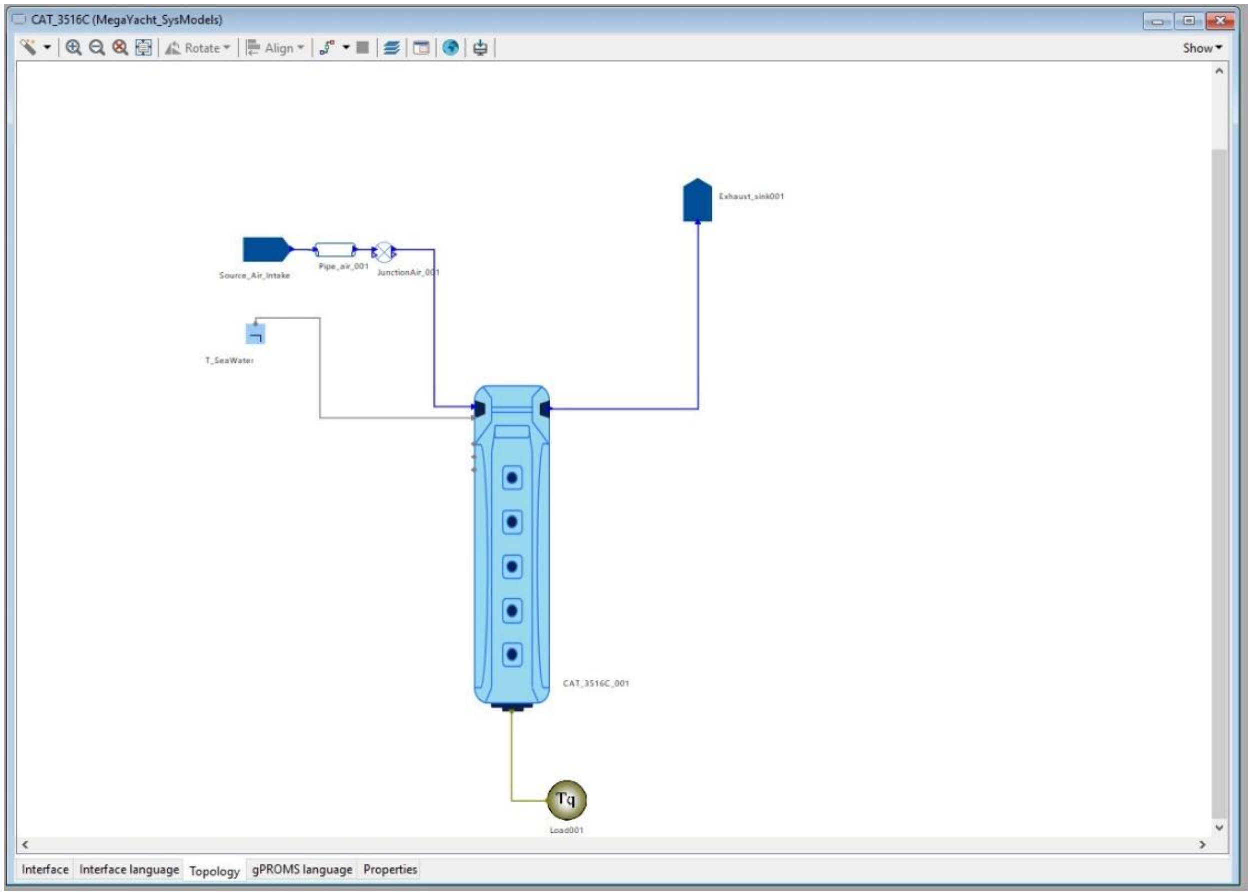
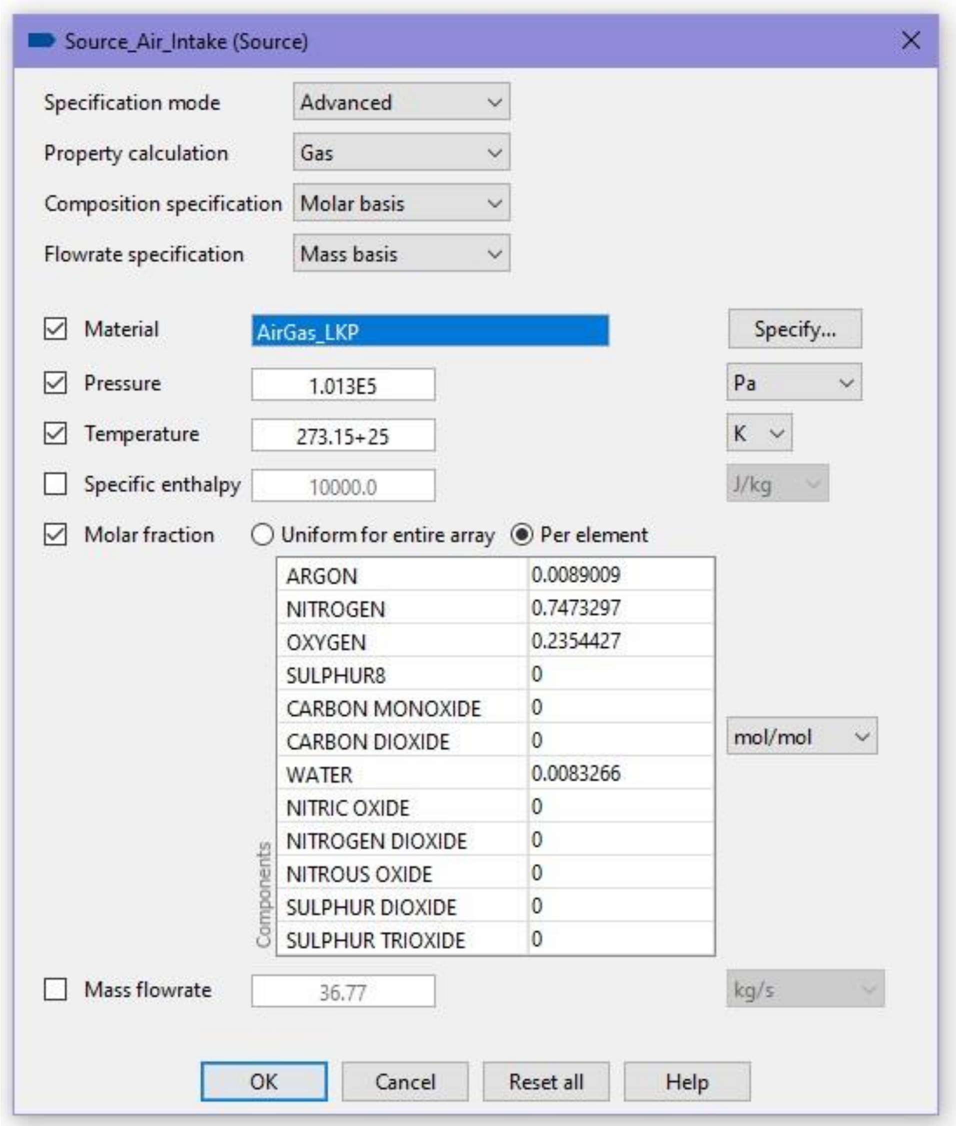


Figure 26. Four-stroke engine as depicted in gPROMS user interface.



Source_Air_Intake (Source)

Specification mode: Advanced
Property calculation: Gas
Composition specification: Molar basis
Flowrate specification: Mass basis

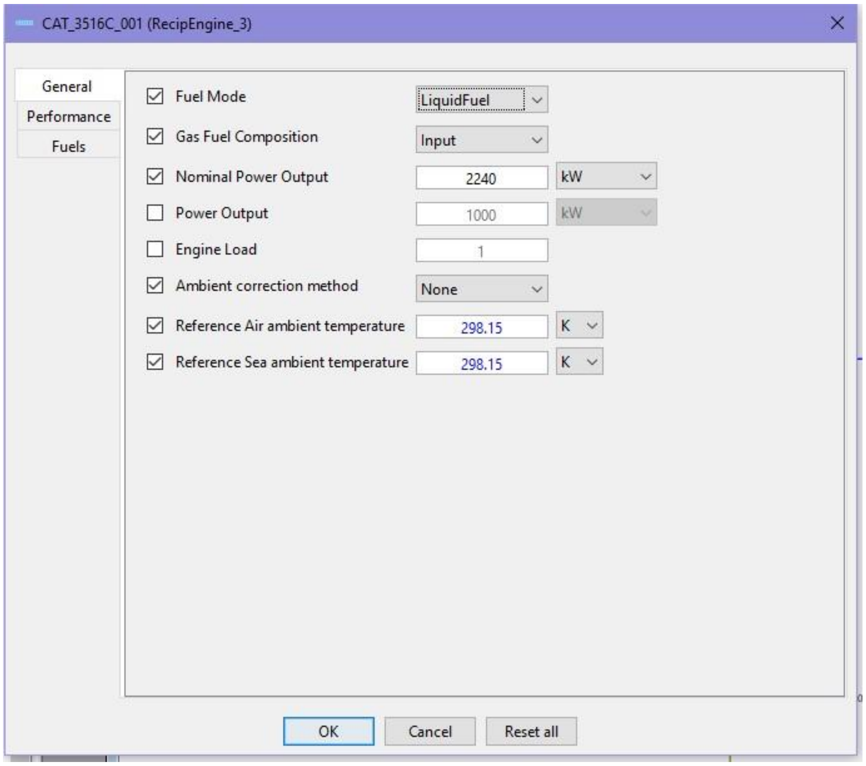
☑ Material: AirGas_LKP
☑ Pressure: 1.013E5 Pa
☑ Temperature: 273.15+25 K
☐ Specific enthalpy: 10000.0 J/kg
☑ Molar fraction: ○ Uniform for entire array ● Per element

Components	mol/mol
ARGON	0.0089009
NITROGEN	0.7473297
OXYGEN	0.2354427
SULPHUR8	0
CARBON MONOXIDE	0
CARBON DIOXIDE	0
WATER	0.0083266
NITRIC OXIDE	0
NITROGEN DIOXIDE	0
NITROUS OXIDE	0
SULPHUR DIOXIDE	0
SULPHUR TRIOXIDE	0

☐ Mass flowrate: 36.77 kg/s

Figure 27. Air Intake Configuration in gPROMS.

Configuring the performance of the engine can easily be done by importing the data that has been collected from manufacturers into the component's properties section. In order for the model to run properly, the data has been converted to SI units and expressed as a function of load, as shown in the figure below.



☑ Fuel Mode: LiquidFuel

☑ Gas Fuel Composition: Input

☑ Nominal Power Output: 2240 kW

☐ Power Output: 1000 kW

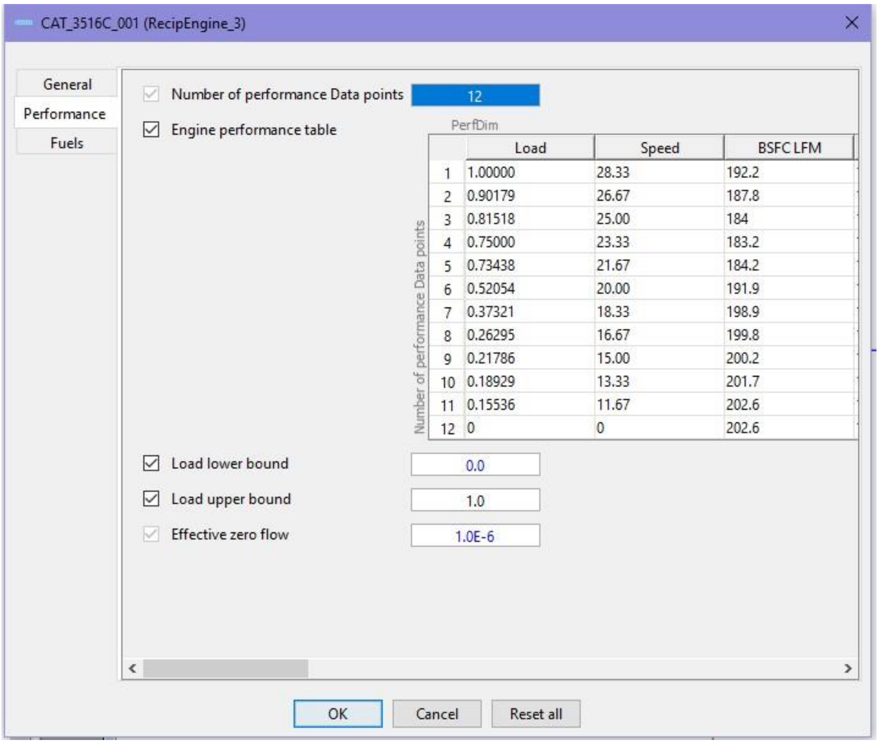
☐ Engine Load: 1

☑ Ambient correction method: None

☑ Reference Air ambient temperature: 298.15 K

☑ Reference Sea ambient temperature: 298.15 K

Figure 28. Four-Stroke Engine general configuration tab.



☑ Number of performance Data points: 12

☑ Engine performance table

	Load	Speed	BSFC LFM
1	1.00000	28.33	192.2
2	0.90179	26.67	187.8
3	0.81518	25.00	184
4	0.75000	23.33	183.2
5	0.73438	21.67	184.2
6	0.52054	20.00	191.9
7	0.37321	18.33	198.9
8	0.26295	16.67	199.8
9	0.21786	15.00	200.2
10	0.18929	13.33	201.7
11	0.15536	11.67	202.6
12	0	0	202.6

☑ Load lower bound: 0.0

☑ Load upper bound: 1.0

☑ Effective zero flow: 1.0E-6

Figure 29. Four-Stroke Engine performance configuration tab.

The process of configuring the four-stroke engine, as described above, serves as a standard procedure for the configuration of all engines incorporated within the five propulsion configurations that we are to examine. Regardless of engine type or specific attributes, each engine undergoes an identical configuration process. This uniform methodology ensures consistency in the modeling approach across all propulsion configurations.

7.2.2. Electric motors and generators

To simulate the operation of both electric motors and generators a model from COSSMOS_electric_library_v05 was used called "Electric machine" has been used. This model can let the user select whether the machine should operate as a generator or a motor. In addition, to the selection of the operation mode the nominal electrical power of each component has been selected according to the manufacturer's technical documents. Finally, through private communication with an electric motors' manufacturer, ABB [19], efficiency curves as a function of load were acquired so that an accurate description of these machines can be conducted.

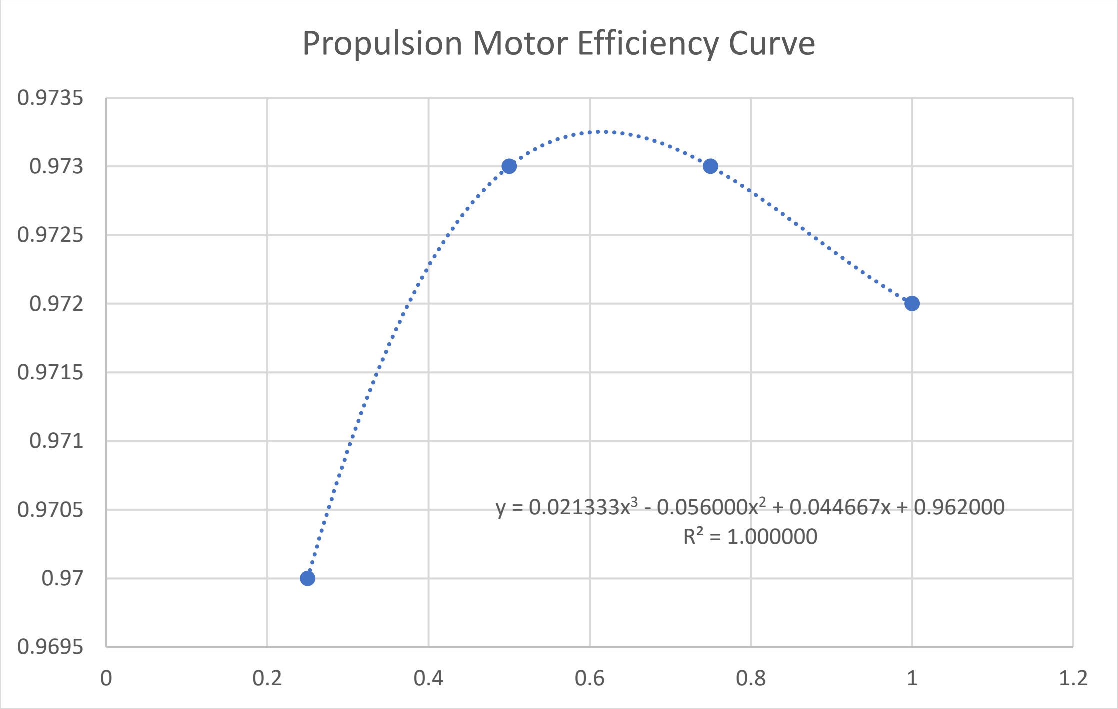


Figure 30. Propulsion Motor efficiency as a function of load.

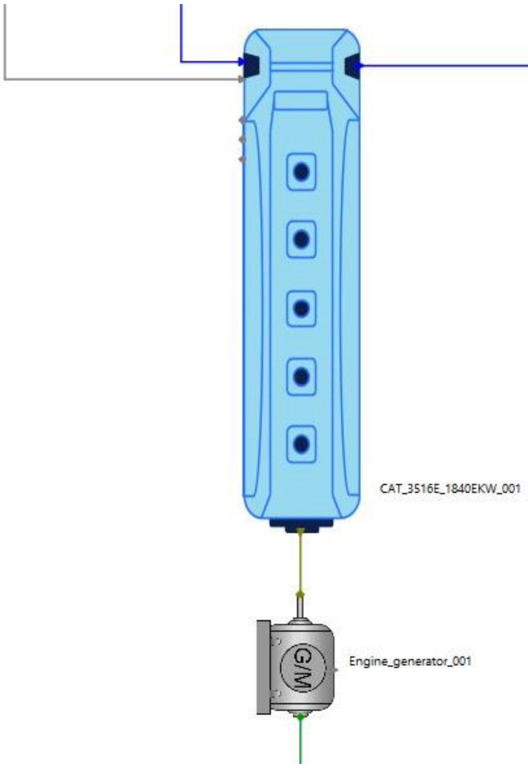
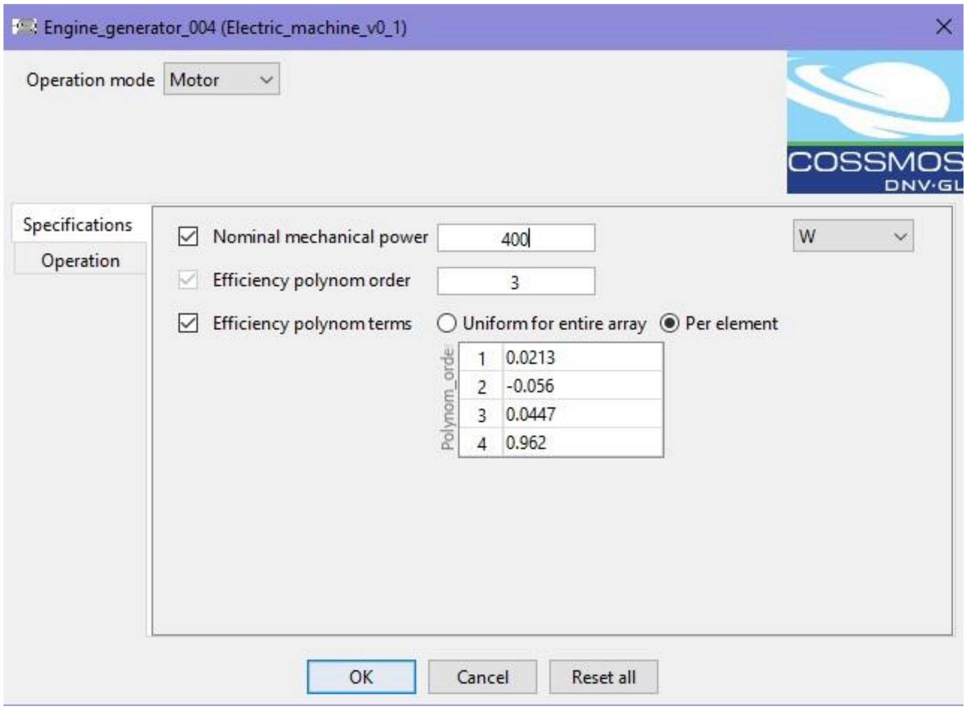


Figure 31. Propulsion Motor connected to a Diesel Generator Set as depicted in gPROMS user interface.



Engine_generator_004 (Electric_machine_v0_1)

Operation mode: Motor

☑ Nominal mechanical power: 400 W

☑ Efficiency polynom order: 3

☑ Efficiency polynom terms ○ Uniform for entire array ● Per element

Polynom_orde	
1	0.0213
2	-0.056
3	0.0447
4	0.962

Figure 32. Propulsion Motor configuration tab.

Expressing the efficiency curves of the generators used in the selected propulsion configuration could only be done through converting the data provided to polynomial equations. To achieve this, the data points were placed in a scatter plot and by using Microsoft Excel, accurate polynomial trendlines were calculated for each individual engine.

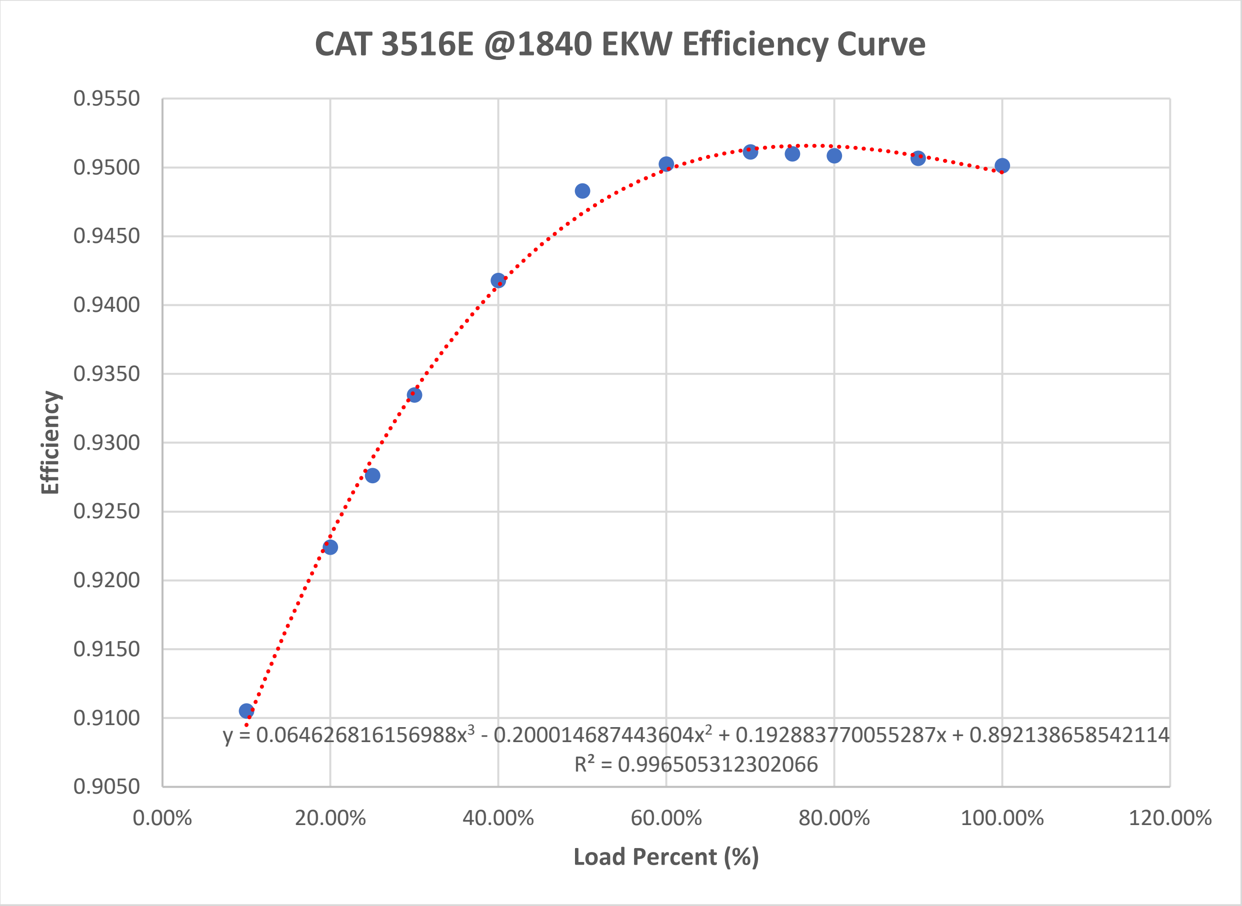


Figure 33. Efficiency Curve of CAT 3516E @1840ekW, generated from data provided by the manufacturer through private communication.

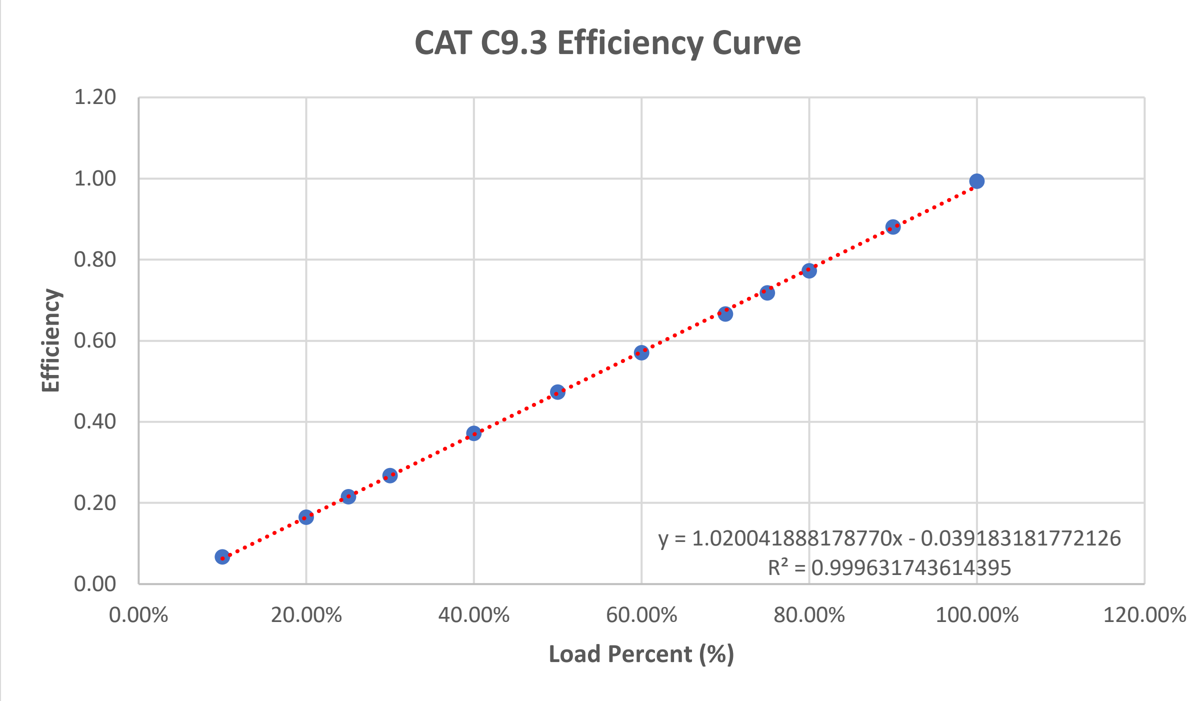


Figure 34. Efficiency Curve of CAT C9.3, generated from data provided by the manufacturer through private communication.

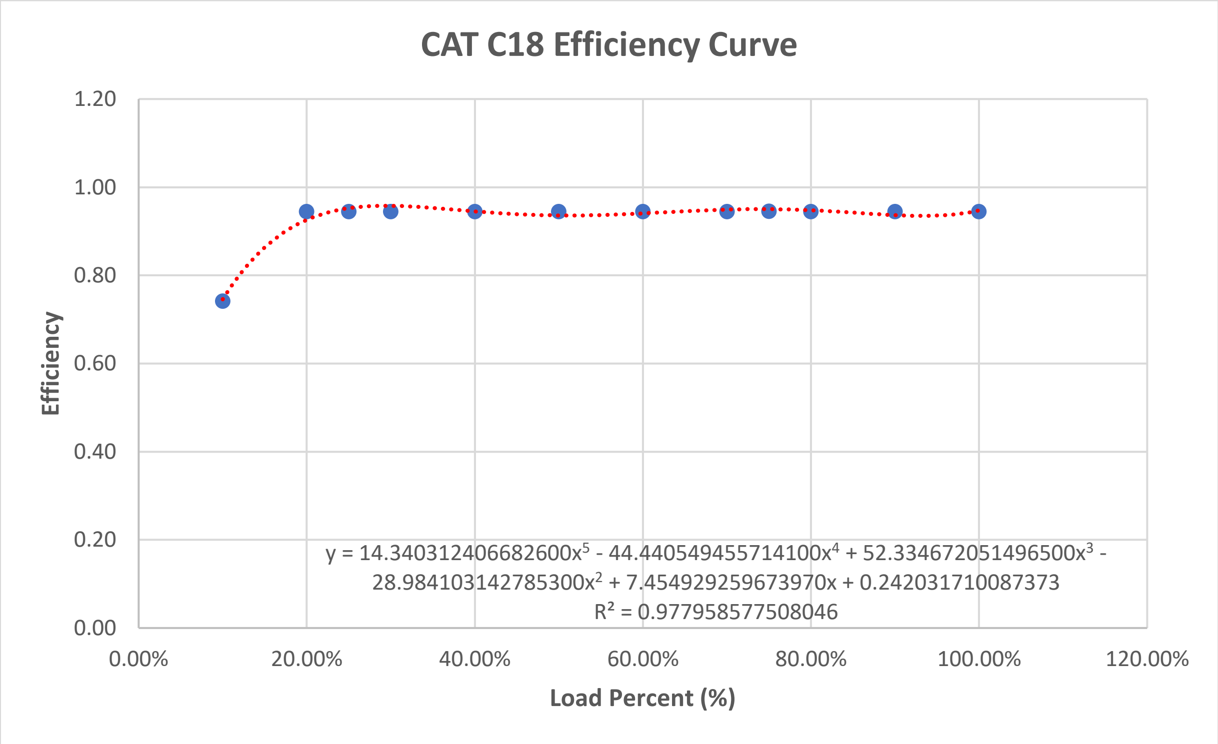
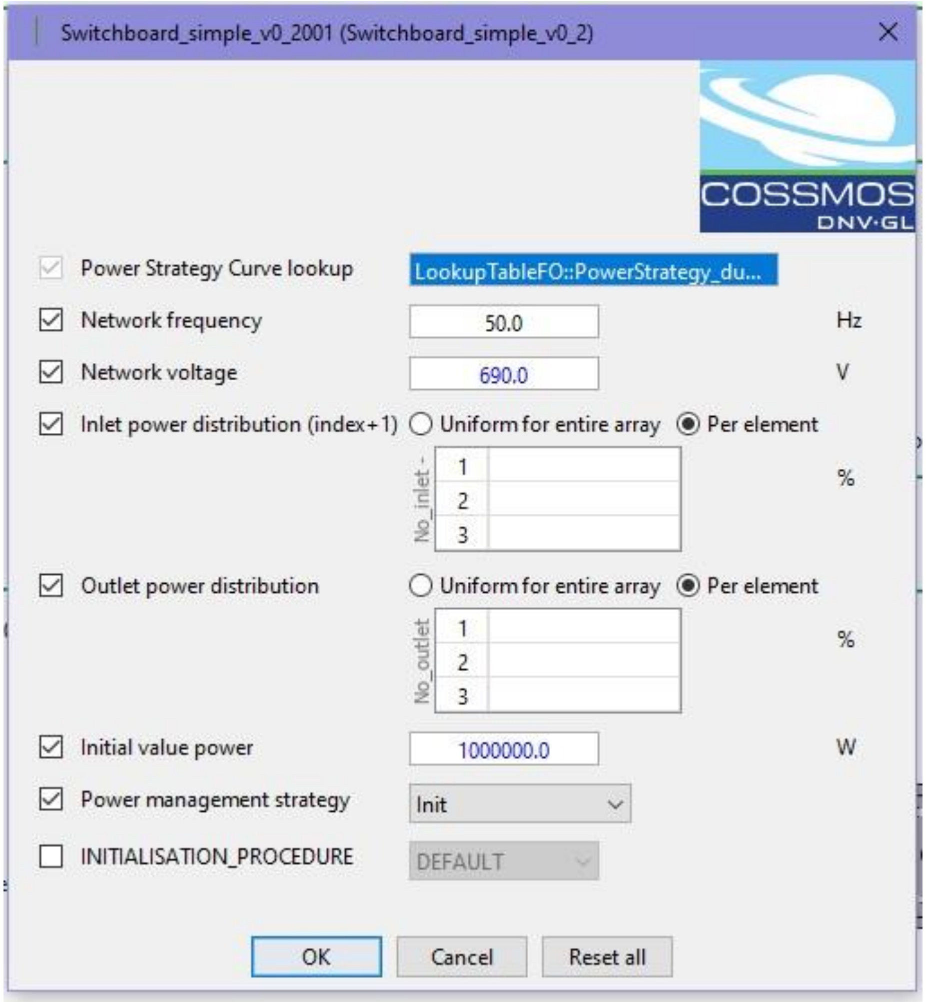


Figure 35. Efficiency Curve of CAT C18, generated from data provided by the manufacturer through private communication.

7.2.3. Switchboard and electric losses

Switchboards are modeled as power distributors that have inputs connected to electric generators (electricity providers) and outputs connected to all power consumers, such as electric motors, auxiliary machinery, and accommodation. Moreover, the switchboard model is highly configurable and thus a detailed representation of the vessel's electrical network can be constructed. The switchboard model was imported from COSSMOS_electric_library_v05.

Power consumers are depicted using the "electric_load_v2" model from SENSE_Library_v2, while electric losses from various components such as frequency converters are depicted using the "electric_losses_v2" model from the same library. The efficiency of the above-mentioned components can be given as a function of load or a constant number.



Switchboard_simple_v0_2001 (Switchboard_simple_v0_2)

☑ Power Strategy Curve lookup: LookupTableFO::PowerStrategy_du...
☑ Network frequency: 50.0 Hz
☑ Network voltage: 690.0 V
☑ Inlet power distribution (index+1): ○ Uniform for entire array ● Per element; No_inlet - 1, 2, 3 (%)
☑ Outlet power distribution: ○ Uniform for entire array ● Per element; No_outlet 1, 2, 3 (%)
☑ Initial value power: 1000000.0 W
☑ Power management strategy: Init
☐ INITIALISATION_PROCEDURE: DEFAULT

Figure 36. Switchboard configuration tab.

Electric_Losses_v003 (Electric_Losses_v2)

☑ Nominal power at inlet 1000000.0 W

☑ Polynom_order_eff 0

☑ Polynom_terms_eff ○ Uniform for entire array ● Per element

Po 1 0.99

Figure 37. Electric Power Consumer configuration tab.

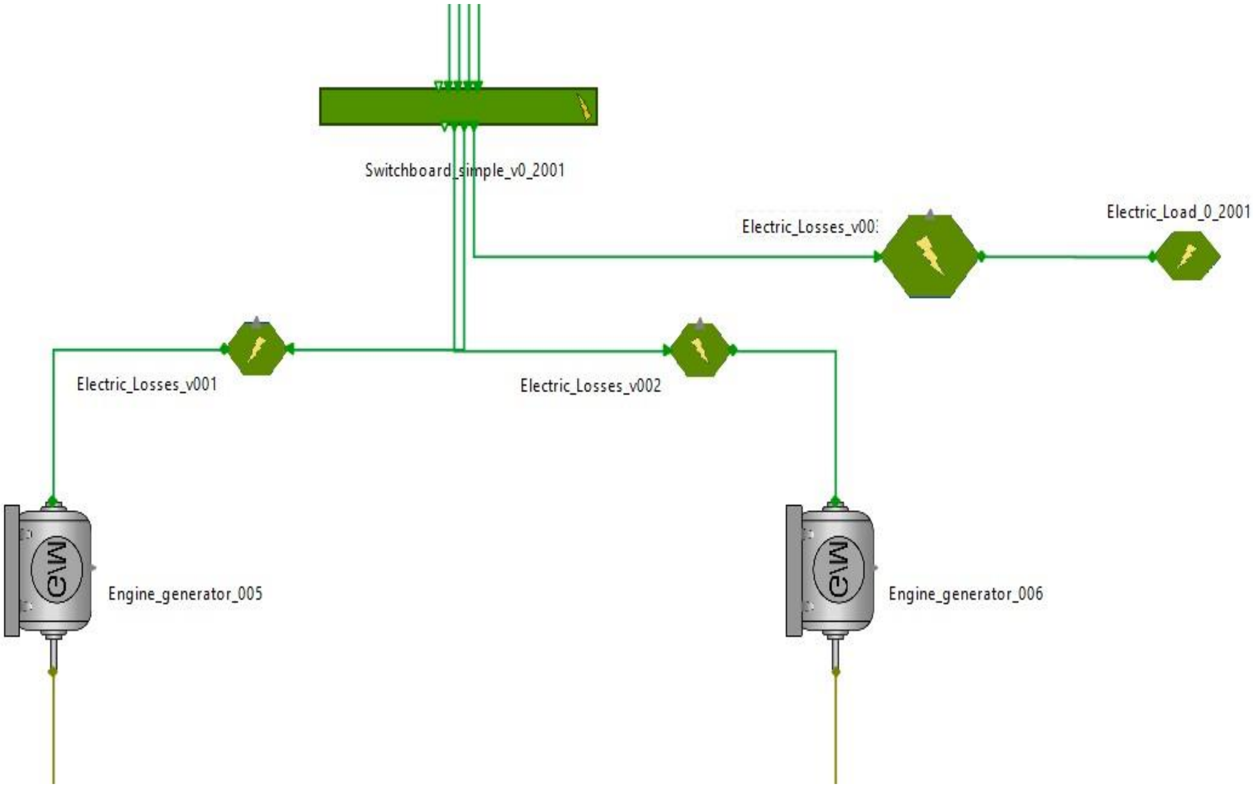


Figure 38. Example of a switchboard connected to two (2) electric motors and one (1) power consumer.

7.2.4. Gearbox and torque junctions.

As we have also mentioned in chapter 4.2, a gearbox is a mechanical device used to transmit power and torque from the engine of a vessel to the propeller. In order to implement gearboxes in our propulsion configuration models a model called “ReductionGear_v1” from COSSMOS_library was used. The efficiency of the gearboxes used was described through a third-degree polynomial equation that was generated from efficiency data points that were acquired through private communication with a marine gearbox manufacturer.

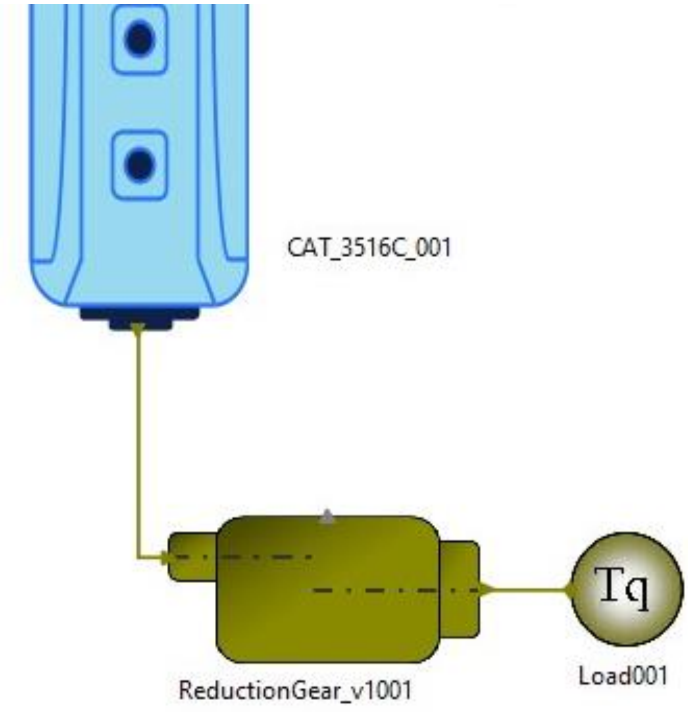
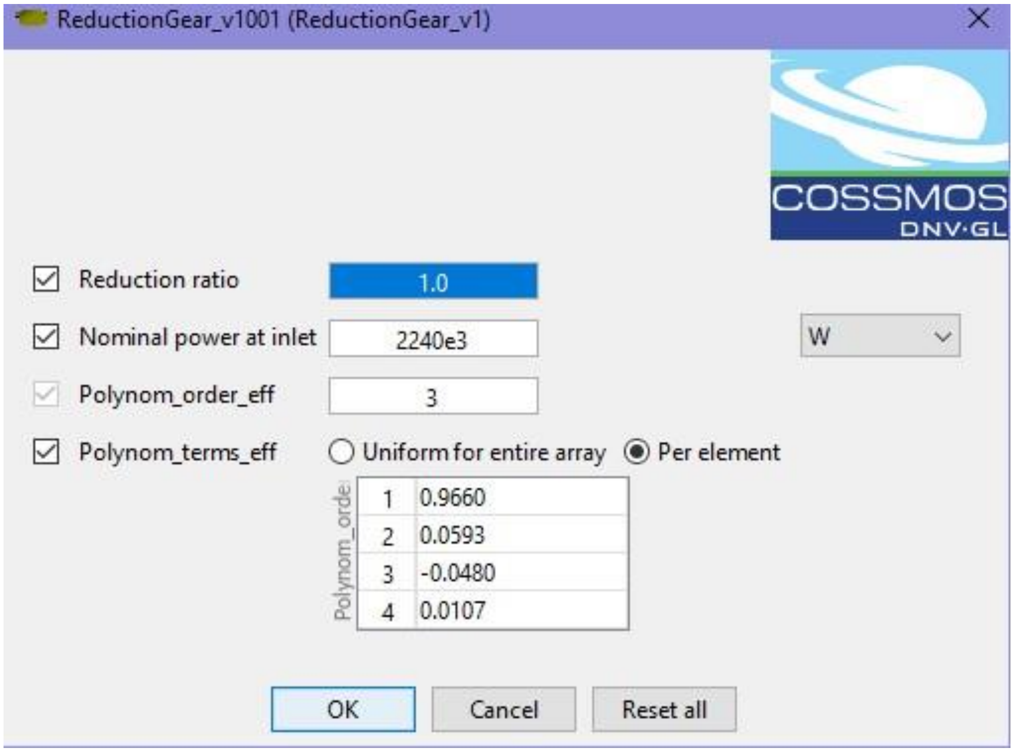


Figure 39. Gearbox as depicted in gPROMS user interface.



ReductionGear_v1001 (ReductionGear_v1)

☑ Reduction ratio 1.0

☑ Nominal power at inlet 2240e3 W

☑ Polynom_order_eff 3

☑ Polynom_terms_eff ○ Uniform for entire array ● Per element

Polynom_orde	
1	0.9660
2	0.0593
3	-0.0480
4	0.0107

Figure 40. Gearbox configuration tab.

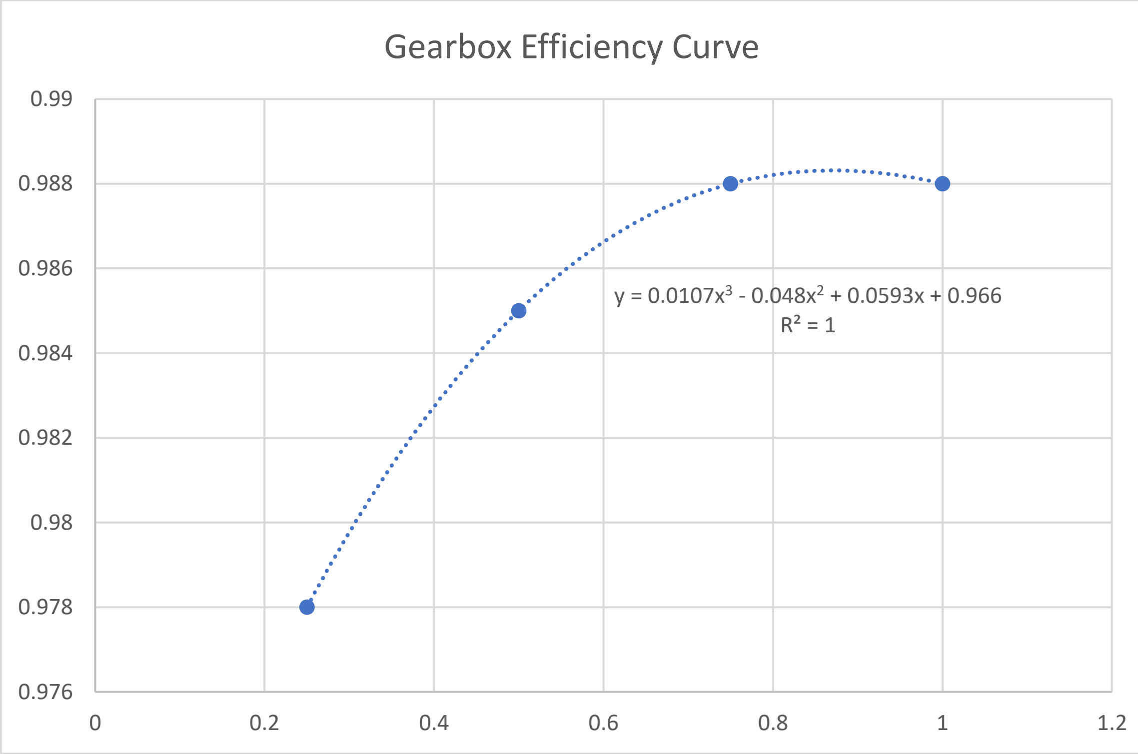


Figure 41. Gearbox efficiency as function of load. Curve generated from data provided by manufacturer through private communication.

However, in hybrid propulsion configurations a gearbox needs to have two (2) torque inputs, one for the main engine and one for the PTI/PTO motor. To aggregate the torques generated by each of these components a model called Torque Junction from SENSE_library_v02 was used. By using this model in conjunction with a single input gearbox model we are able to represent a dual input gearbox.

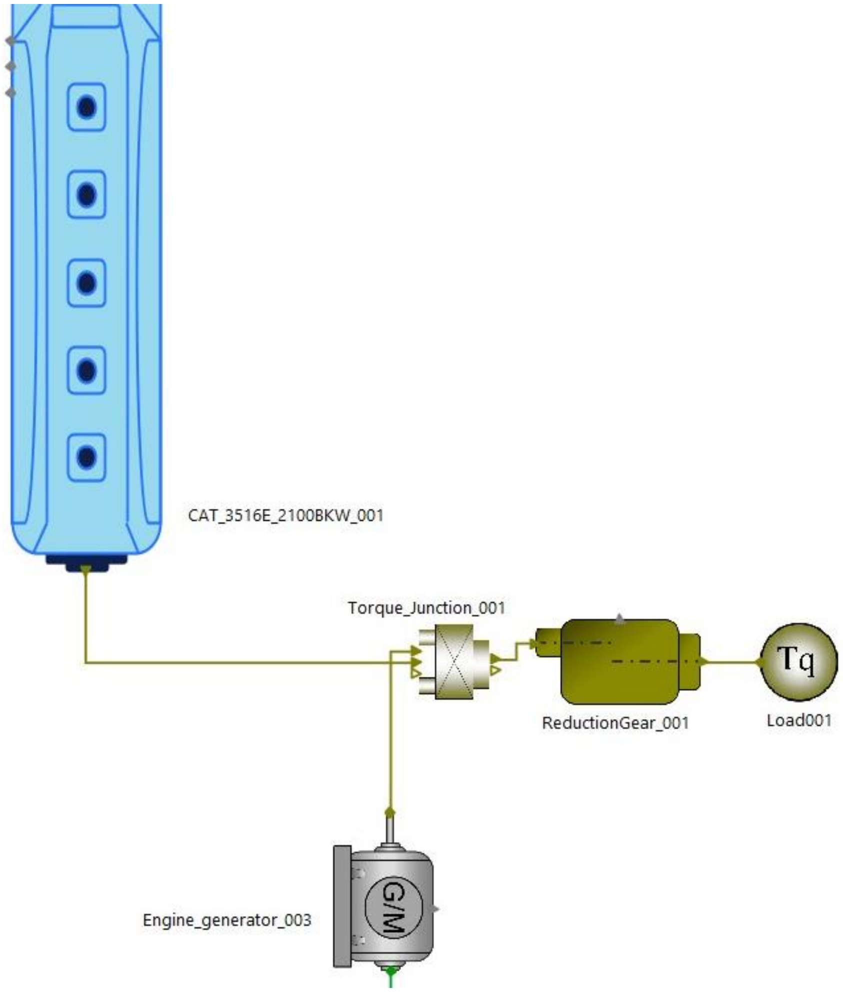


Figure 42. Example of a Torque Junction with two (2) inputs (Diesel Engine and Electric Motor) and one (1) output.

7.2.5. Battery Packs

Batteries serve as a pivotal component in the propulsion and power management systems of modern mega-yachts, offering a versatile solution to meet a wide array of power needs. In mechanical configurations, batteries primarily supply power to auxiliary systems and accommodations, ensuring seamless operation without engaging the main engines. This not only enhances efficiency but also contributes to a significant reduction in fuel consumption and emissions. In more advanced diesel-electric and hybrid configurations, batteries extend their utility to include the propulsion power needs. This dual functionality allows for greater operational flexibility, enabling vessels to operate in a more environmentally friendly manner by reducing reliance on traditional fuel sources and minimizing noise and vibration levels.

The effectiveness of a battery in a yacht's power system is determined by several key characteristics, including its capacity and the operational limits of its State of Charge (SOC). SOC is a critical parameter that represents the current charge level of a battery relative to its total capacity, expressed as a percentage. Essentially, the SOC indicates how much energy is stored in the battery at any given time compared to what it can hold when fully charged.

To ensure longevity and optimal performance, batteries are typically operated within a specific SOC range, often between a minimum threshold (set by manufacturers to ensure long lifespan) and a maximum capacity limit. For instance, in our models in order to preserve battery health, the manufacturer has set the SOC to be maintained between 20% (minimum) and 80% (maximum).

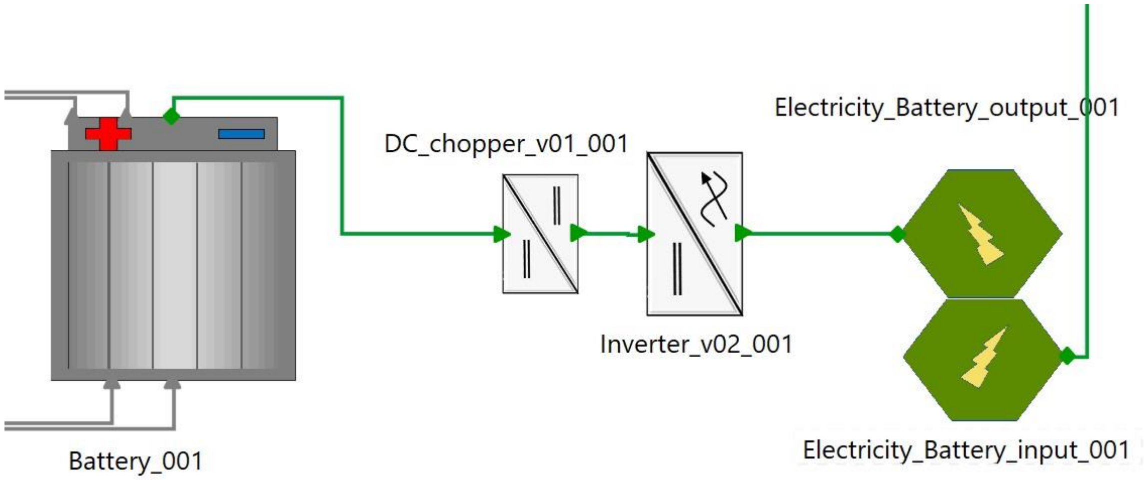
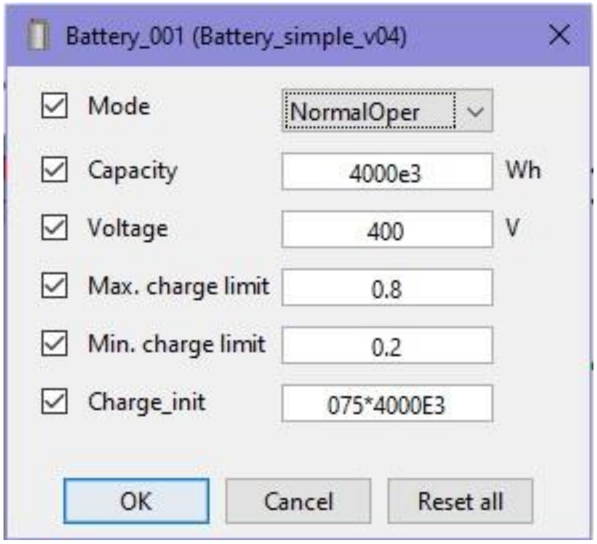


Figure 43. Model of a battery pack in gPROMS user interface.



Battery_001 (Battery_simple_v04)

☑ Mode NormalOper

☑ Capacity 4000e3 Wh

☑ Voltage 400 V

☑ Max. charge limit 0.8

☑ Min. charge limit 0.2

☑ Charge_init 075*4000E3

Figure 44. Battery configuration tab in gPROMS.

Integral to the efficient operation of battery packs is the Battery Management System (BMS), a component that oversees the battery's operational modes and facilitates the seamless transition between the battery’s modes of operation based on the vessel's power requirements. The BMS is configured to operate in two primary modes:

1. **On-Off Mode**: Functions as a charging cycle, where the battery charges up to the max SOC point and discharges down to the min SOC point. In this operational mode the battery is basically doing full charging/discharging circles. The On-Off mode of the battery is predominantly utilized in situations where the yacht is either berthed, anchored, or maneuvering. During these periods, the demand for propulsion power is significantly reduced or varies minimally, making it an ideal scenario for engaging this mode.

2. **Peak Shaving Mode**: In this mode, the battery acts as a supportive element to the main engines or generator sets. By maintaining a desired steady load on the engines, peak shaving enhances operational efficiency and mitigates load fluctuations. Batteries discharge to supplement power when demands exceed the engines' optimal output and charge when excess power is available, based on a moving average calculated by a scheduler. This strategic use of batteries helps achieve a balance between power supply and demand, optimizing overall system efficiency. The Peak Shaving mode is primarily activated during cruising, when the yacht is under consistent propulsion and the power demands are more predictable yet subject to fluctuations.

Through these distinct operational modes, the BMS effectively leverages battery capacity to meet the yacht's power requirements across different scenarios, ensuring an efficient, sustainable, and cost-effective power management strategy.

Moreover, the charging rate of the battery, determined through extensive model optimization, plays a crucial role in achieving the best possible efficiency within the yacht's power management system. This rate is calibrated to align with the operational demands and energy management strategies of the vessel, ensuring that the batteries contribute effectively to the yacht's efficiency and environmental sustainability objectives.

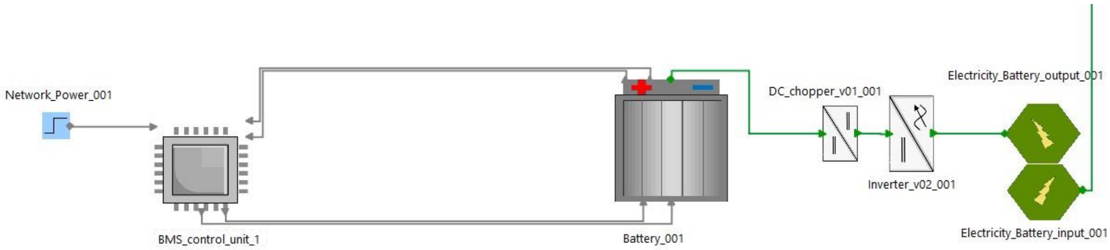
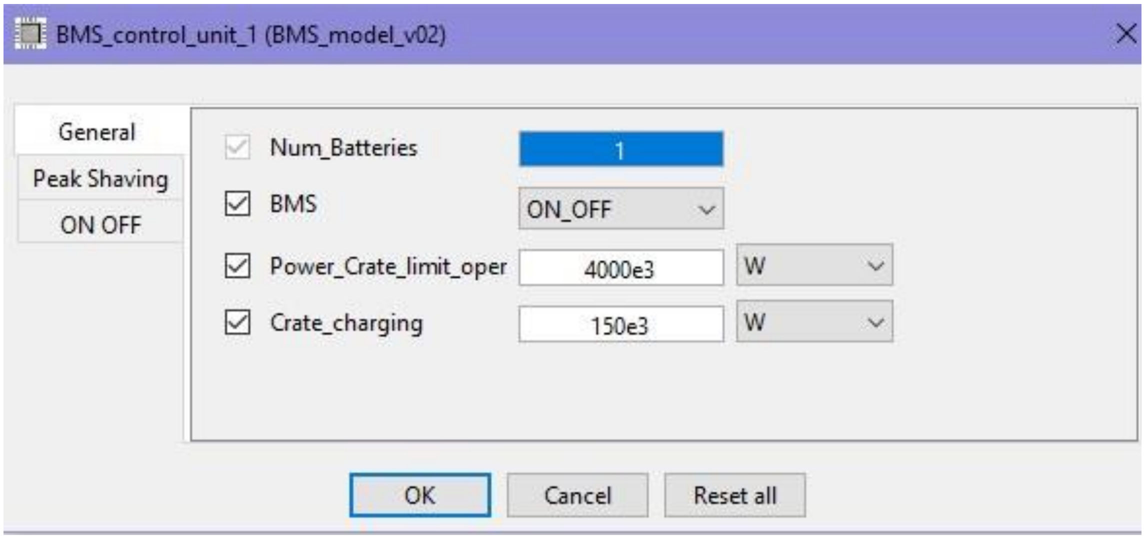


Figure 45. Model of a battery management system (BMS) in gPROMS user interface.



BMS_control_unit_1 (BMS_model_v02)

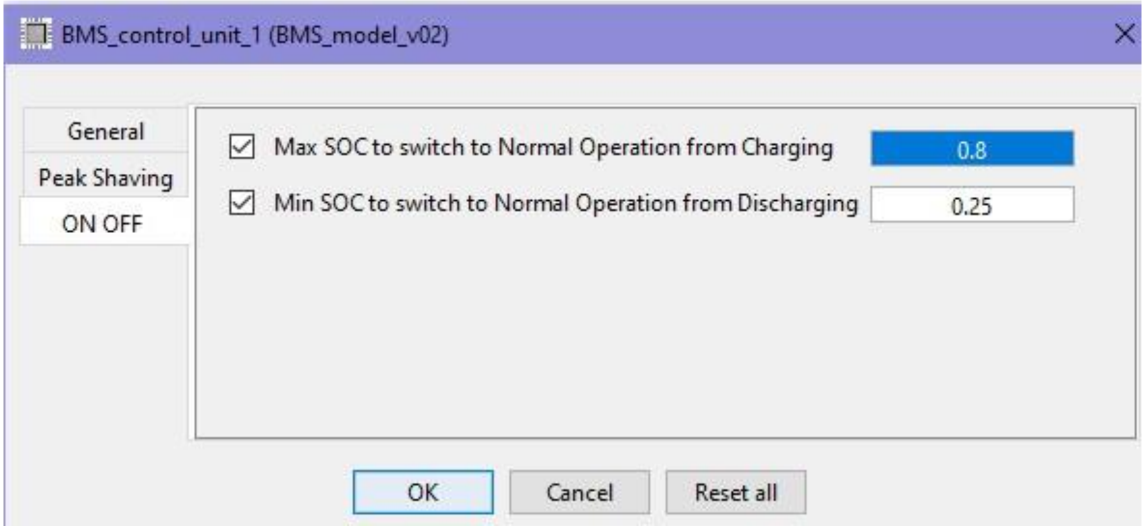
☑ Num_Batteries 1

☑ BMS ON_OFF

☑ Power_Crate_limit_oper 4000e3 W

☑ Crate_charging 150e3 W

Figure 46. BMS configuration tab in gPROMS.

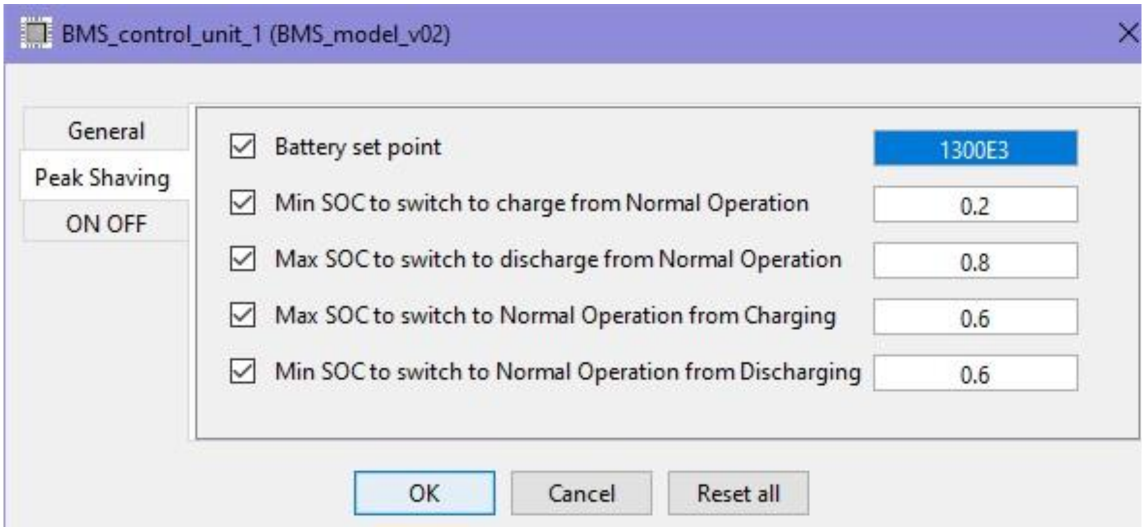


BMS_control_unit_1 (BMS_model_v02)

☑ Max SOC to switch to Normal Operation from Charging 0.8

☑ Min SOC to switch to Normal Operation from Discharging 0.25

Figure 47. BMS ON/OFF mode configuration tab in gPROMS.



☑ Battery set point 1300E3
☑ Min SOC to switch to charge from Normal Operation 0.2
☑ Max SOC to switch to discharge from Normal Operation 0.8
☑ Max SOC to switch to Normal Operation from Charging 0.6
☑ Min SOC to switch to Normal Operation from Discharging 0.6

Figure 48. BMS Peak Shaving mode configuration tab in gPROMS.

7.2.6. Shore connection

Shore connection plays a crucial role when the vessel is berthed, enabling it to fulfill its electrical needs directly from the shore-based power supply, thus obviating the need to run its engines for electricity generation. This capability not only contributes to significant reductions in fuel consumption and emissions but also enhances operational efficiency and noise reduction at port.

To accurately simulate the activation and utilization of shore power within our model, it is essential to define specific timestamps marking the vessel's connection to and disconnection from shore power. These timestamps act as triggers, toggling a flag within the model that signifies the activation of the shore connection. This procedural delineation ensures that the model precisely mirrors the real-world operation of transitioning to shore power when the vessel is moored.

Within the gPROMS User Interface (UI), the shore connection is conceptualized as an electric loss model that interfaces with the switchboard. Distinctively, the "power" attribute assigned to this model must be input as a negative number, reflecting the inflow of power from the shore to the vessel. This negative value is crucial for the model to correctly interpret the shore connection as a source of power, in contrast to other electric loss components that typically denote power consumption. By aligning the magnitude of this negative power value with the vessel’s current electrical power requirements, the model can accurately simulate the provision of shore power, effectively replacing the need for onboard power generation during mooring periods.

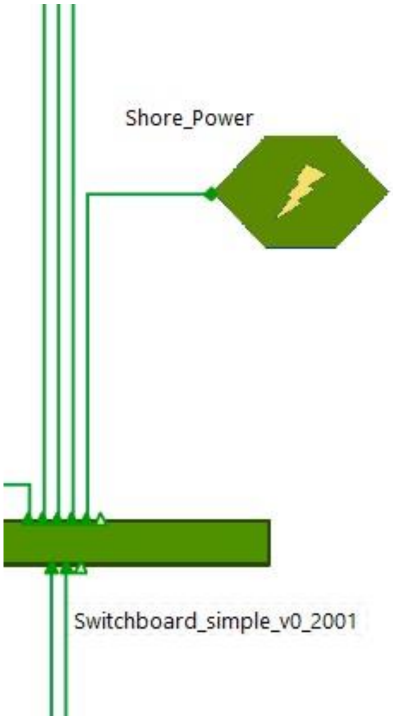


Figure 49. Shore connection representation in gPROMS user interface.

7.3. Propulsion Configuration Models

Building on the components outlined in Section 7.2, this section delves into how these parts are connected and function together in the models. Central to this are the four-stroke engines, each precisely linked to air intakes and sea water piping, reflecting real-world operations. This modeling is key to analyzing the propulsion system's efficiency and environmental impact.

Through this section, with the aid of screenshots of the user interface of Model Builder, we aim to provide a comprehensive understanding of the propulsion configuration models within the gPROMS environment. This detailed insight into the model structure and connectivity is fundamental for a thorough analysis of propulsion systems, offering a foundation for assessing their efficiency.

In the gPROMS models, a color-coding system is employed to highlight the interplay of different components and their connections. As it can also be observed in the following screenshots the following color-code is implemented:

- **Blue** for Air Intakes: Indicates the crucial role of air in engine operations.
- **Gray** for Sea Water Piping: Represents the sea water piping system, essential for cooling the engines and maintaining operational efficiency.
- **Green** for Electrical Network: Denotes the electrical network, crucial for the vessel’s auxiliary, generator sets.
- **Brown** for Mechanical Power Transmission: Central to the propulsion process of the mechanical and hybrid propulsion configurations.

7.3.1. Model of Configuration 1: Mechanical Propulsion

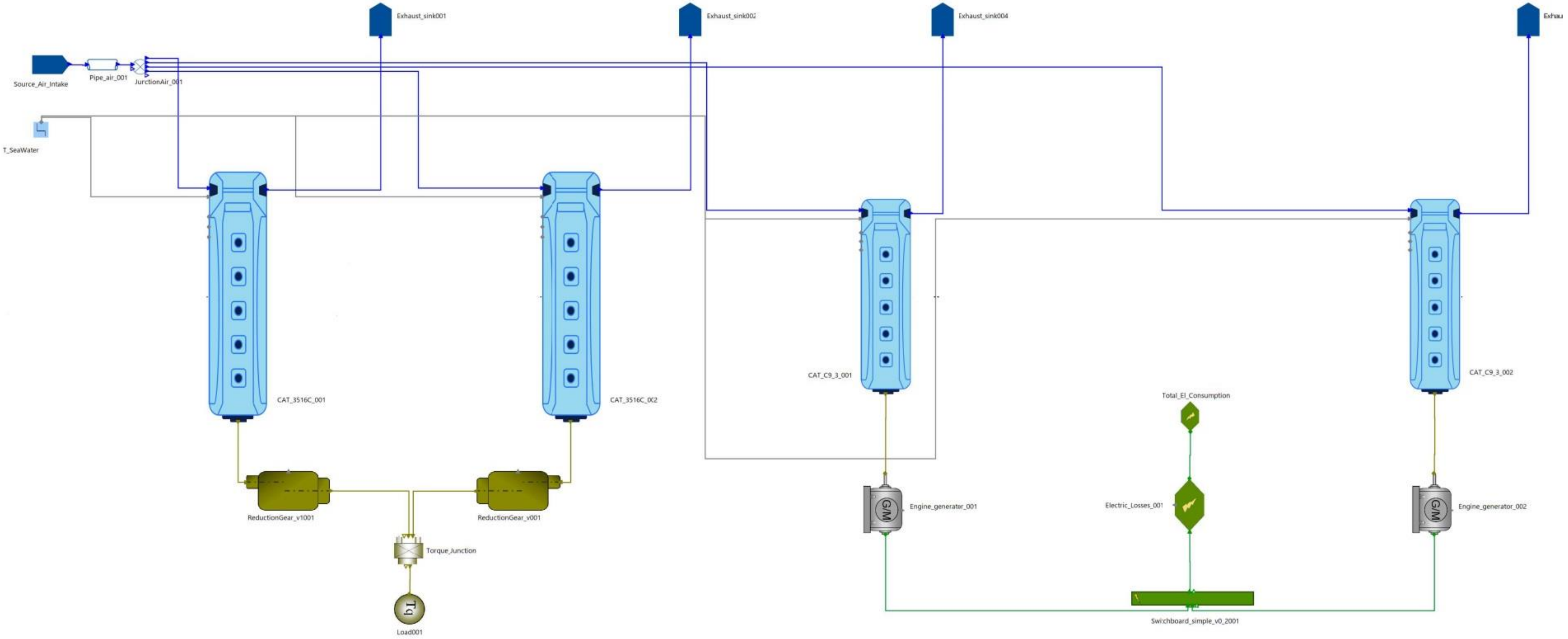


Figure 50. Mechanical propulsion configuration (Configuration 1) in gPROMS user interface.

7.3.2. Model of Configuration 2: Hybrid Propulsion

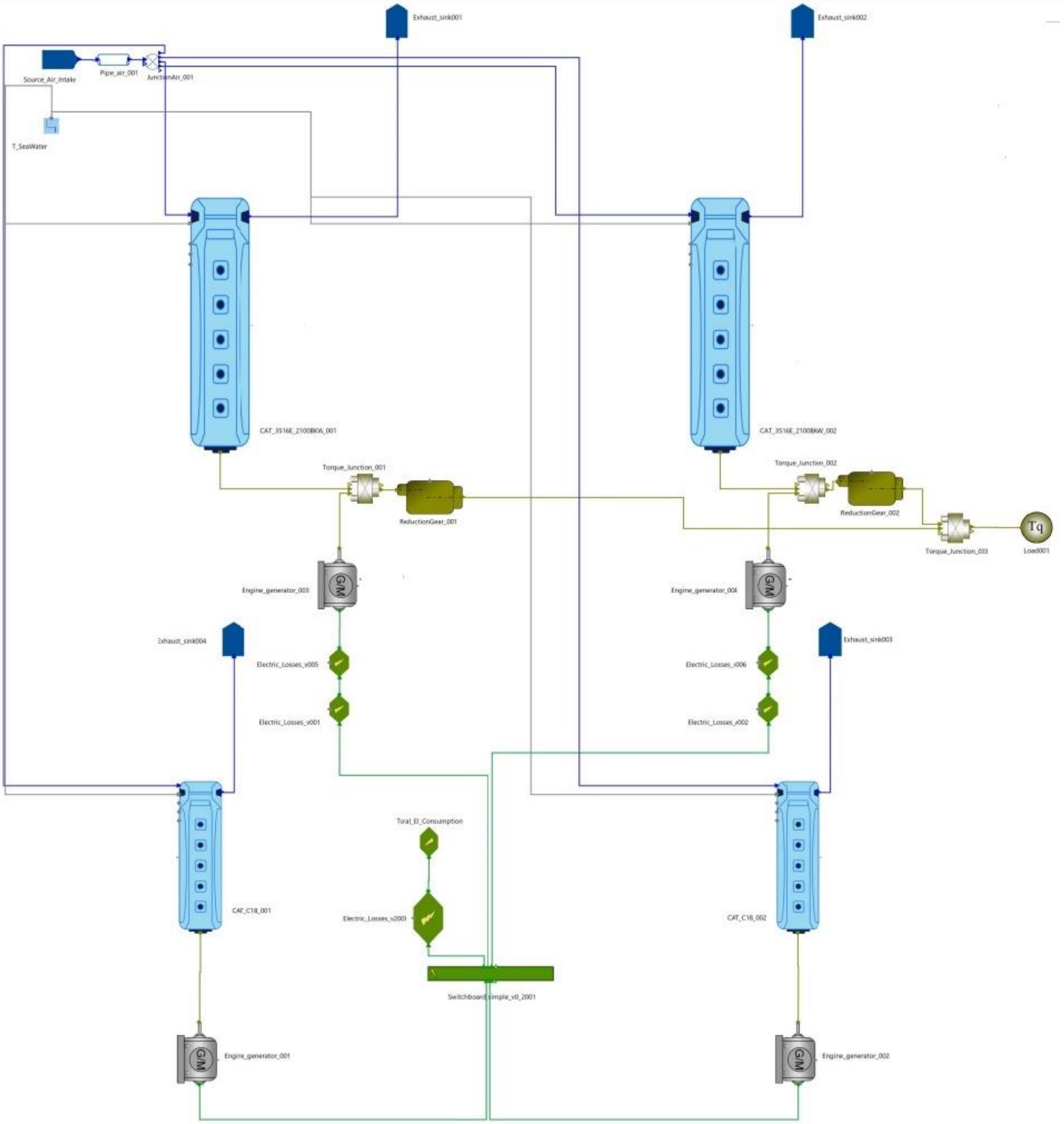


Figure 51. Hybrid propulsion configuration (Configuration 2) in gPROMS user interface.

7.3.3. Model of Configuration 3: Hybrid with batteries Propulsion

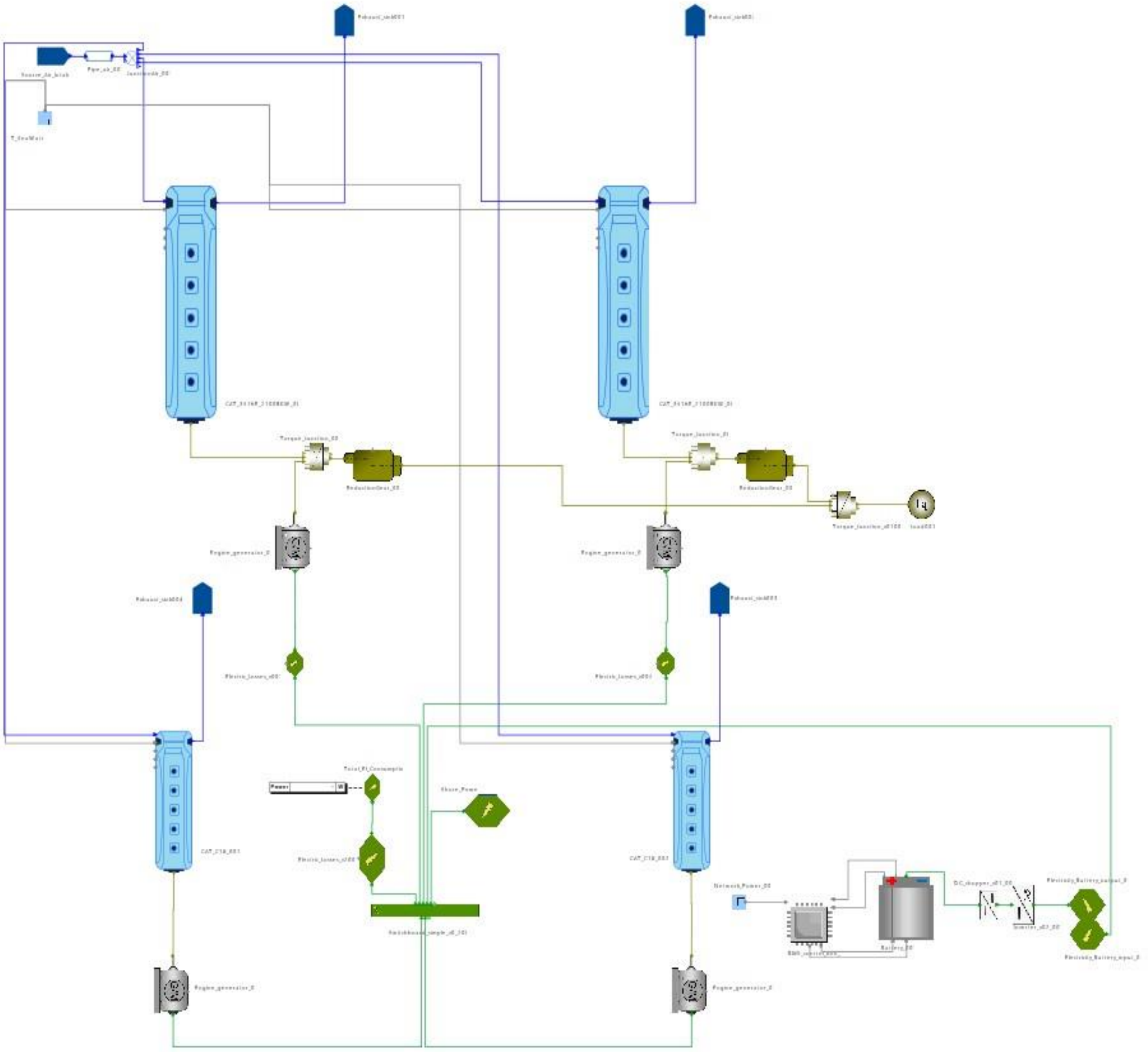


Figure 52. Hybrid with Battery propulsion configuration (Configuration 3) in gPROMS user interface.

7.3.4. Model of Configuration 4: Diesel-Electric Propulsion

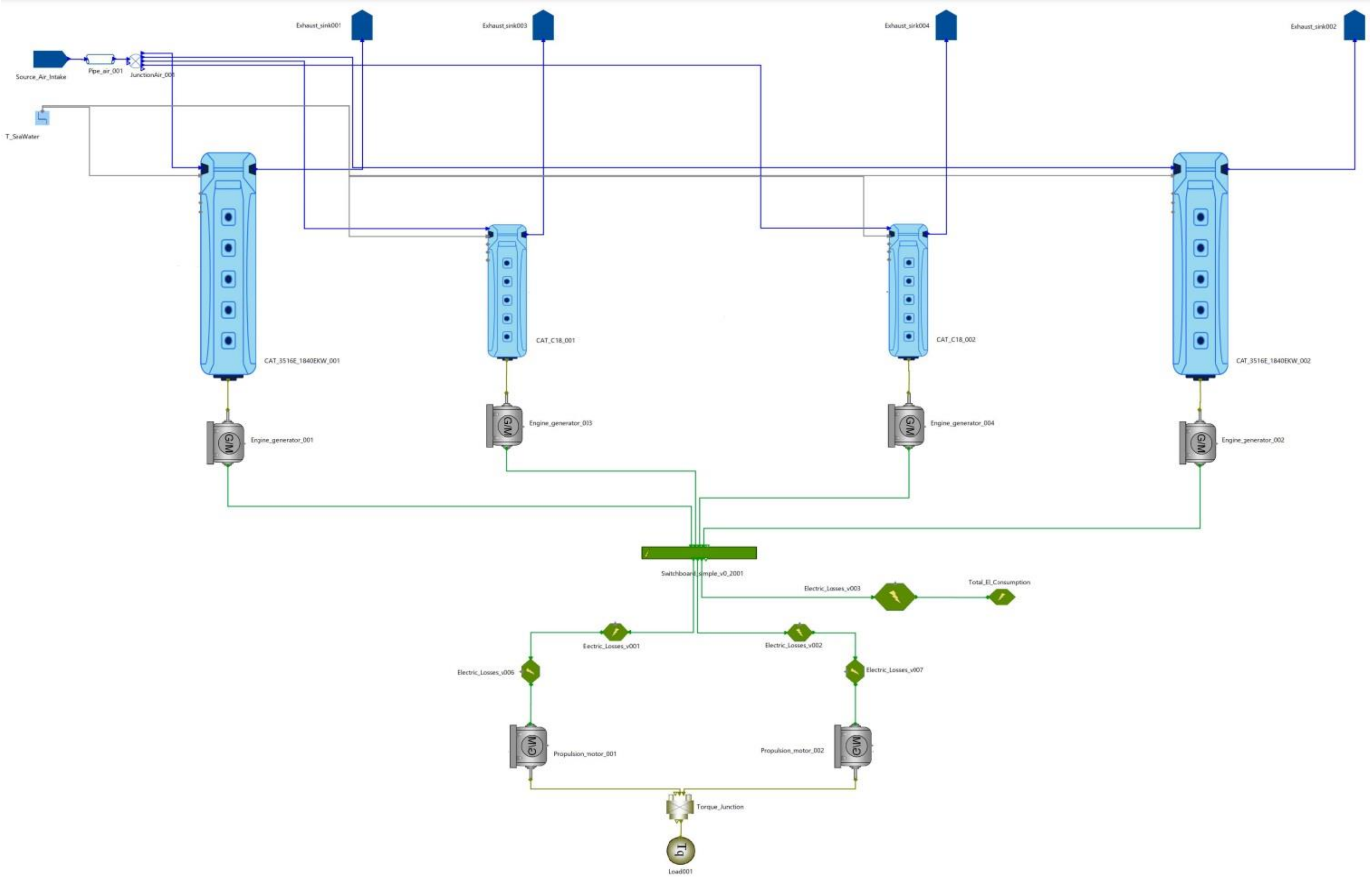


Figure 53. Diesel-Electric propulsion configuration (Configuration 4) in gPROMS user interface.

7.3.5. Model of Configuration 5: Diesel-Electric with batteries Propulsion

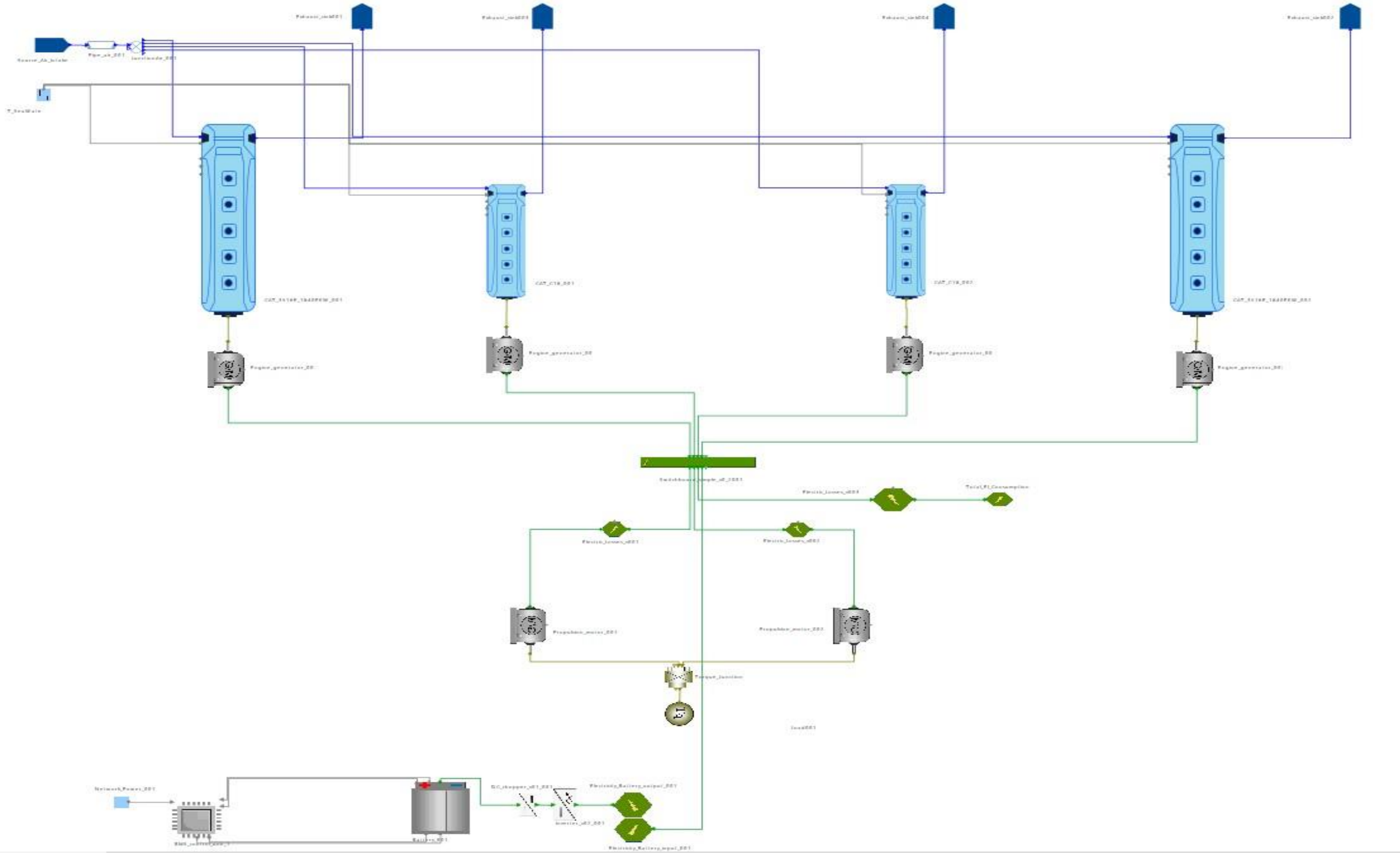


Figure 54. Diesel-Electric with Batteries propulsion configuration (Configuration 5) in gPROMS user interface.

7.4. Implementation of power balance plan into model language.

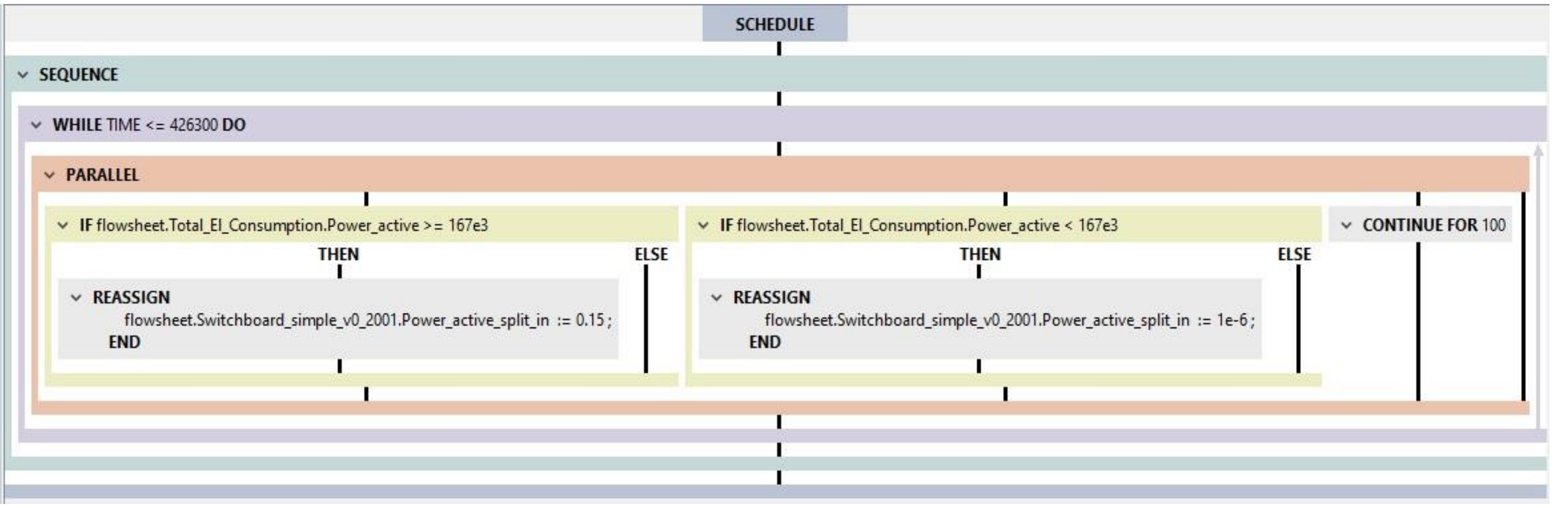
In this section, we transition from the conceptual framework outlined in Section 6.2.5 to its practical application within the gPROMS modeling environment. This crucial phase involves the translation of the power balance plan and the load split strategy into a structured code that the model can interpret and execute. The essence of this process is to take the theoretical strategies developed for optimizing power distribution between generator sets and convert them into executable commands within the gPROMS interface. This transformation is key to ensuring that the model accurately reflects the intended operational dynamics and adheres to the defined efficiency criteria.

To enhance the clarity of this coding process, the section will include screenshots and parts of the coding language from the Schedule tab of the gPROMS interface. These screenshots serve as flow diagrams, providing a visual representation of the operational logic. They detail the conditions under which specific values in the model may change and the sequence of these changes, thereby mapping out the flow of operations as dictated by the power balance plan. This graphical depiction of the model's logic aids in demystifying the code, making the complex interplay of conditions and operational sequences more accessible and understandable. By bridging the gap between theoretical planning and modeling, this section plays a pivotal role in bringing the power management strategy to life within the simulation environment.

- Configuration 1: Mechanical propulsion.

```
SCHEDULE
  SEQUENCE
    WHILE TIME <= 426300 DO
      PARALLEL
          IF flowsheet.Total_El_Consumption.Power_active >= 167e3
            THEN REASSIGN
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in  := 0.15 ;
            END
          END
          IF flowsheet.Total_El_Consumption.Power_active < 167e3
            THEN REASSIGN
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in  := 1e-6 ;
            END
          END
          CONTINUE FOR 100
      END
    END
```

Figure 55. gPROMS Code translating the load management strategy for Configuration 1.



```
SCHEDULE
SEQUENCE
WHILE TIME <= 426300 DO
PARALLEL
IF flowsheet.Total_El_Consumption.Power_active >= 167e3
THEN
REASSIGN
flowsheet.Switchboard_simple_v0_2001.Power_active_split_in := 0.15 ;
END
ELSE
IF flowsheet.Total_El_Consumption.Power_active < 167e3
THEN
REASSIGN
flowsheet.Switchboard_simple_v0_2001.Power_active_split_in := 1e-6 ;
END
ELSE
CONTINUE FOR 100
```

Figure 56. Screenshot from schedule section for Configuration 1 process.

- Configuration 2: Hybrid propulsion.

```
SCHEDULE
  SEQUENCE
    WHILE TIME < 195000 DO
      PARALLEL
          IF TIME >= 193000
            THEN REASSIGN
            flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1) := 0.5 ;
            flowsheet.torque_junction_001.Torque_split_in(1) := 0.16;
            flowsheet.torque_junction_002.Torque_split_in(1) := 0.16 ;
            END
          END
          IF flowsheet.Load001.power >= 200e3
            THEN REASSIGN
              flowsheet.torque_junction_001.Torque_split_in(1) := 1e-5 ;
              flowsheet.torque_junction_002.Torque_split_in(1) := 1e-5 ;
            END
          END
          IF flowsheet.Load001.power < 200e3 AND TIME < 193000
            THEN REASSIGN
              flowsheet.torque_junction_001.Torque_split_in(1) := 0.99999;
              flowsheet.torque_junction_002.Torque_split_in(1) := 0.99999 ;
            END
          END
          CONTINUE FOR 100
      END
    END
```

Figure 57. gPROMS Code translating the load management strategy for Configuration 2 (Part 1)

```
WHILE TIME >= 195000 AND TIME < 198900 DO
   PARALLEL
    REASSIGN
     flowsheet.torque_junction_001.Torque_split_in(1) := 0.16;
     flowsheet.torque_junction_002.Torque_split_in(1) := 0.16 ;

    END
    CONTINUE FOR 100
   END
  END
```

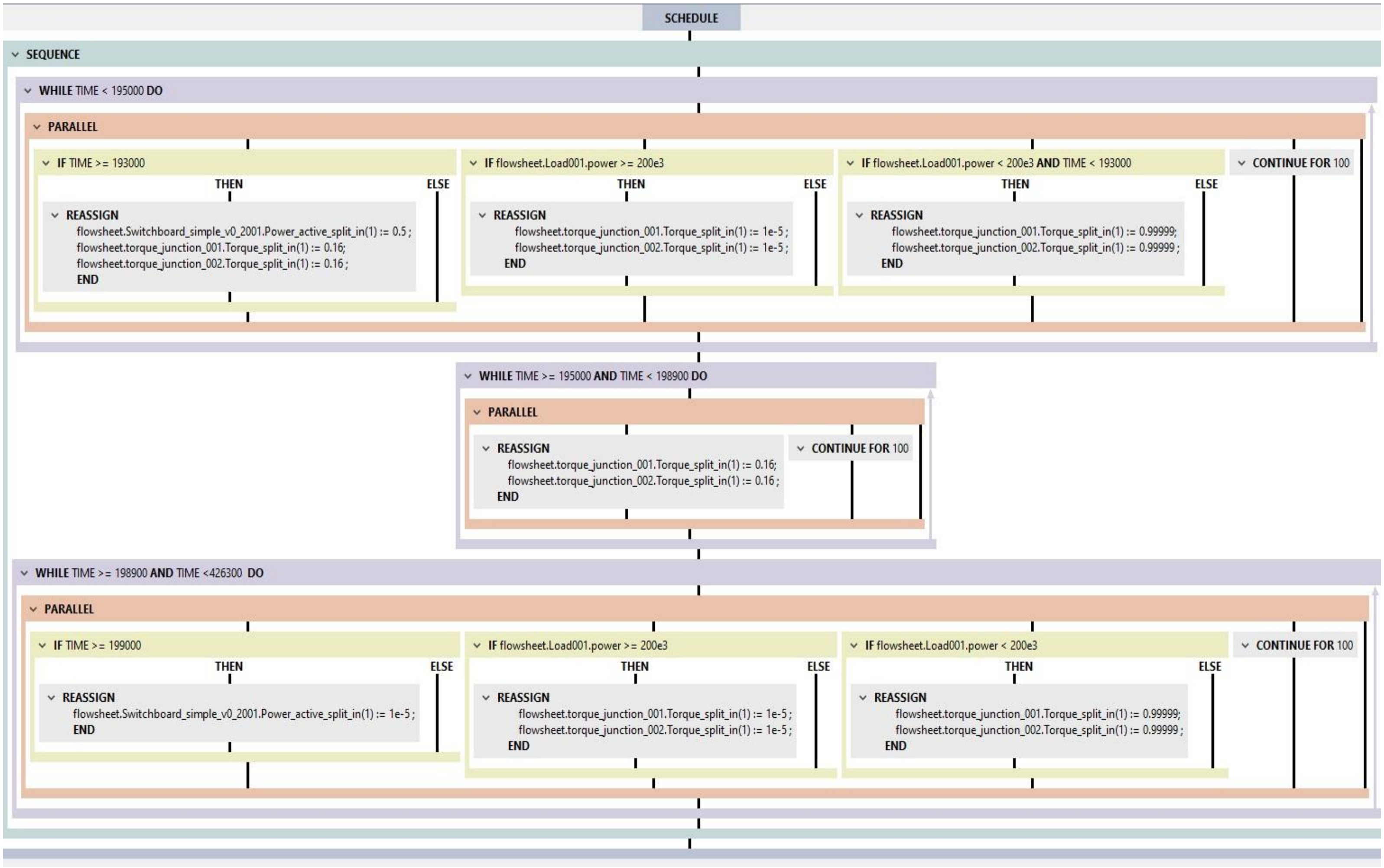
Figure 58. gPROMS Code translating the load management strategy for Configuration 2 (Part 2).

```
WHILE TIME >= 198900 AND TIME <426300  DO
      PARALLEL
          IF TIME >= 199000
            THEN REASSIGN
            flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1) := 1e-5 ;
            END
          END

          IF flowsheet.Load001.power >= 200e3
            THEN REASSIGN
              flowsheet.torque_junction_001.Torque_split_in(1) := 1e-5 ;
              flowsheet.torque_junction_002.Torque_split_in(1) := 1e-5 ;
            END
          END

          IF flowsheet.Load001.power < 200e3
            THEN REASSIGN
              flowsheet.torque_junction_001.Torque_split_in(1) := 0.99999;
              flowsheet.torque_junction_002.Torque_split_in(1) := 0.99999 ;
            END
          END
          CONTINUE FOR 100
      END
    END
END
```

Figure 59. gPROMS Code translating the load management strategy for Configuration 2 (Part 3)



```
SCHEDULE
SEQUENCE
  WHILE TIME < 195000 DO
    PARALLEL
      IF TIME >= 193000
        THEN
          REASSIGN
            flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1) := 0.5 ;
            flowsheet.torque_junction_001.Torque_split_in(1) := 0.16;
            flowsheet.torque_junction_002.Torque_split_in(1) := 0.16 ;
            END
        ELSE
      IF flowsheet.Load001.power >= 200e3
        THEN
          REASSIGN
            flowsheet.torque_junction_001.Torque_split_in(1) := 1e-5 ;
            flowsheet.torque_junction_002.Torque_split_in(1) := 1e-5 ;
          END
        ELSE
      IF flowsheet.Load001.power < 200e3 AND TIME < 193000
        THEN
          REASSIGN
            flowsheet.torque_junction_001.Torque_split_in(1) := 0.99999;
            flowsheet.torque_junction_002.Torque_split_in(1) := 0.99999 ;
          END
        ELSE
      CONTINUE FOR 100
  WHILE TIME >= 195000 AND TIME < 198900 DO
    PARALLEL
      REASSIGN
        flowsheet.torque_junction_001.Torque_split_in(1) := 0.16;
        flowsheet.torque_junction_002.Torque_split_in(1) := 0.16 ;
      END
      CONTINUE FOR 100
  WHILE TIME >= 198900 AND TIME <426300  DO
    PARALLEL
      IF TIME >= 199000
        THEN
          REASSIGN
            flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1) := 1e-5 ;
            END
        ELSE
      IF flowsheet.Load001.power >= 200e3
        THEN
          REASSIGN
            flowsheet.torque_junction_001.Torque_split_in(1) := 1e-5 ;
            flowsheet.torque_junction_002.Torque_split_in(1) := 1e-5 ;
          END
        ELSE
      IF flowsheet.Load001.power < 200e3
        THEN
          REASSIGN
            flowsheet.torque_junction_001.Torque_split_in(1) := 0.99999;
            flowsheet.torque_junction_002.Torque_split_in(1) := 0.99999 ;
          END
        ELSE
      CONTINUE FOR 100
```

Figure 60. Screenshot from schedule section for Configuration 2 process.

- Configuration 3: Hybrid with batteries propulsion.

```
SCHEDULE

PARALLEL
  SEQUENCE
    BMS_Logic_Hyb_Cycl(Flowsheet IS Flowsheet, TimeHorizon IS 426300, TimeInterval_ResetAveraging IS 900, TimeInterval_ResetPowerThreshold IS 1800)
  END
  SEQUENCE
    WHILE TIME < 195000 DO
      PARALLEL
          IF TIME >= 193000
            THEN
            PARALLEL
              REASSIGN
                flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1) := 0.5 ;
                flowsheet.torque_junction_001.Torque_split_in(1) := 0.14;
                flowsheet.torque_junction_002.Torque_split_in(1) := 0.14;
              END
            END
          END
          IF flowsheet.Load001.power >= 200e3
            THEN
            PARALLEL
            SEQUENCE
              SWITCH
                Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.Peak_Shaving;
              END
```

Figure 61. gPROMS Code translating the load management for Configuration 3 (part 1).

```
          REASSIGN
          flowsheet.torque_junction_001.Torque_split_in(1) := 1e-5 ;
          flowsheet.torque_junction_002.Torque_split_in(1) := 1e-5 ;
          END
        END
        END
      END
      IF flowsheet.Load001.power < 200e3 AND TIME < 441000
        THEN
        PARALLEL
        SEQUENCE
          SWITCH
            Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.ON_OFF;
          END
          REASSIGN
          flowsheet.torque_junction_001.Torque_split_in(1) := 0.99999;
          flowsheet.torque_junction_002.Torque_split_in(1) := 0.99999 ;
          END
        END
        END
      END

      CONTINUE FOR 100
  END
END
```

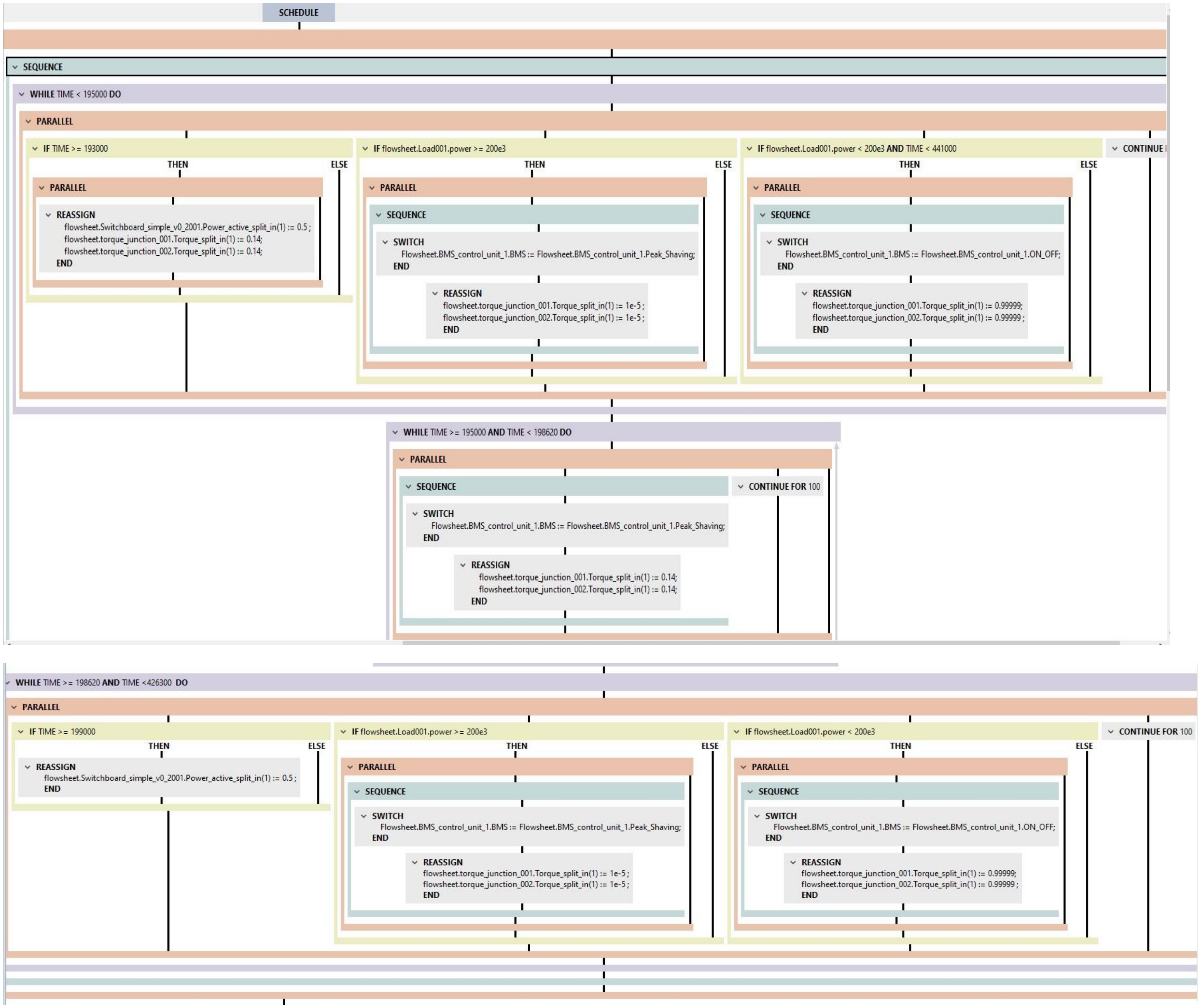
Figure 62. gPROMS Code translating the load management for Configuration 3 (part 2).

```
WHILE TIME >= 195000 AND TIME < 198620 DO
  PARALLEL
  SEQUENCE
    SWITCH
      Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.Peak_Shaving;
    END
    REASSIGN
      flowsheet.torque_junction_001.Torque_split_in(1) := 0.14;
      flowsheet.torque_junction_002.Torque_split_in(1) := 0.14;
    END
 END
    CONTINUE FOR 100
  END
END
WHILE TIME >= 198620 AND TIME <426300  DO
  PARALLEL
      IF TIME >= 199000
        THEN REASSIGN
        flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1) := 0.5 ;
        END
      END
      IF flowsheet.Load001.power >= 200e3
        THEN
        PARALLEL
           SEQUENCE
          SWITCH
            Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.Peak_Shaving;
```

Figure 63. gPROMS Code translating the load management for Configuration 3 (part 3).

```
    REASSIGN
              flowsheet.torque_junction_001.Torque_split_in(1) := 1e-5 ;
              flowsheet.torque_junction_002.Torque_split_in(1) := 1e-5 ;
              END
            END
            END
          END
          IF flowsheet.Load001.power < 200e3
            THEN
            PARALLEL
            SEQUENCE
              SWITCH
                Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.ON_OFF;
              END
              REASSIGN
              flowsheet.torque_junction_001.Torque_split_in(1) := 0.99999;
              flowsheet.torque_junction_002.Torque_split_in(1) := 0.99999 ;
              END
            END
            END
          END
          CONTINUE FOR 100
      END
    END
  END
END
```

Figure 64. gPROMS Code translating the load management for Configuration 3 (part 4).



```
SEQUENCE
  WHILE TIME < 195000 DO
    PARALLEL
      IF TIME >= 193000
        THEN
          PARALLEL
            REASSIGN
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1) := 0.5 ;
              flowsheet.torque_junction_001.Torque_split_in(1) := 0.14;
              flowsheet.torque_junction_002.Torque_split_in(1) := 0.14;
            END
        ELSE
      IF flowsheet.Load001.power >= 200e3
        THEN
          PARALLEL
            SEQUENCE
              SWITCH
                Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.Peak_Shaving;
              END
              REASSIGN
                flowsheet.torque_junction_001.Torque_split_in(1) := 1e-5 ;
                flowsheet.torque_junction_002.Torque_split_in(1) := 1e-5 ;
              END
        ELSE
      IF flowsheet.Load001.power < 200e3 AND TIME < 441000
        THEN
          PARALLEL
            SEQUENCE
              SWITCH
                Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.ON_OFF;
              END
              REASSIGN
                flowsheet.torque_junction_001.Torque_split_in(1) := 0.99999;
                flowsheet.torque_junction_002.Torque_split_in(1) := 0.99999 ;
              END
        ELSE
      CONTINUE
  WHILE TIME >= 195000 AND TIME < 198620 DO
    PARALLEL
      SEQUENCE
        SWITCH
          Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.Peak_Shaving;
        END
        REASSIGN
          flowsheet.torque_junction_001.Torque_split_in(1) := 0.14;
          flowsheet.torque_junction_002.Torque_split_in(1) := 0.14;
        END
      CONTINUE FOR 100
  WHILE TIME >= 198620 AND TIME <426300  DO
    PARALLEL
      IF TIME >= 199000
        THEN
          REASSIGN
            flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1) := 0.5 ;
          END
        ELSE
      IF flowsheet.Load001.power >= 200e3
        THEN
          PARALLEL
            SEQUENCE
              SWITCH
                Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.Peak_Shaving;
              END
              REASSIGN
                flowsheet.torque_junction_001.Torque_split_in(1) := 1e-5 ;
                flowsheet.torque_junction_002.Torque_split_in(1) := 1e-5 ;
              END
        ELSE
      IF flowsheet.Load001.power < 200e3
        THEN
          PARALLEL
            SEQUENCE
              SWITCH
                Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.ON_OFF;
              END
              REASSIGN
                flowsheet.torque_junction_001.Torque_split_in(1) := 0.99999;
                flowsheet.torque_junction_002.Torque_split_in(1) := 0.99999 ;
              END
        ELSE
      CONTINUE FOR 100
```

Figure 65. Screenshot from schedule section for Configuration 3 process.

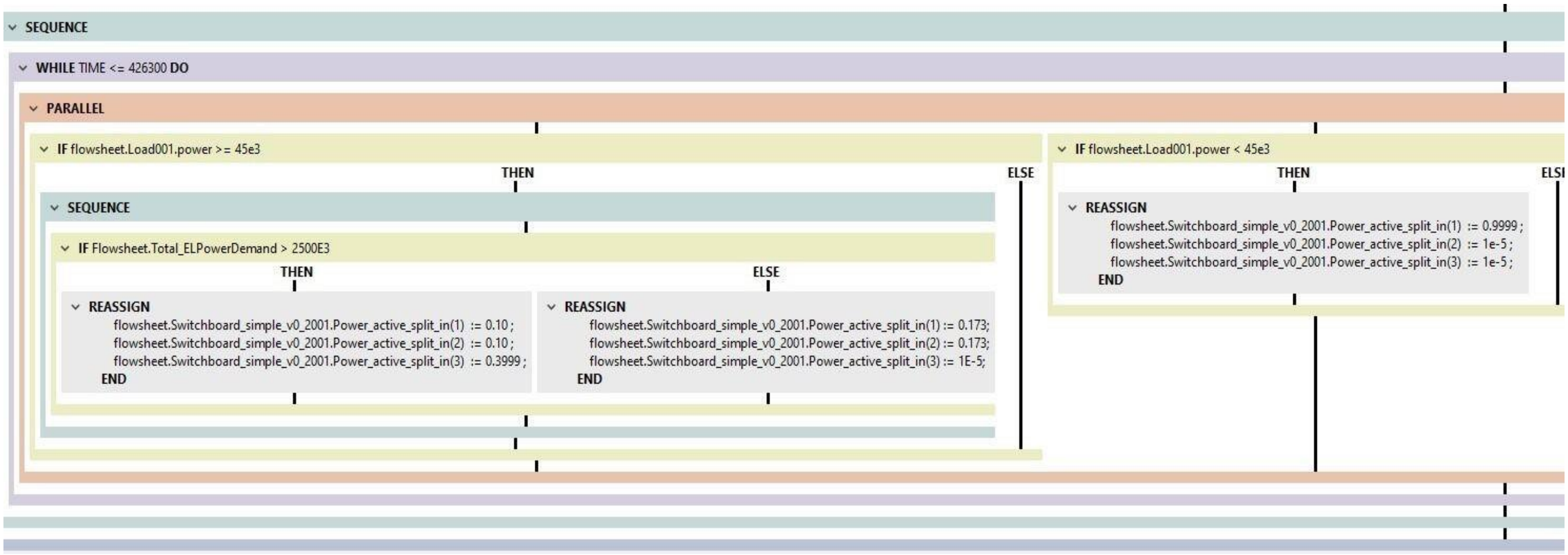
- Configuration 4: Diesel-Electric propulsion.

```
SCHEDULE
  SEQUENCE
    WHILE TIME <= 426300 DO
      PARALLEL
          IF flowsheet.Load001.power >= 45e3
            THEN
             SEQUENCE
               IF Flowsheet.Total_ELPowerDemand > 2500E3 THEN
                 REASSIGN
                  flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1)  := 0.10 ;
                  flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(2)  := 0.10 ;
                  flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(3)  := 0.3999 ;
                END
              ELSE
                REASSIGN
                  flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1)  := 0.173 ;
                  flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(2)  := 0.173 ;
                  flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(3)  := 1E-5 ;
                END
              END
            END
          END
```

Figure 66. gPROMS Code translating the load management strategy for Configuration 4 (part 1).

```
            IF flowsheet.Load001.power < 45e3
              THEN REASSIGN
                flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1)  := 0.9999 ;
                flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(2)  := 1e-5 ;
                flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(3)  := 1e-5 ;
              END
            END
            CONTINUE FOR 100
        END
      END
END
```

Figure 67. gPROMS Code translating the load management for Configuration 4 (part 2).



```
SEQUENCE
 WHILE TIME <= 426300 DO
  PARALLEL
   IF flowsheet.Load001.power >= 45e3
    THEN
     SEQUENCE
      IF Flowsheet.Total_ELPowerDemand > 2500E3
       THEN
        REASSIGN
          flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1)  := 0.10 ;
          flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(2)  := 0.10 ;
          flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(3)  := 0.3999 ;
        END
       ELSE
        REASSIGN
          flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1) := 0.173;
          flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(2) := 0.173;
          flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(3) := 1E-5;
        END
    ELSE
   IF flowsheet.Load001.power < 45e3
    THEN
     REASSIGN
       flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1)  := 0.9999 ;
       flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(2)  := 1e-5 ;
       flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(3)  := 1e-5 ;
     END
    ELSI
```

Figure 68. Screenshot from schedule section for Configuration 4 process.

- Configuration 5: Diesel-Electric with batteries propulsion.

```
SCHEDULE
PARALLEL
  SEQUENCE
    BMS_Logic(Flowsheet IS Flowsheet, TimeHorizon IS 426300, TimeInterval_ResetAveraging IS 300, TimeInterval_ResetPowerThreshold IS 300)
  END
  SEQUENCE
    WHILE TIME <= 426300 DO
      PARALLEL
          IF flowsheet.Load001.power >= 45e3
            THEN
            SEQUENCE
              SWITCH
                Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.Peak_Shaving ;
              END
              IF Flowsheet.Total_ELPowerDemand > 2500E3 THEN
                REASSIGN
                      flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1)  := 0.10 ;
                      flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(2)  := 0.10 ;
                      flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(3)  := 0.3999 ;
                            END
              ELSE
                REASSIGN
                      flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1) := 0.173;
                      flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(2) := 0.173;
                      flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(3) := 1E-5;
                END
```

Figure 69. gPROMS Code translating the load management for Configuration 5 (part 1).

```
               END
            END
          END
          IF flowsheet.Load001.power < 45e3
            THEN
            PARALLEL
            SEQUENCE
              SWITCH
                Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.ON_OFF ;
              END
            REASSIGN
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1) := 1e-5;
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(2)  := 1e-5 ;
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(3) := 1e-5;
            END
            END
            END
          END
          CONTINUE FOR 100
      END
    END
END
END
```

Figure 70. gPROMS Code translating the load management for Configuration 5 (part 2).

```
SEQUENCE
  WHILE TIME <= 426300 DO
    PARALLEL
      IF flowsheet.Load001.power >= 45e3
      THEN
        SEQUENCE
          SWITCH
            Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.Peak_Shaving ;
          END
          IF Flowsheet.Total_ELPowerDemand > 2500E3
          THEN
            REASSIGN
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1)  := 0.10 ;
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(2)  := 0.10 ;
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(3)  := 0.3999 ;
            END
          ELSE
            REASSIGN
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1) := 0.173;
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(2) := 0.173;
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(3) := 1E-5;
            END
      ELSE
      IF flowsheet.Load001.power < 45e3
      THEN
        PARALLEL
          SEQUENCE
            SWITCH
              Flowsheet.BMS_control_unit_1.BMS := Flowsheet.BMS_control_unit_1.ON_OFF ;
            END
            REASSIGN
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(1) := 1.0E-5;
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(2)  := 1e-5 ;
              flowsheet.Switchboard_simple_v0_2001.Power_active_split_in(3) := 1.0E-5;
            END
      ELSE
      CONTINUE FOR 100
```

Figure 71. Screenshot from schedule section for Configuration 5 process.

7.5. Key metrics and performance indicators

In the technical evaluation of mega-yacht propulsion systems, the focus on specific key performance indicators (KPIs) and operational metrics is of paramount importance. This detailed assessment depends on the careful analysis of a spectrum of engine metrics, each offering critical insights into various aspects of the propulsion system's performance. The metrics under consideration are not only indicative of the system's current operational state but also provide a comprehensive understanding of its efficiency, fuel economy, and environmental impact. This section aims to dissect and interpret these metrics, as displayed in the accompanying screenshot of the data table [Figure 72].

The metrics presented are as follows:

- **Engine Load**: This metric indicates the percentage of the engine's full capacity currently being utilized. It's a crucial indicator of how hard the engine is working relative to its maximum potential.

- **Power Output (Watt)**: This represents the actual power being generated by the engine. Measured in Watts, it directly reflects the engine's capacity to perform work at any given moment.

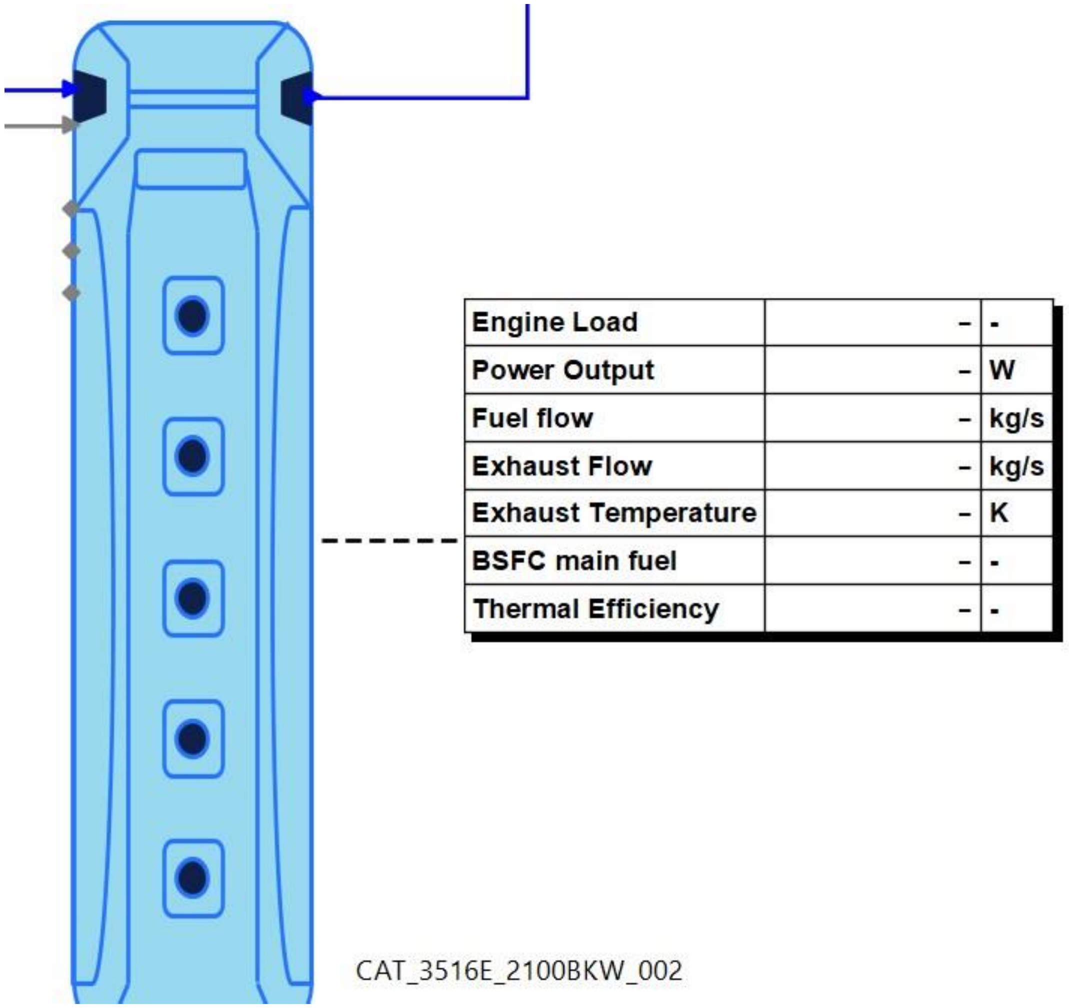
- **Fuel Flow (kg/s)**: The rate at which fuel is consumed by the engine, measured in kilograms per second. This metric is fundamental for understanding the fuel economy of the system.

- **Exhaust Flow (kg/s)**: This parameter measures the mass flow rate of exhaust gases, providing insights into the combustion process's efficiency and the engine's environmental impact.

- **Exhaust Temperature (K)**: The temperature of the exhaust gases, measured in Kelvin, which is indicative of the heat recovery potential and overall combustion efficiency.

- **BSFC Main Fuel (Brake Specific Fuel Consumption)**: This metric evaluates the fuel efficiency of the engine in terms of the fuel consumption per unit of power output. Lower values indicate higher fuel efficiency.

- **Thermal Efficiency**: A critical measure of how effectively the engine converts the energy stored in fuel into mechanical work. Higher thermal efficiency implies a more efficient engine with less wasted energy.



Engine Load	-	-
Power Output	-	W
Fuel flow	-	kg/s
Exhaust Flow	-	kg/s
Exhaust Temperature	-	K
BSFC main fuel	-	-
Thermal Efficiency	-	-

Figure 72. Key performance indicators for four-stroke engines in gPROMS interface.

The tabular presentation of these metrics offers a snapshot of the propulsion system's operational health in real-time, providing a structured overview of the system's performance. Moreover, these metrics serve as a foundation for graphical analyses, facilitating the visualization of trends and patterns in system behavior across different operational scenarios.

In our analysis, graphical representations provide insights into the performance of key metrics over various operational scenarios. These graphs, supplementing the data tables, enable a dynamic visualization of system efficiency under simulated conditions.

Key graphs to be presented include:

- **Overall Thermal Efficiency**: This graph plots the system's overall thermal efficiency, providing a visual representation of fuel energy conversion into useful work. The efficiency equation, to be detailed, encompasses factors like fuel consumption and power output.

$$Thermal\ Eff = \frac{Total\ Power\ Produced}{Total\ Heat\ Input}$$

Equation 5. System's overall thermal efficiency.

Where,

- Total Heat Input is equal to the total energy provided to the system from the fuel consumed
- Total Power Produced is the total output energy that the system managed to convert

- **Thermal Efficiency of Main Engines and Generator Sets**: This graph compares the thermal efficiencies of both the main engines and generator sets, illustrating the performance contributions of each component within the propulsion system.

- **Total Fuel Consumption**: This graph presents the total fuel consumed by the whole propulsion configuration during the time period examined.

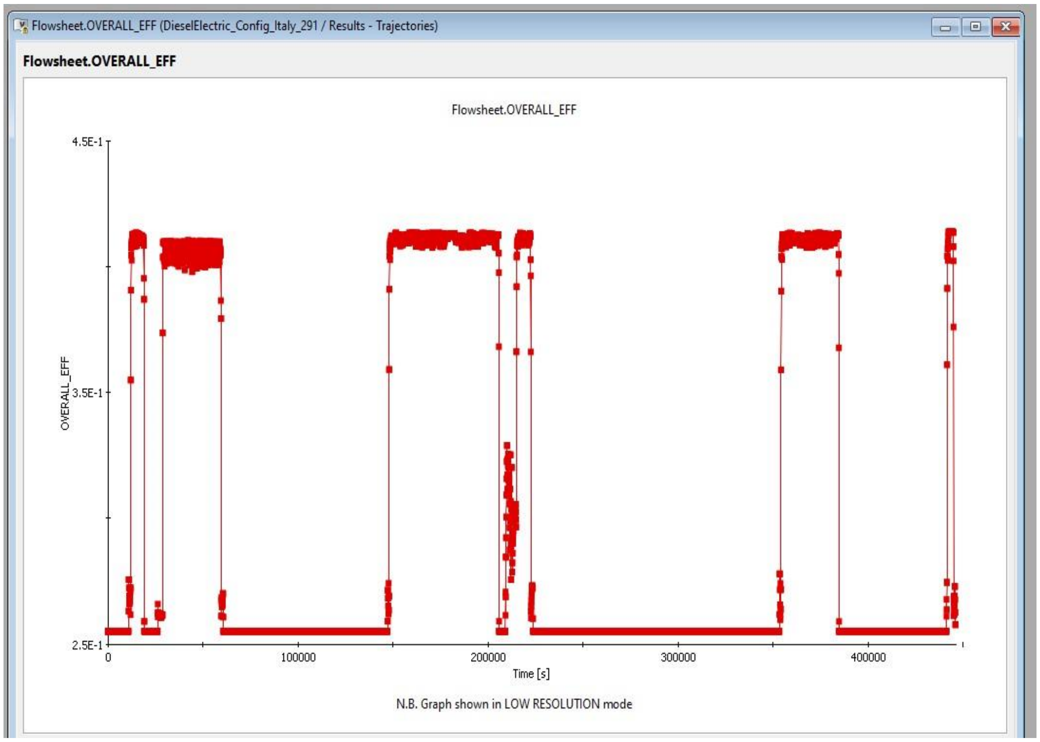


Figure 73. Example of a graphical representation of the system's overall thermal efficiency in GPROMS interface.

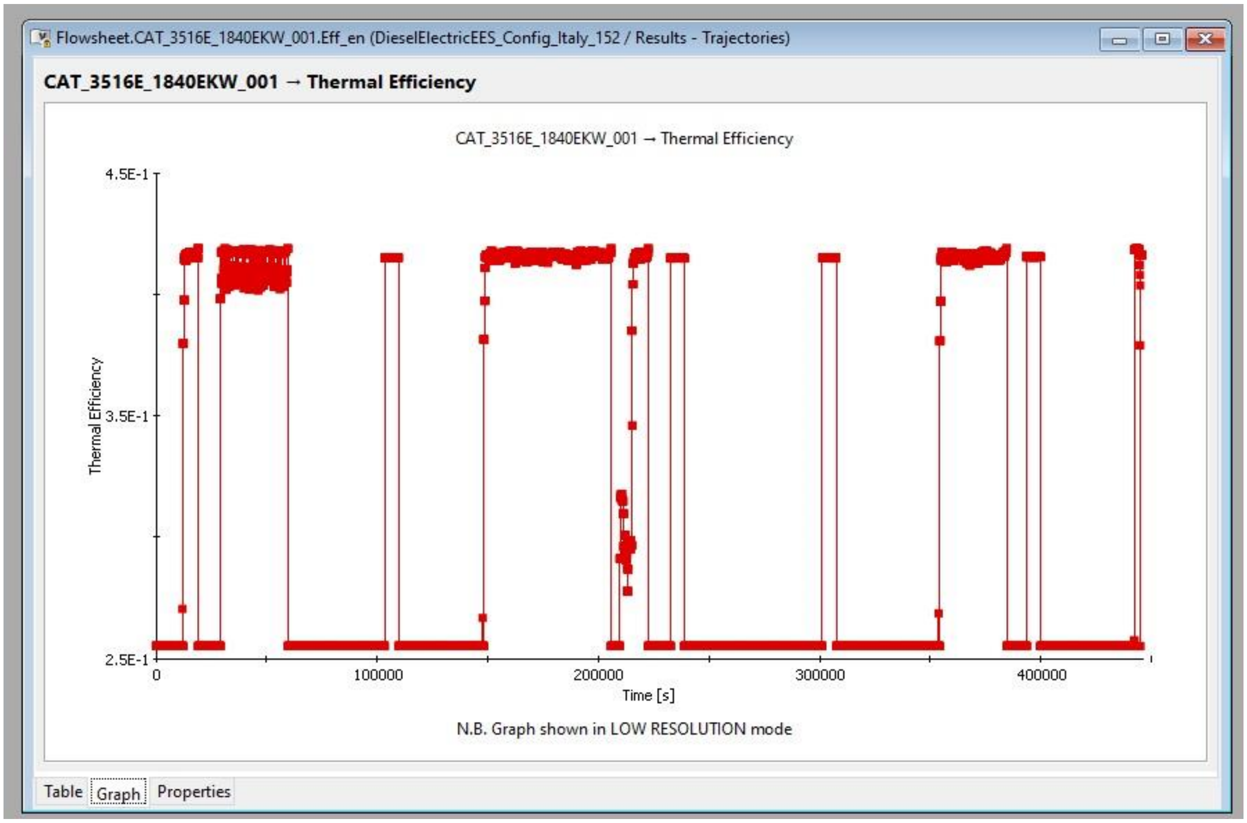


Figure 74. Example of a graphical representation of main engines' thermal efficiency in GPROMS interface.

These graphical analyses transform complex data into comprehensible trends, offering a deeper understanding of the propulsion system's performance. They play a crucial role in ensuring that design and operational decisions are informed by a comprehensive, data-driven perspective.

8. Simulation results

This chapter delves into the analytical evaluation of simulation outcomes, derived from the systematic assessment of the propulsion configurations examined in this thesis, using the SIEMENS gPROMS Model Builder. The results encompass a range of scenarios, meticulously examining the operational efficiency, fuel consumption patterns, and environmental impact under varying conditions. The analysis is grounded in a data-driven approach, utilizing advanced computational techniques to extract meaningful insights. These insights are critical in assessing the feasibility, effectiveness, and sustainability of different propulsion configurations, ultimately guiding the optimization of the mega-yacht's operation in alignment with energy, economic, and environmental objectives.

8.1. Simulations campaign.

This section presents the results of the simulations conducted to evaluate the propulsion configurations in mega-yachts, offering a detailed insight into their performance outcomes.

Our focus will be on presenting key results that include the thermal efficiency of the main engines and generator sets, the overall thermal efficiency of the system, total fuel consumption, and a breakdown of the system's thermal efficiency across different operational modes.

8.1.1. Results for Scenario 1 (Cyclades).

This subsection details the results from Scenario 1 of our simulation series, providing an analysis of the specific outcomes and key findings for all different propulsion configurations examined.

8.1.1.1. Scenario 1: Configuration 1 - Mechanical.

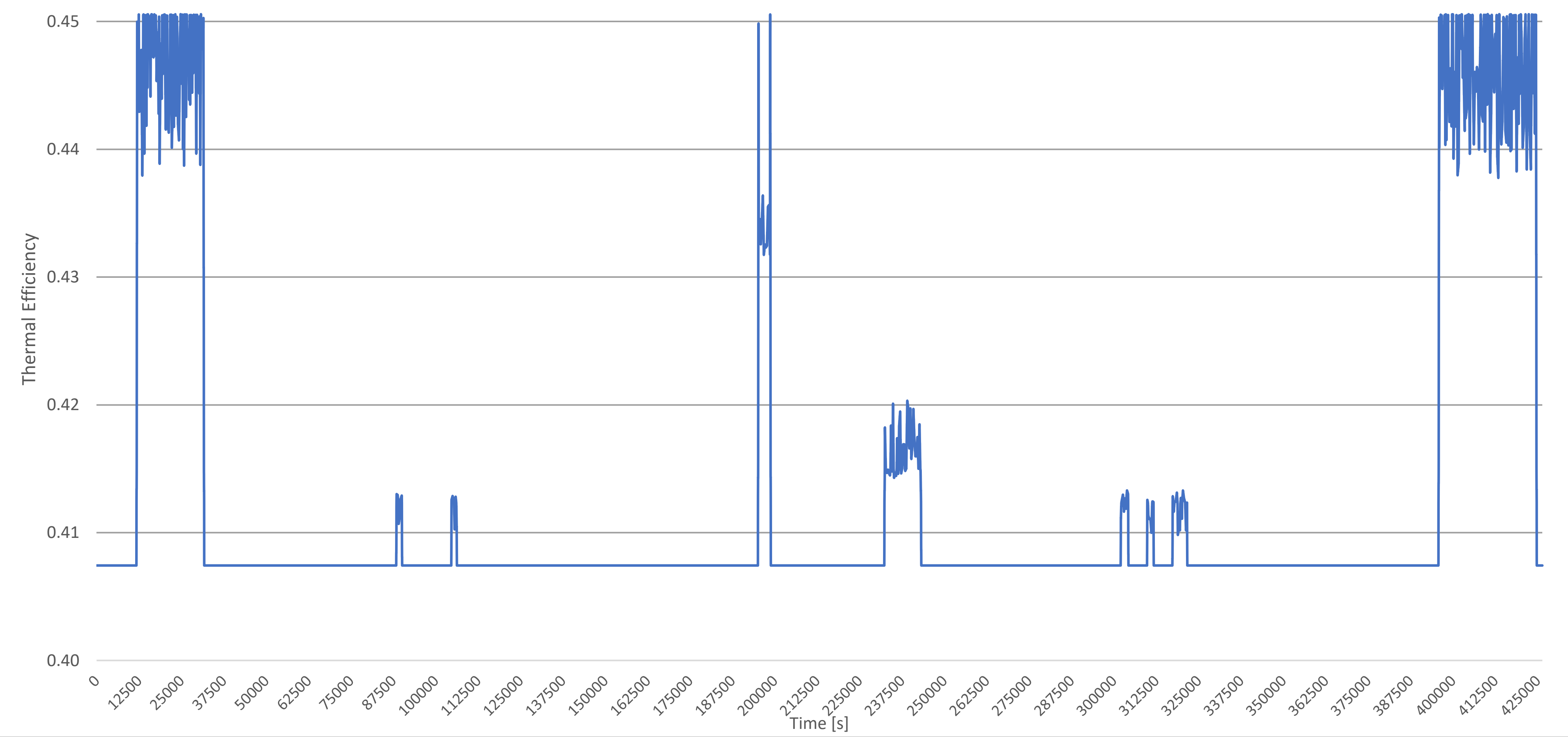


Figure 75. Thermal efficiency of the main engines of Configuration 1/Scenario 1.

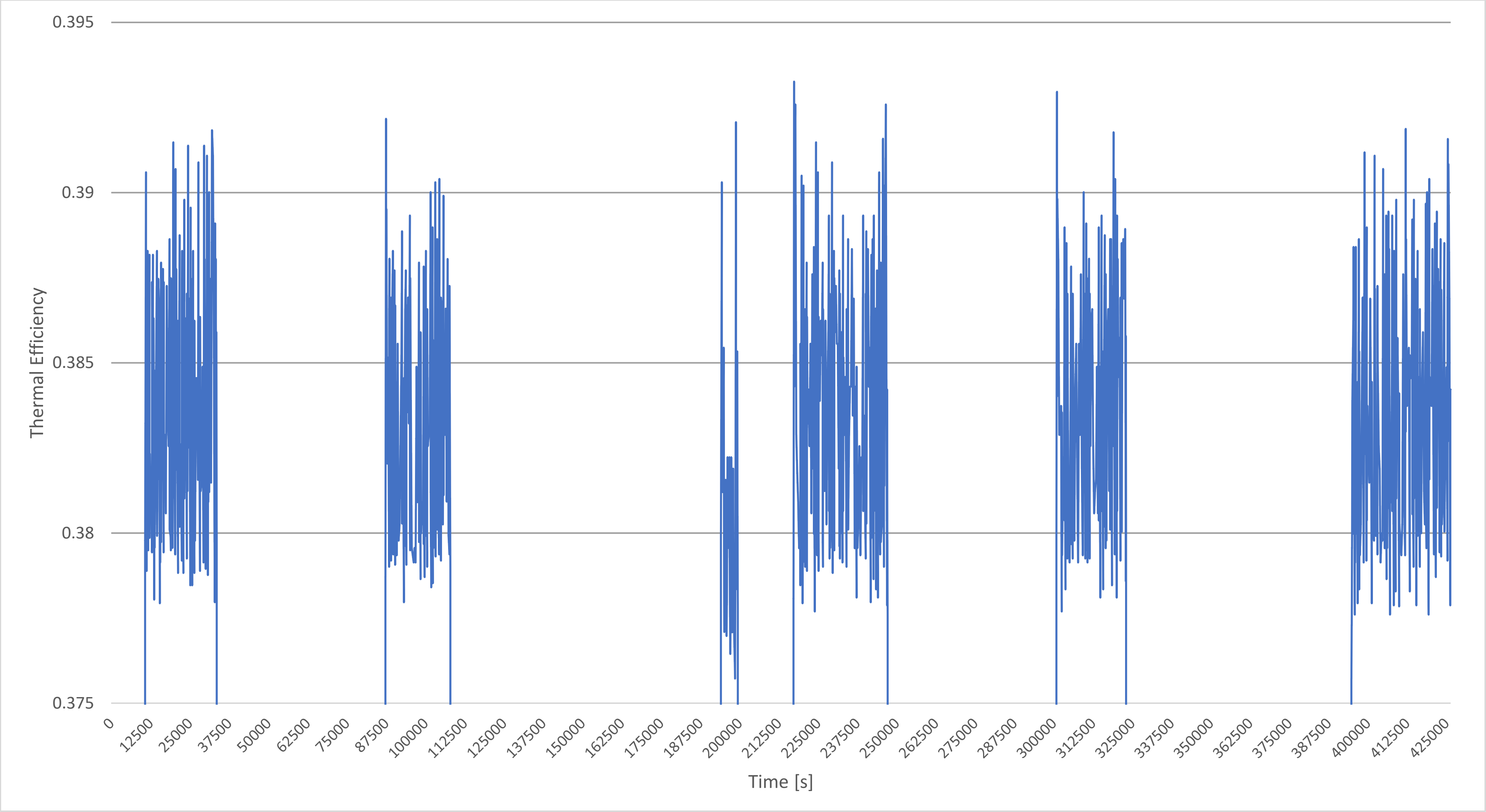


Figure 76. Thermal efficiency of the generator set no. 1 of Configuration 1/Scenario 1.

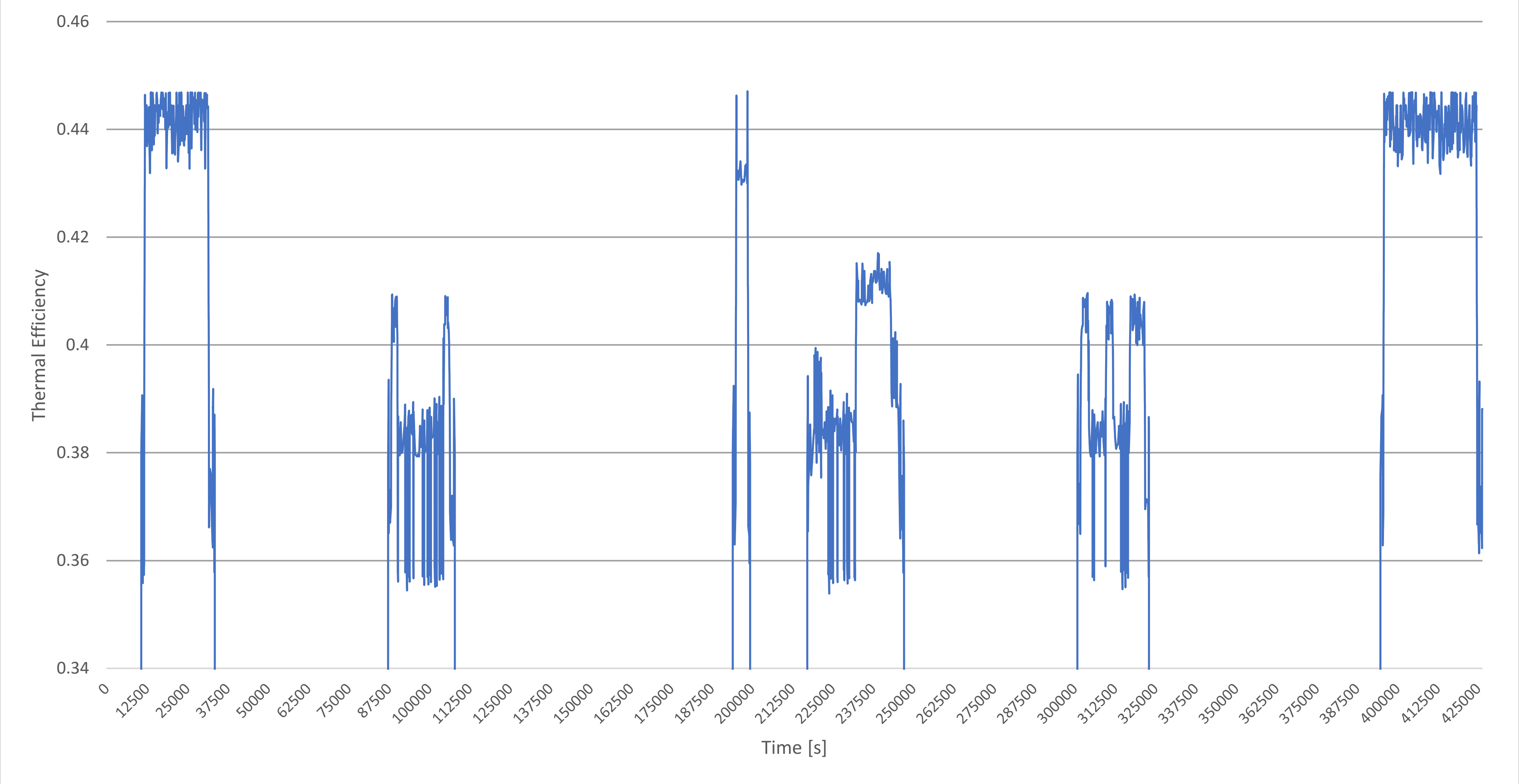


Figure 77. Overall thermal efficiency of Configuration 1/Scenario 1.

- Total fuel consumed

Fuel Consumption = 12.8245 tons

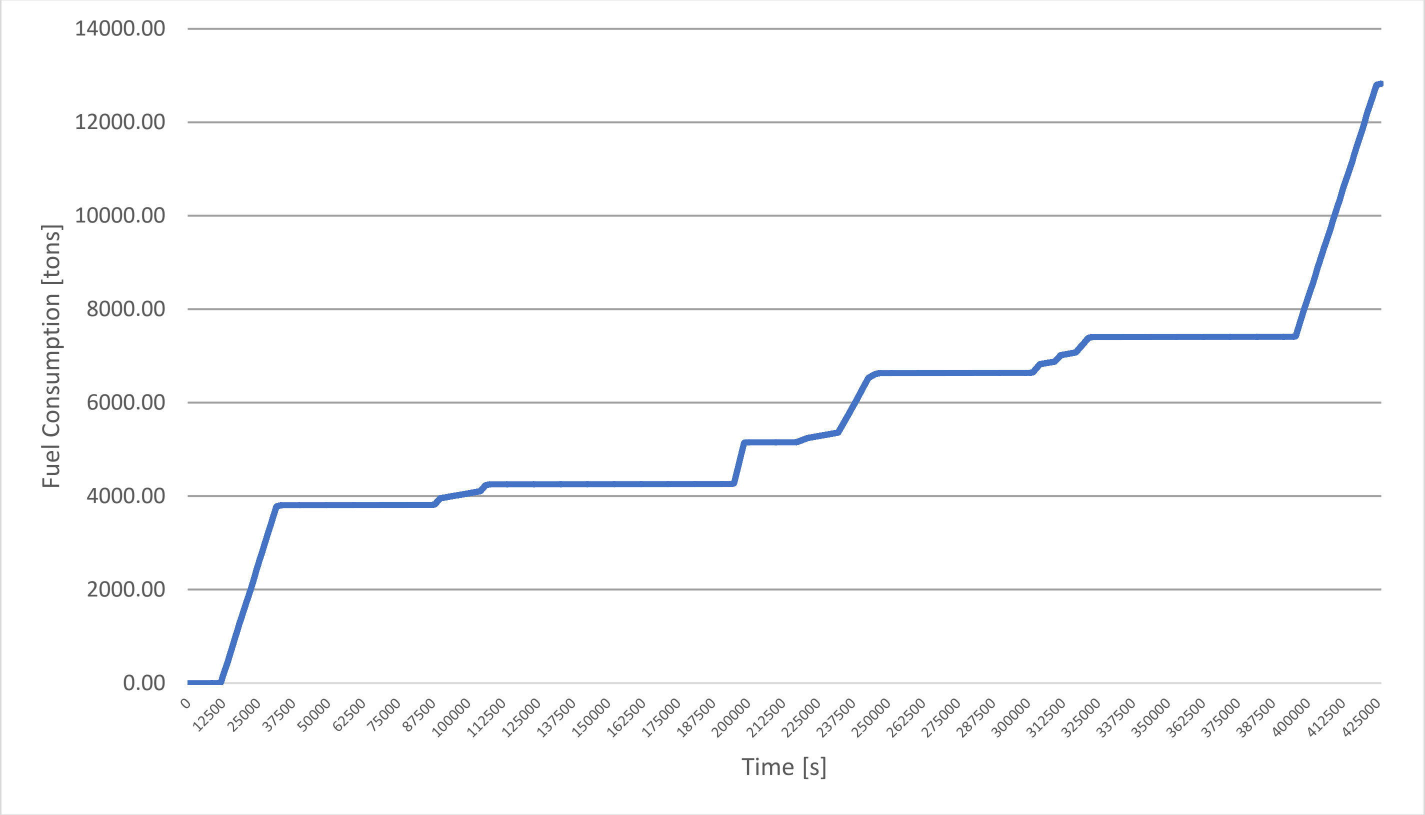


Figure 78. Fuel Consumption for Configuration 1/Scenario 1.

- CO_2 Emissions

Evaluating CO2 production is essential for understanding the environmental impact of propulsion configurations in mega-yachts. This analysis is pivotal in addressing the growing environmental concerns and regulatory demands facing the maritime industry. By quantifying the carbon emissions, stakeholders can make informed decisions to reduce environmental footprints, aligning operational practices with sustainability goals.

The methodology for calculating the CO2 production from the combustion of Diesel Oil, as specified by ISO 8217 Grades, involves the use of the carbon content factor (Cf), which is the ratio of tons of CO2 produced per ton of fuel consumed. For Diesel Oil, this factor is established at 3.206 [20].

$$\text{Total CO2 Production (tons)} = \text{Fuel Consumption (tons)} \times \text{Cf}$$

Equation 6. CO2 production per ton of fuel

CO_2 Produced = 41.115 tons

8.1.1.2. Scenario 1: Configuration 2 - Hybrid.

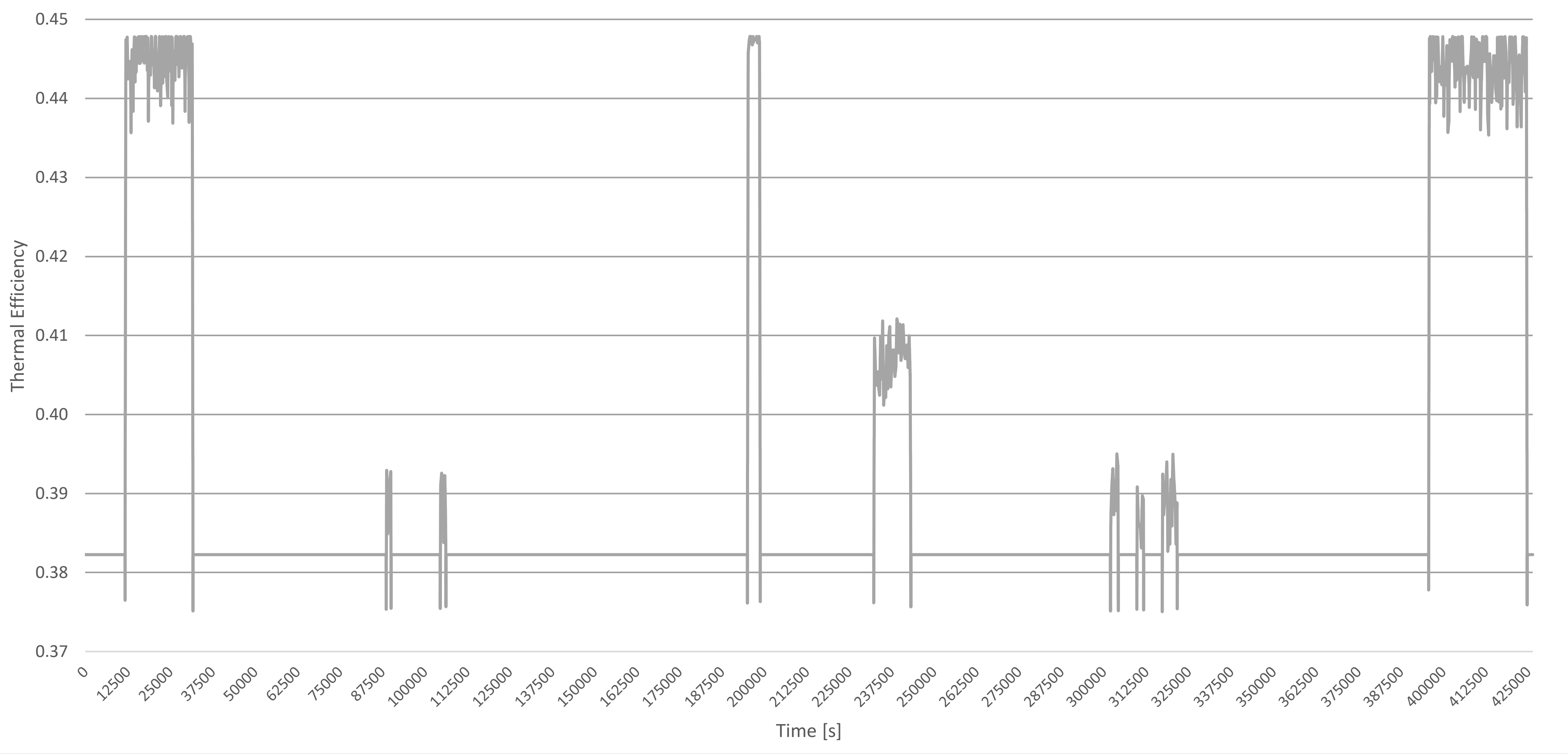


Figure 79. Thermal efficiency of the main engines of Configuration 2/Scenario 1.

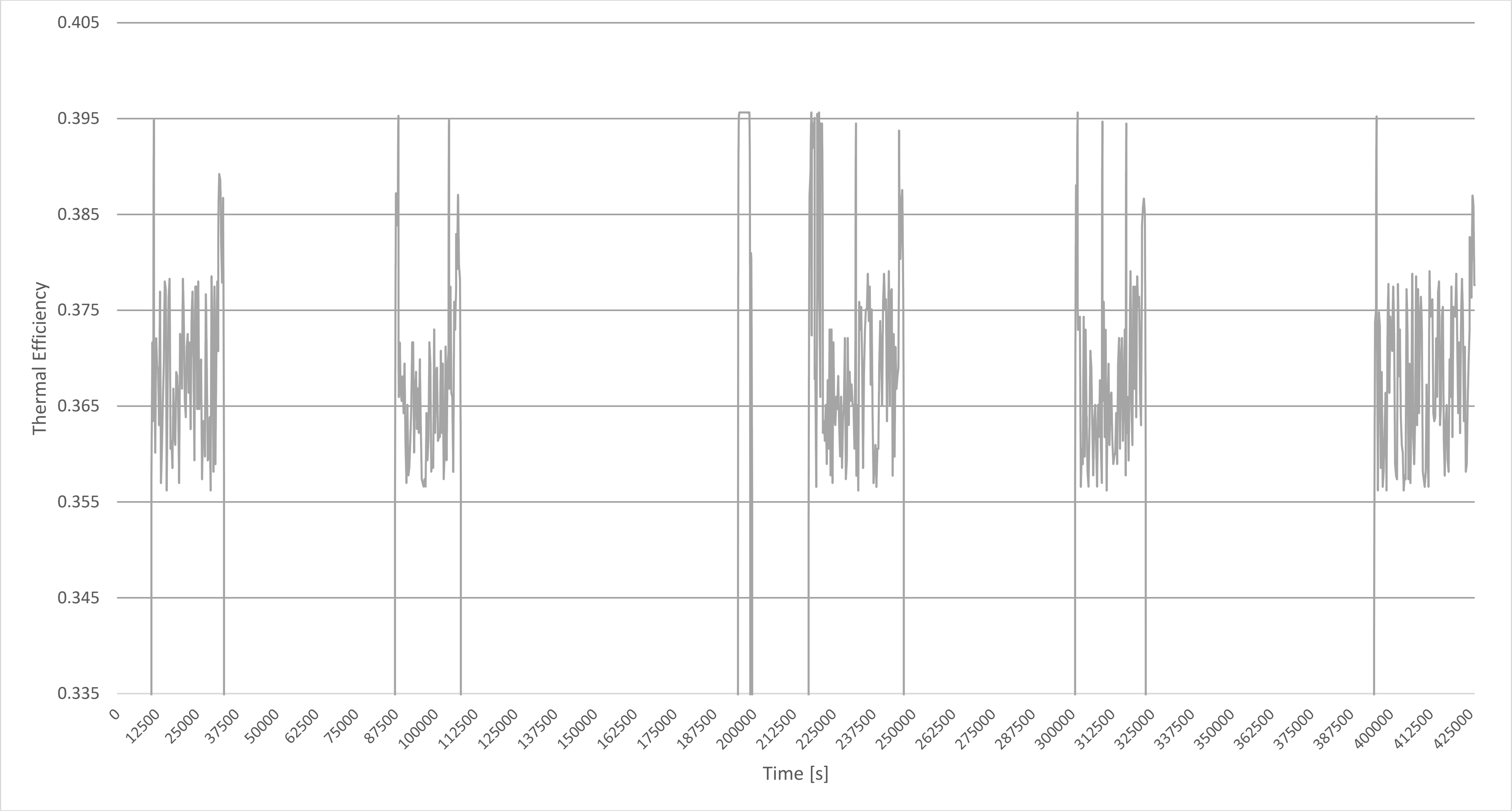


Figure 80. Thermal efficiency of the generator set no. 1 of Configuration 2/Scenario 1.

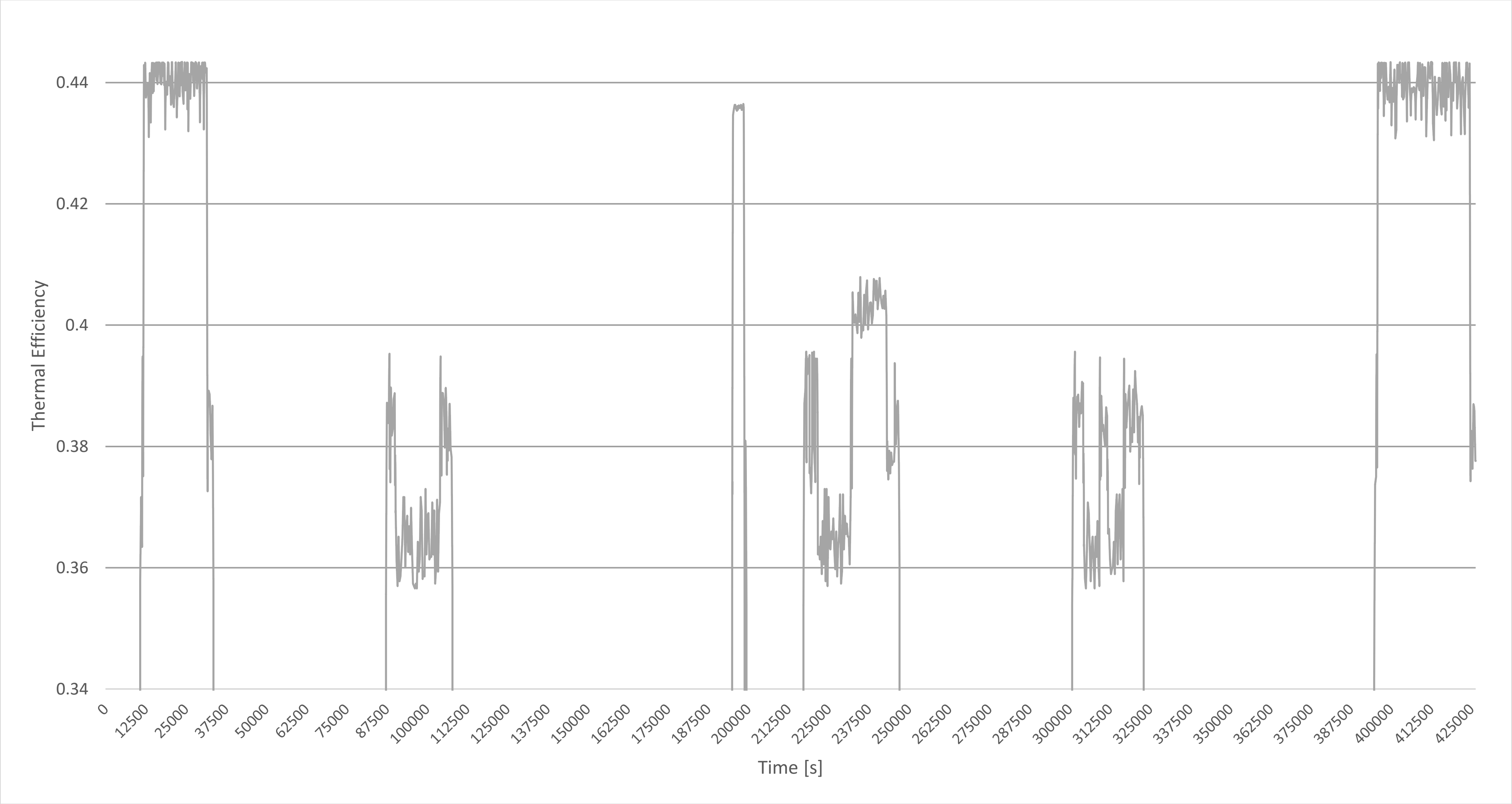


Figure 81. Overall thermal efficiency of Configuration 2/Scenario 1.

- Total fuel consumed

Fuel Consumption = 12.9574 tons

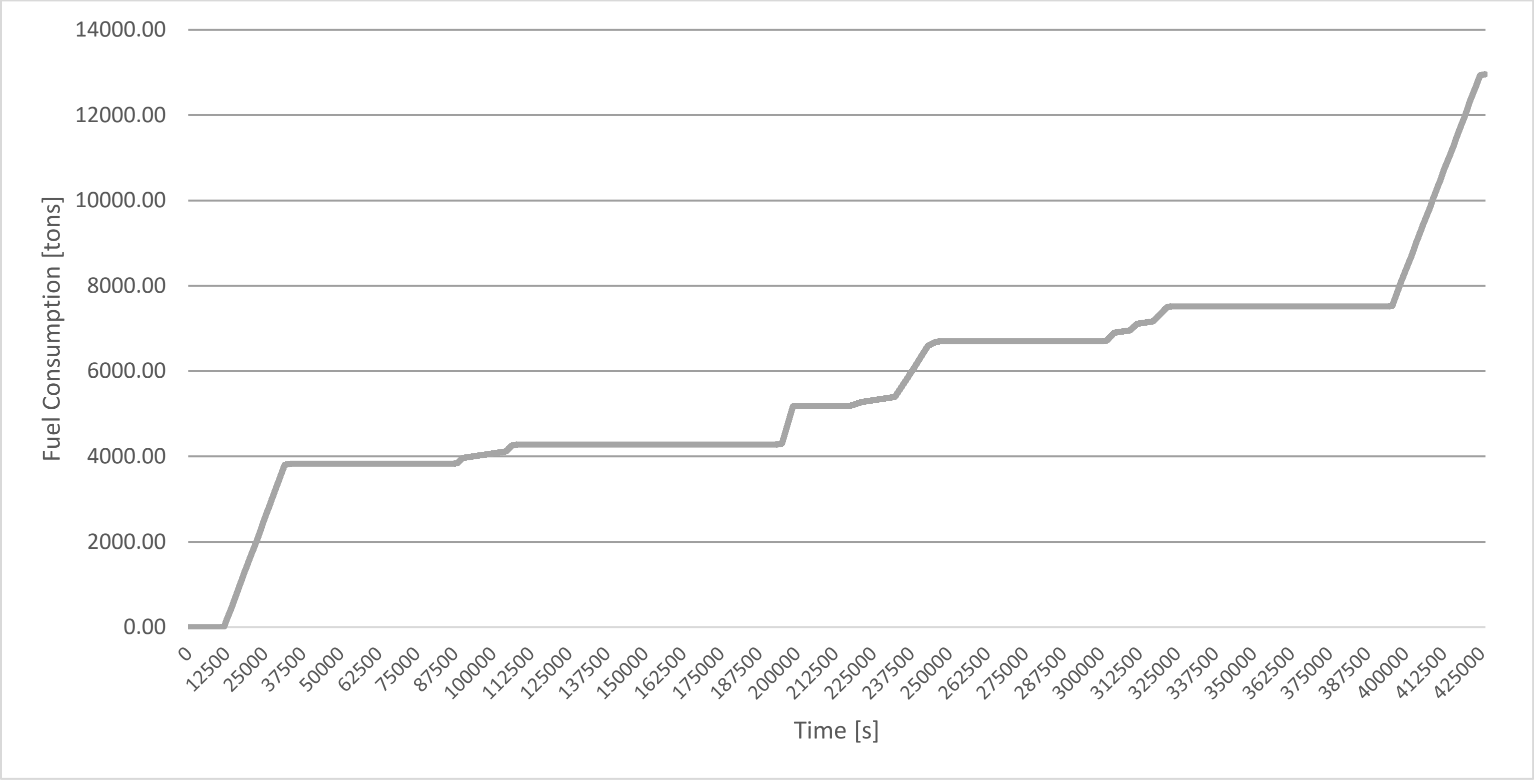


Figure 82. Fuel Consumption for Configuration 2/Scenario 1.

- CO_2 Emissions

CO_2 Produced = 41.542 tons

8.1.1.3. Scenario 1: Configuration 3 – Hybrid with batteries.

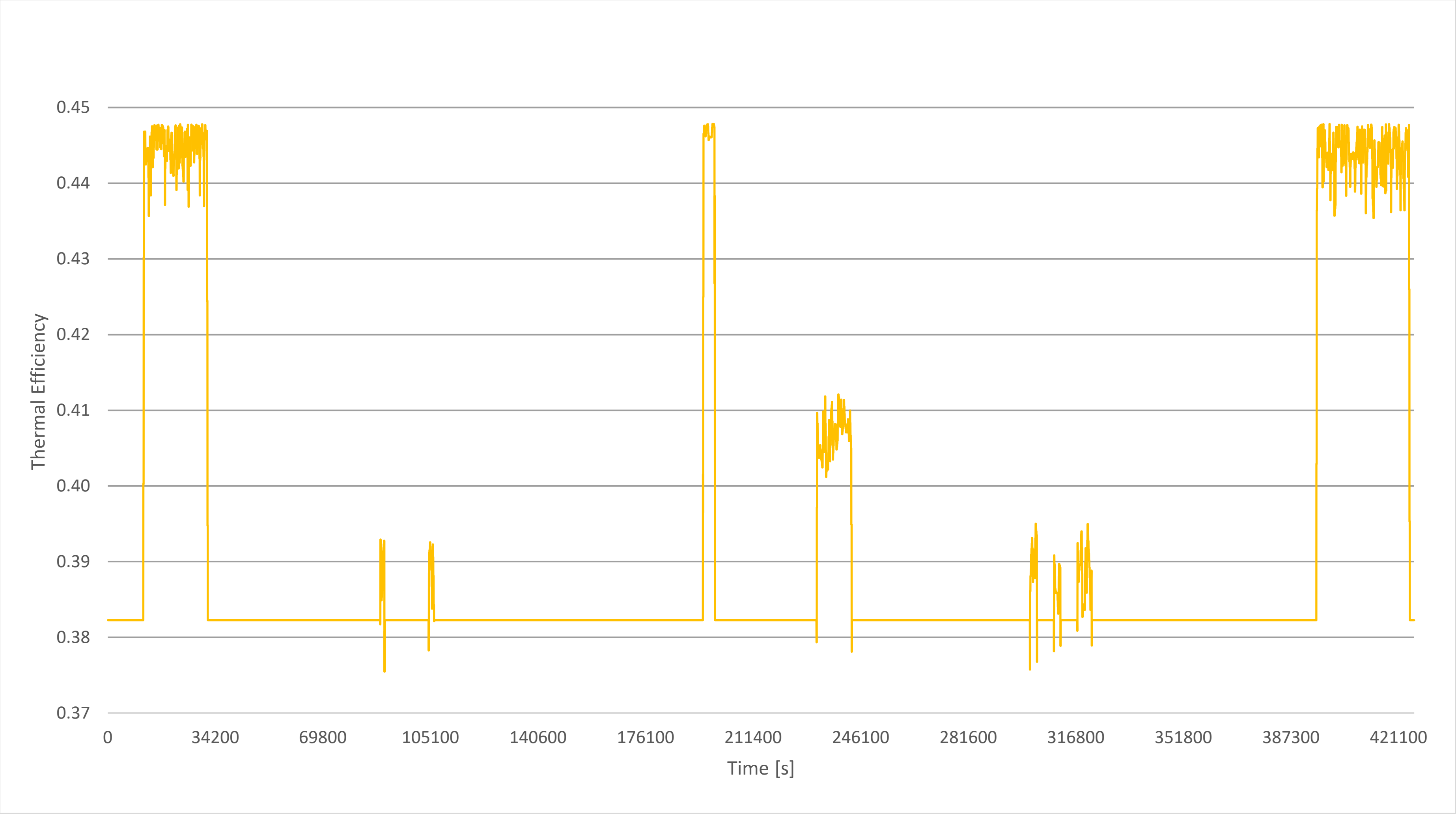


Figure 83. Thermal efficiency of the main engines of Configuration 3/Scenario 1.

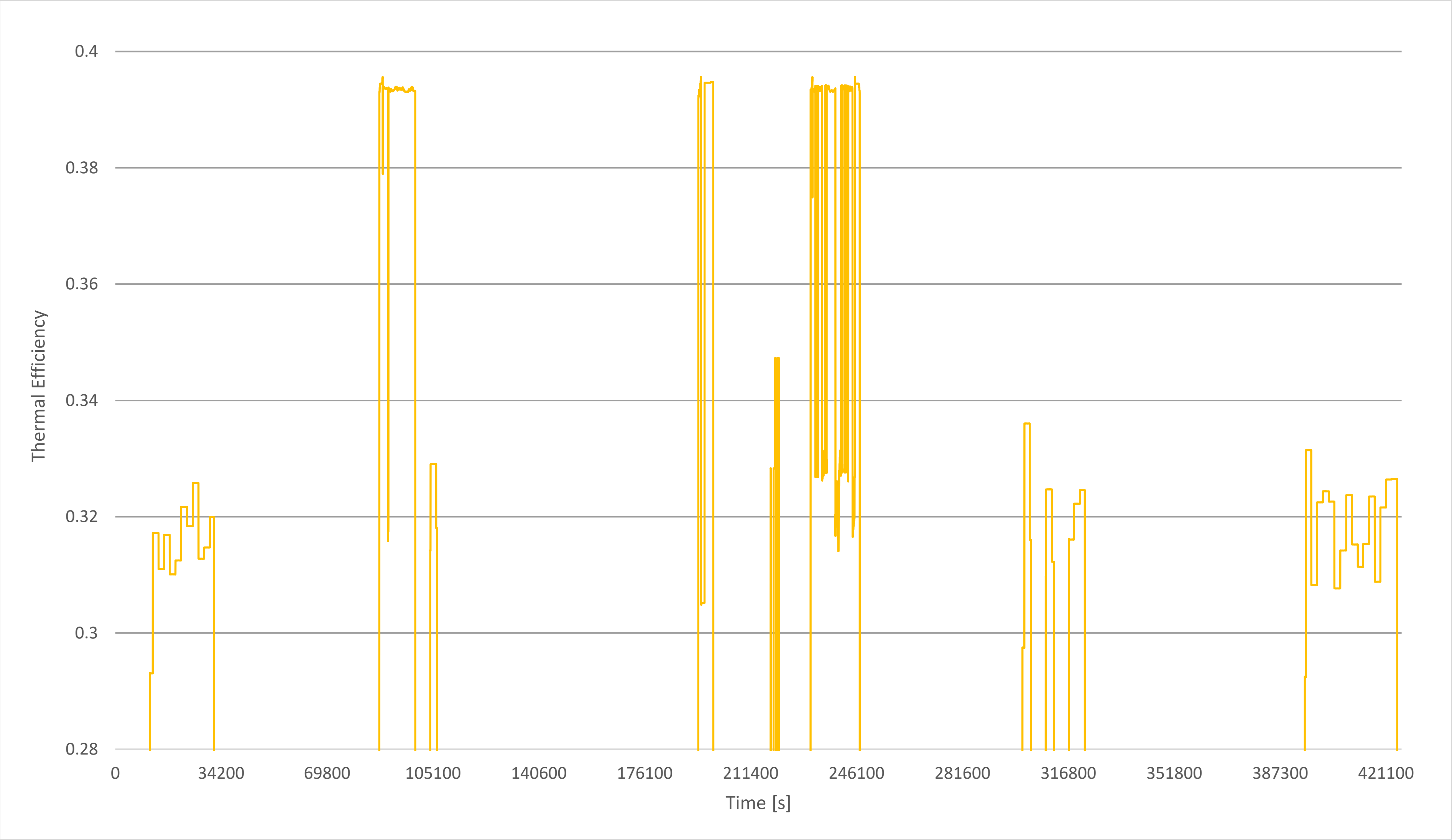


Figure 84. Thermal efficiency of the primary generator set of Configuration 3/Scenario 1.

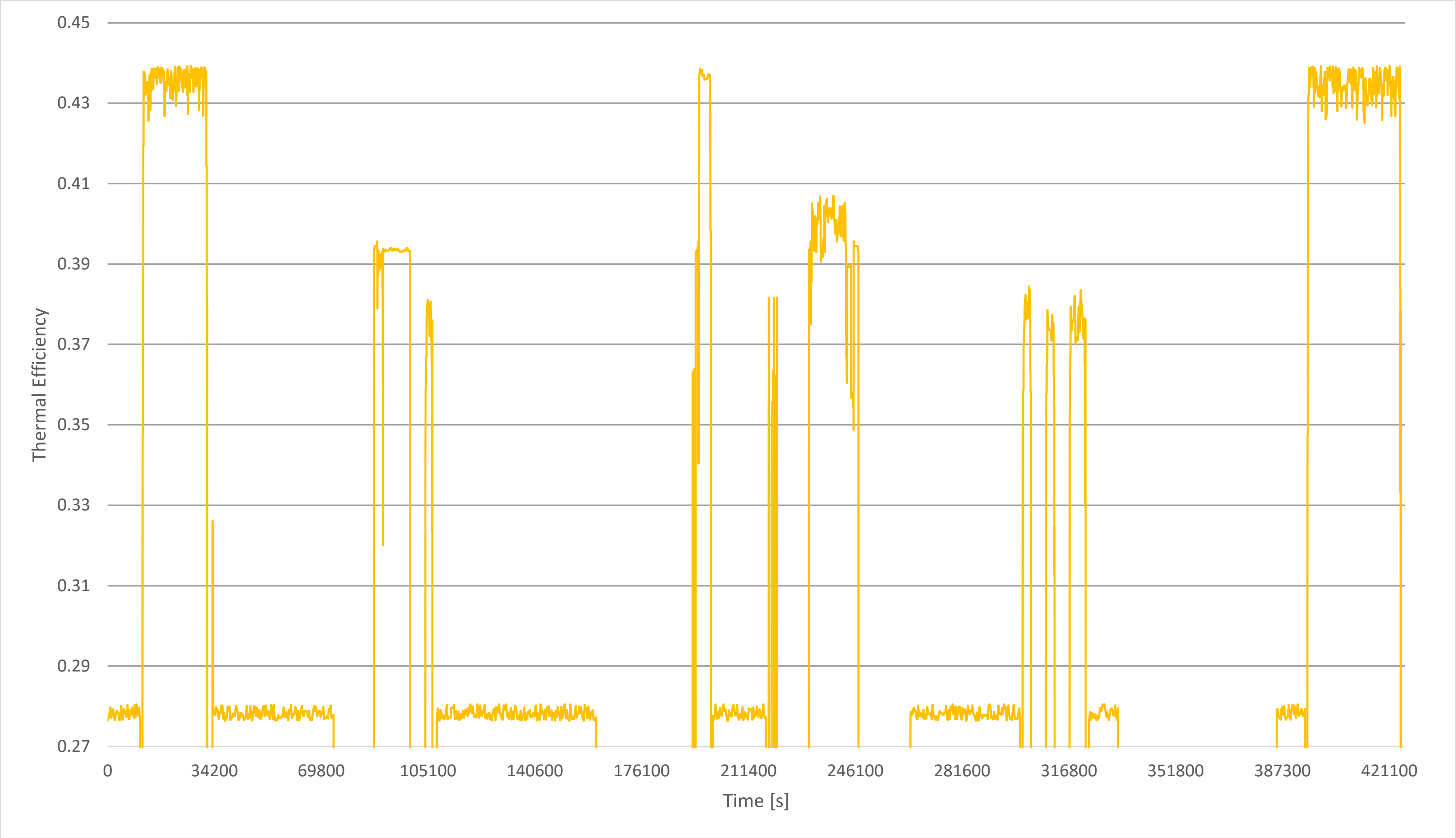


Figure 85. Overall thermal efficiency of the Configuration 3/Scenario 1.

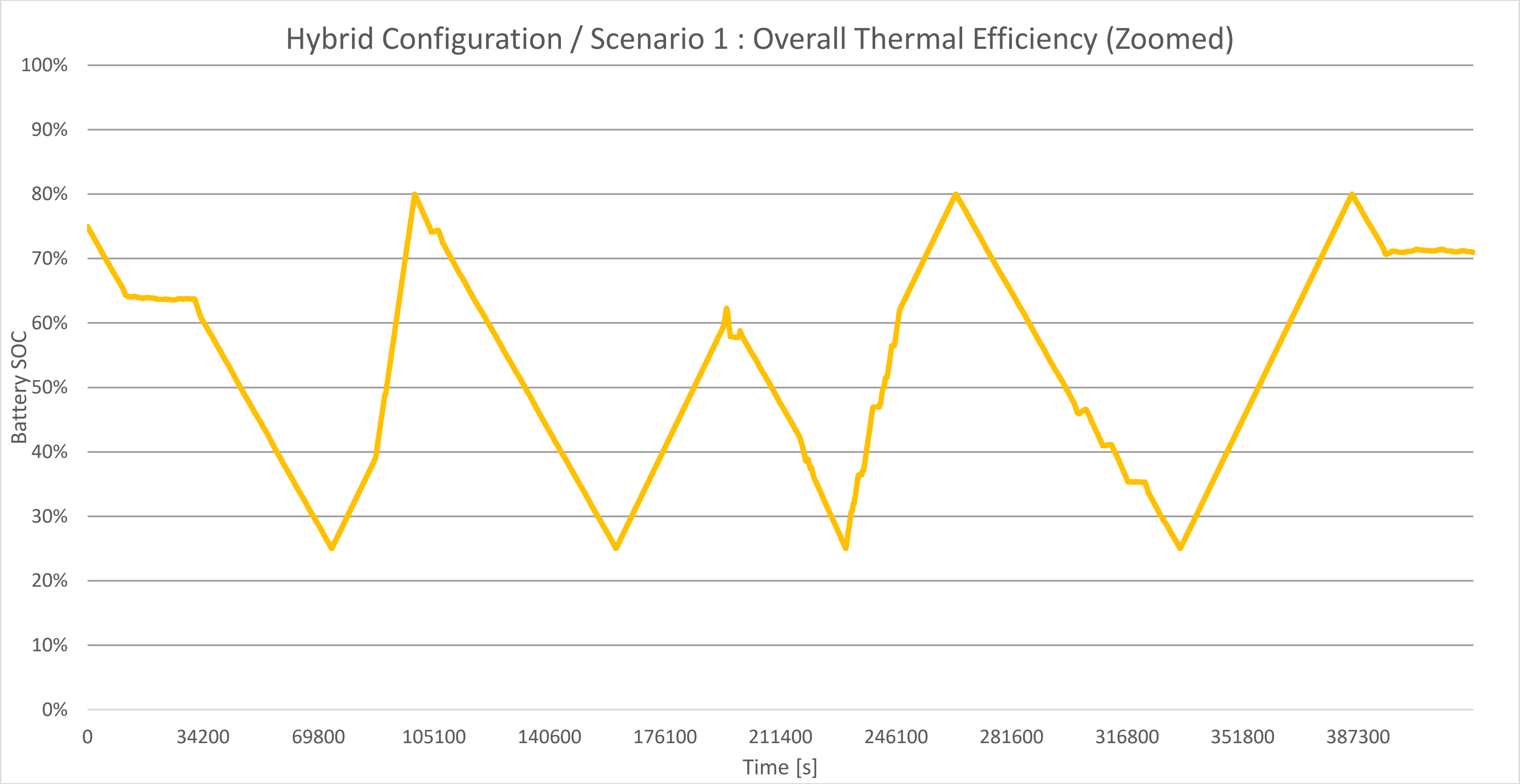


Figure 86. Battery SOC of the Configuration 3/Scenario 1.

- Total fuel consumed

Fuel Consumption = 13.342 tons

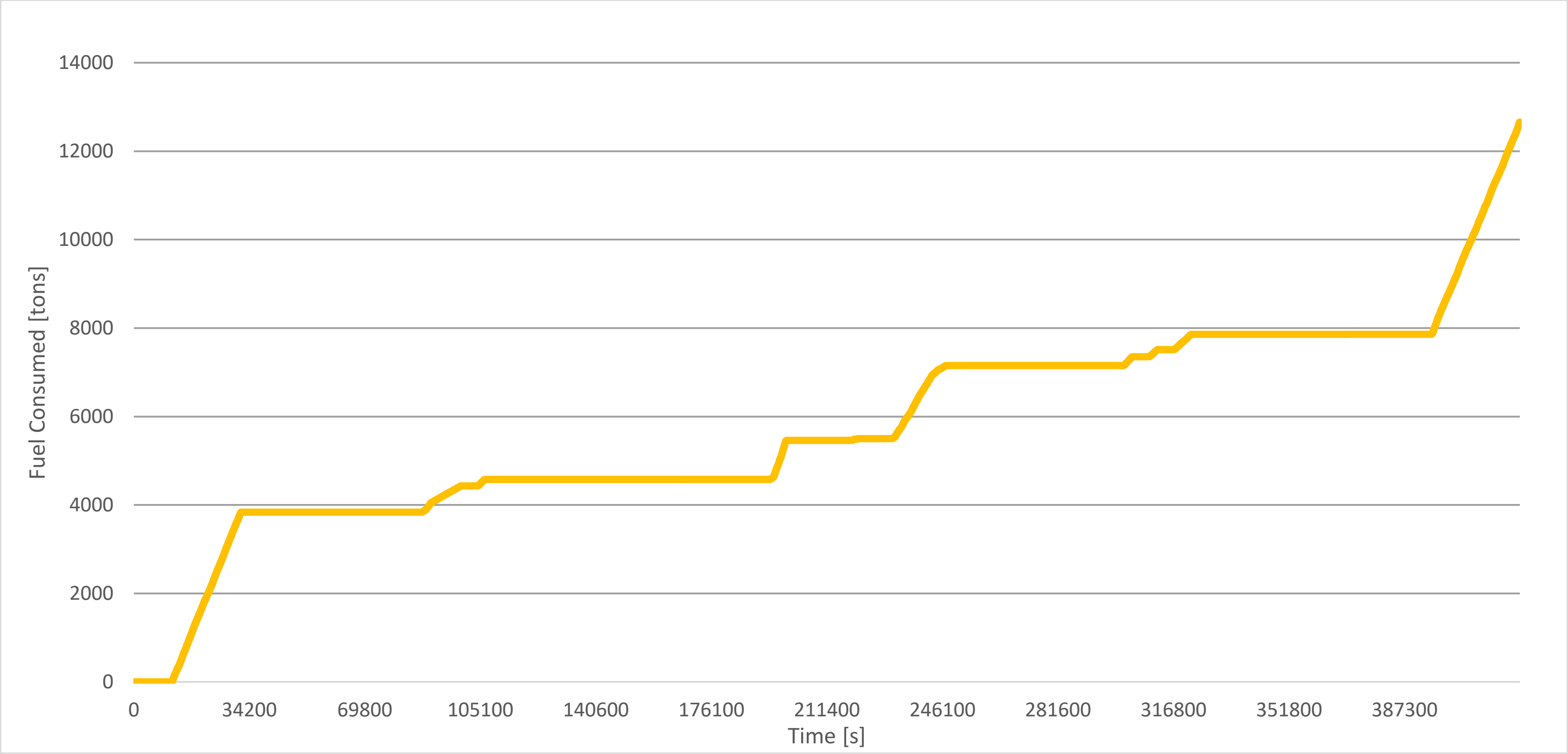


Figure 87. Fuel consumption of the Configuration 3/Scenario 1.

- CO_2 Emissions

$$CO_2\ Produced = 42.774\ tons$$

8.1.1.4. Scenario 1: Configuration 4 - Diesel-Electric.

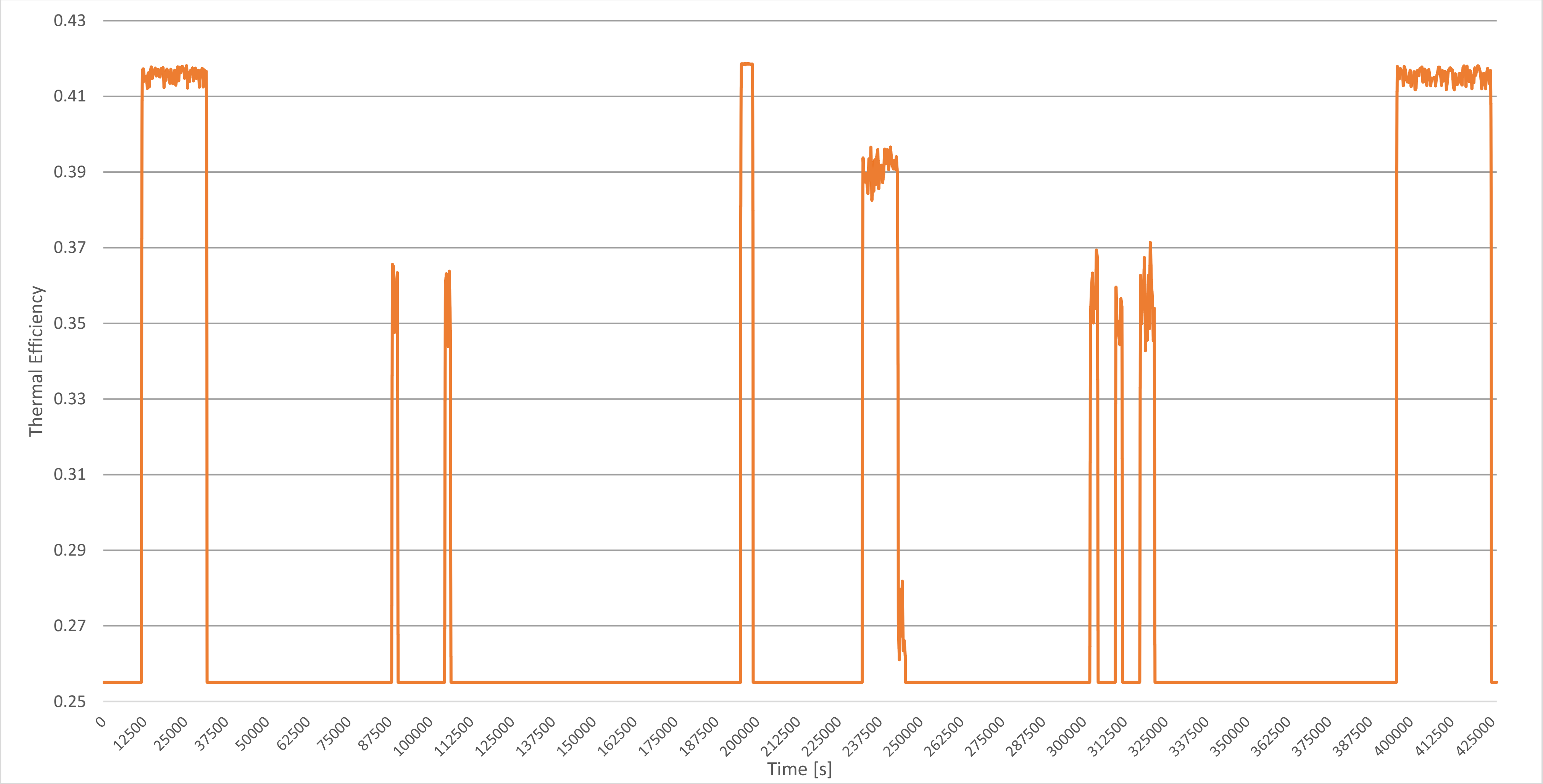


Figure 88. Thermal efficiency of the primary generator sets of Configuration 4/Scenario 1.

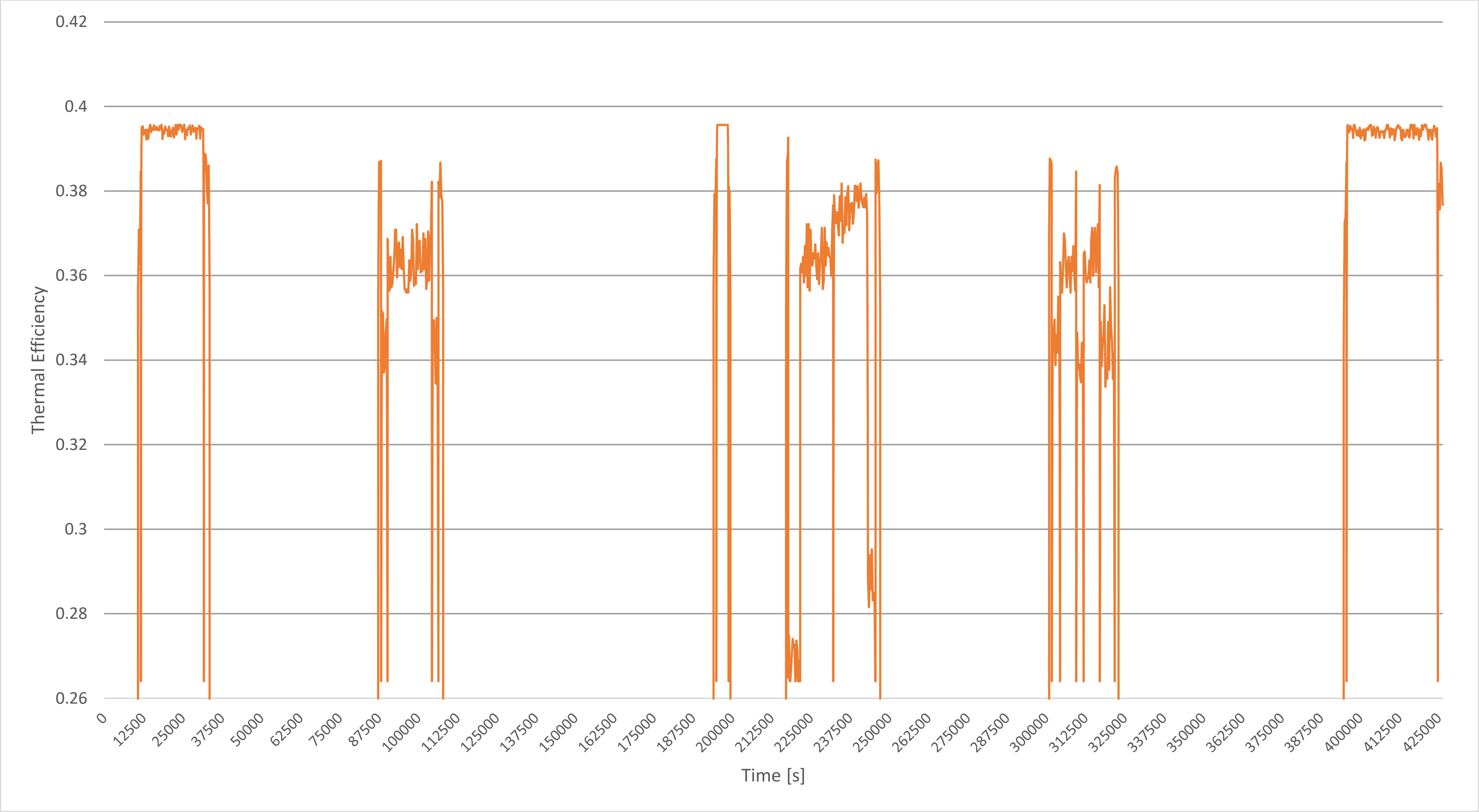


Figure 89. Thermal efficiency of the secondary generator sets of Configuration 4/Scenario 1.

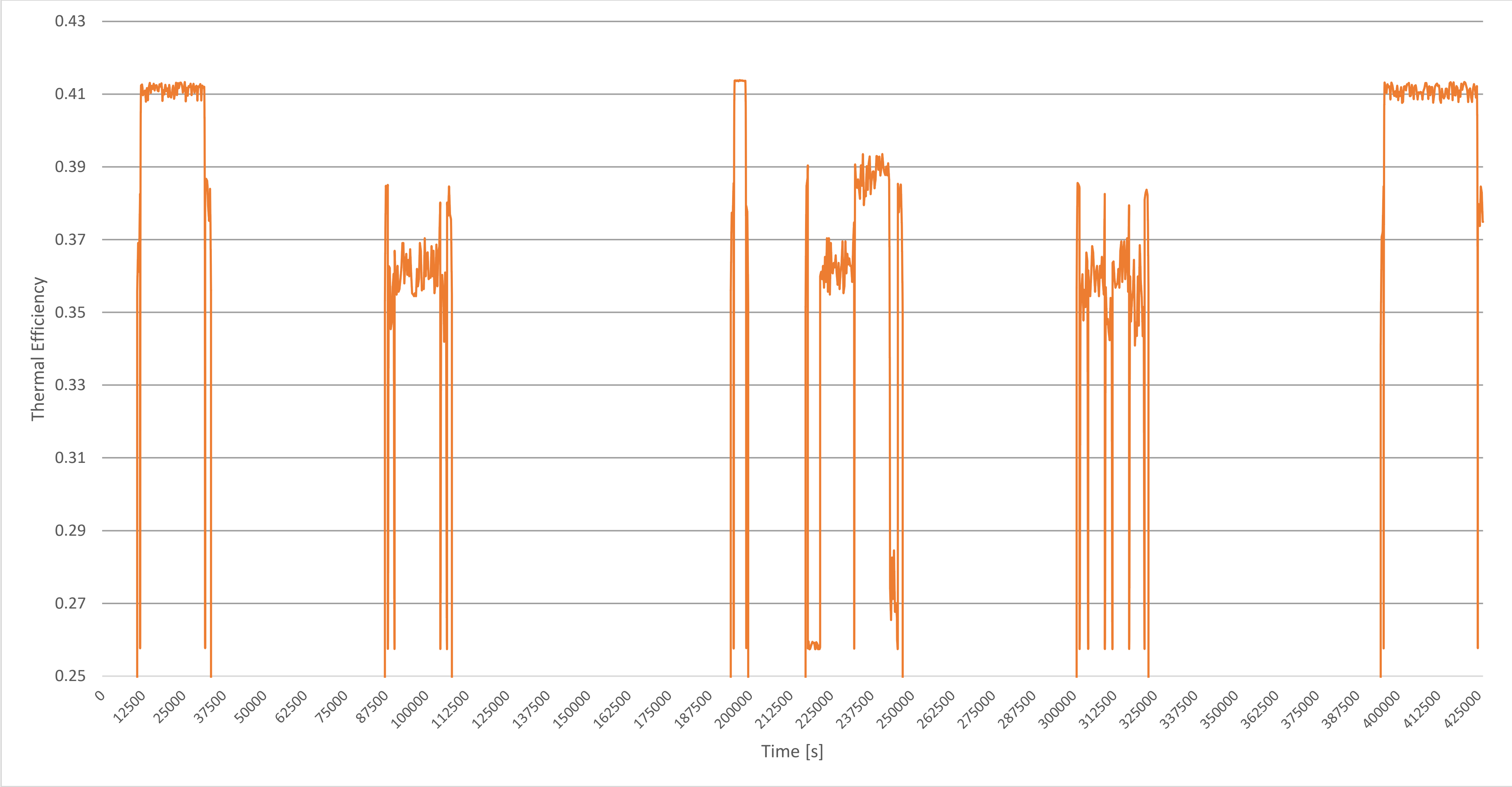


Figure 90. Overall thermal efficiency of Configuration 4/Scenario 1.

- Total fuel consumed

Fuel Consumption = 14.8215 tons

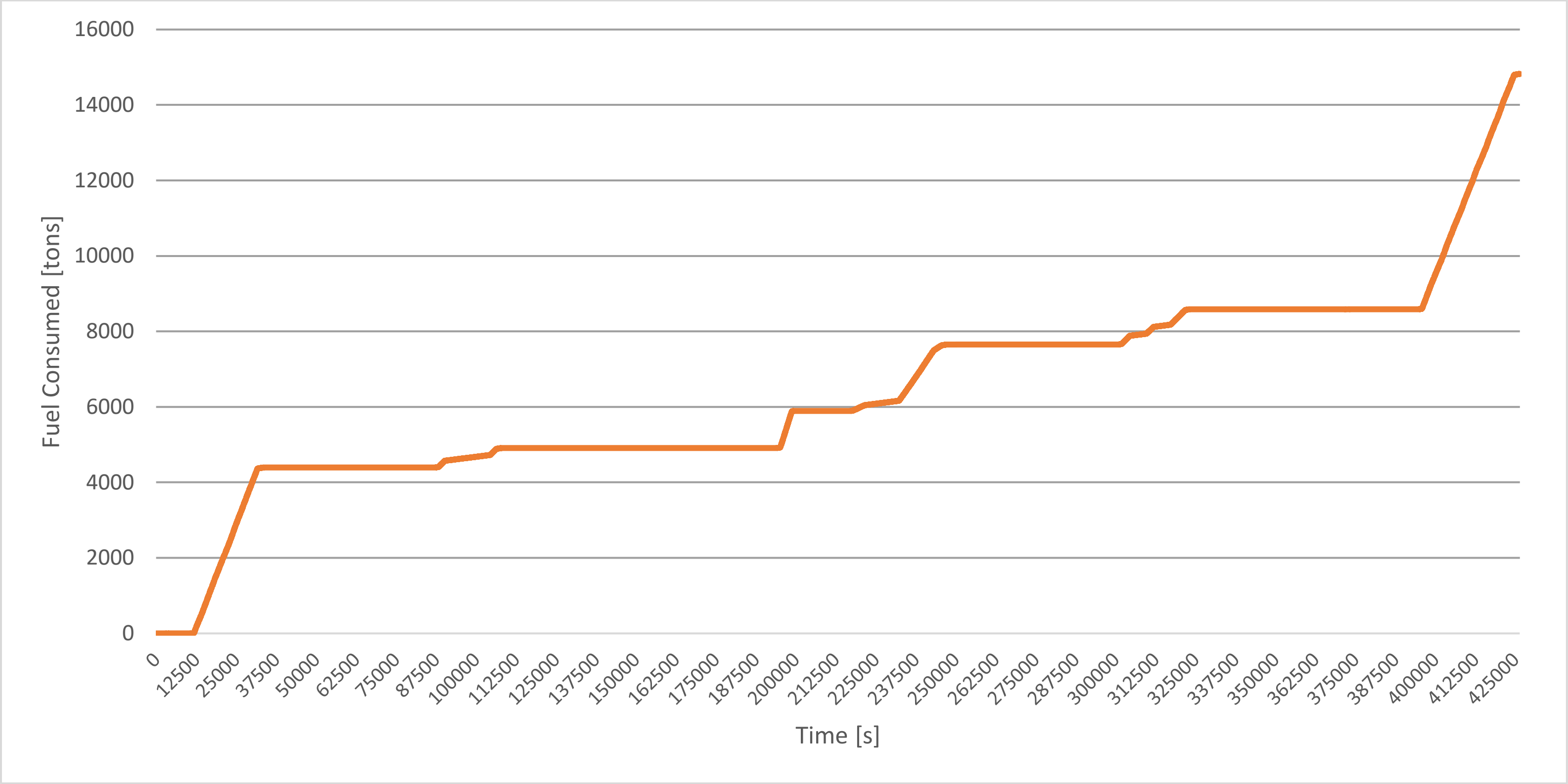


Figure 91. Fuel Consumption for Configuration 4/Scenario 1.

- CO_2 Emissions

CO_2 Produced = 47.518 tons

8.1.1.5. Scenario 1: Configuration 5 - Diesel-Electric with batteries.

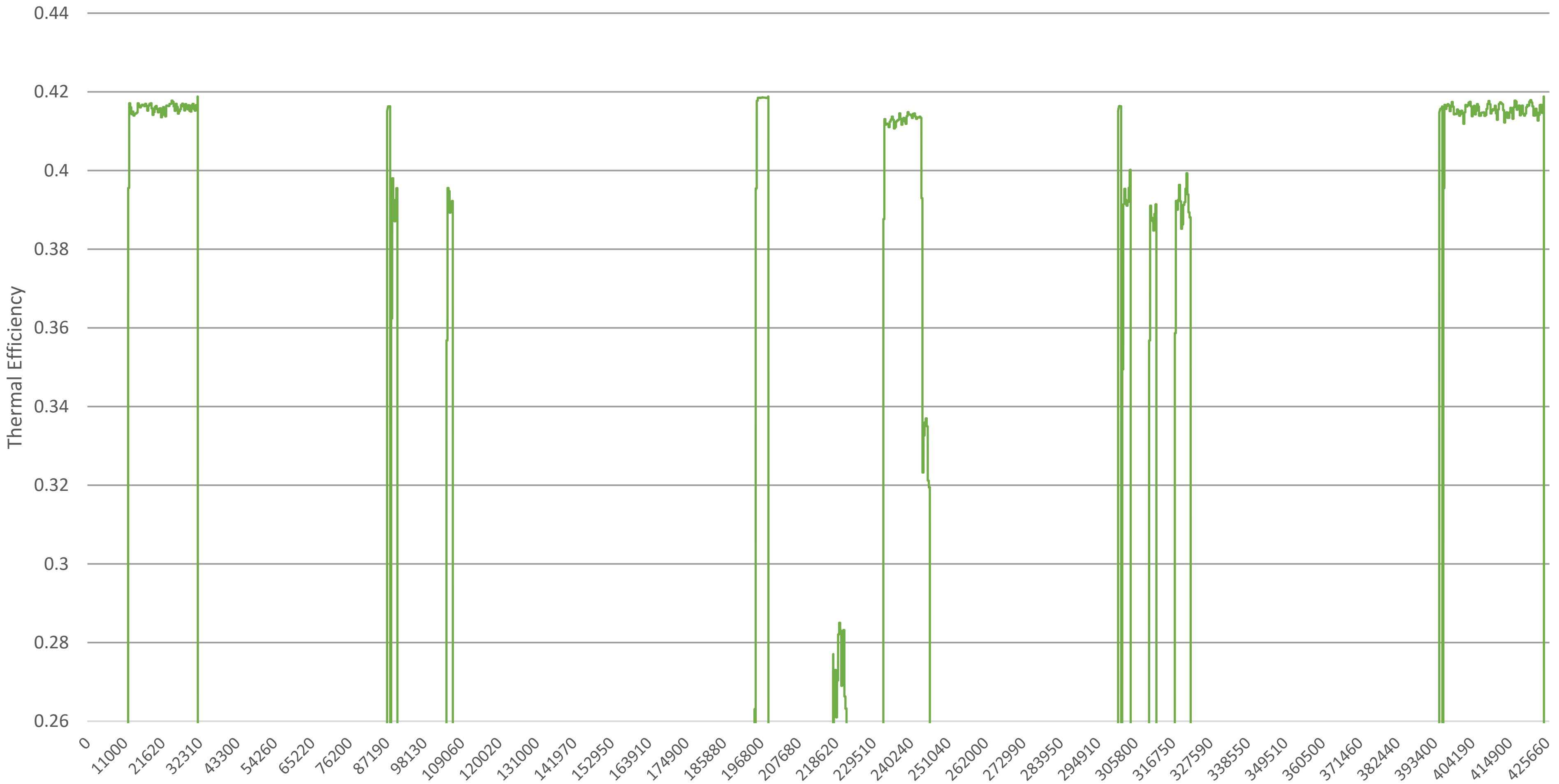


Figure 92. Thermal efficiency of the primary generator sets of Configuration 5/Scenario 1.

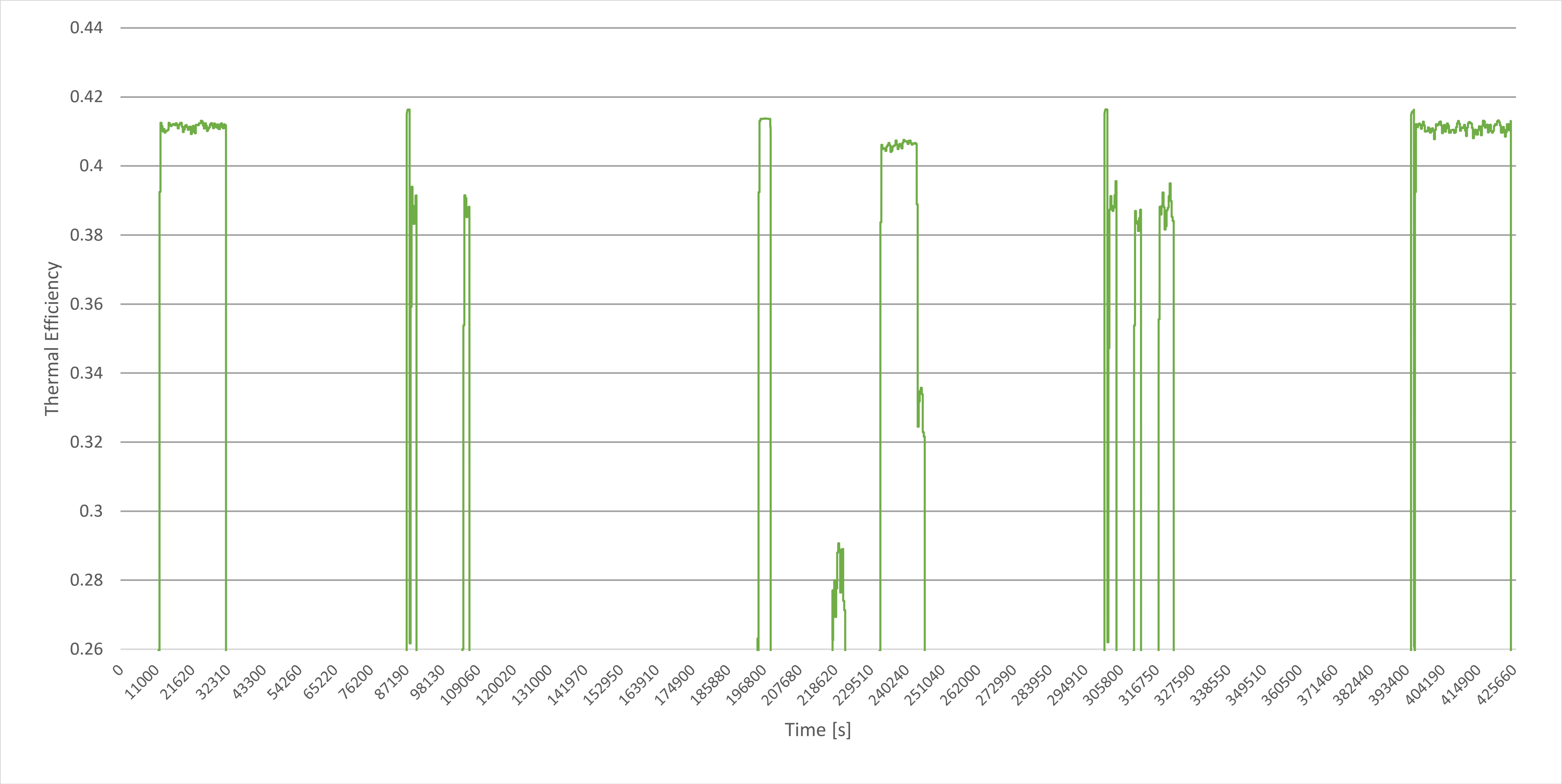


Figure 93. Thermal efficiency of the secondary generator sets of Configuration 5/Scenario 1.

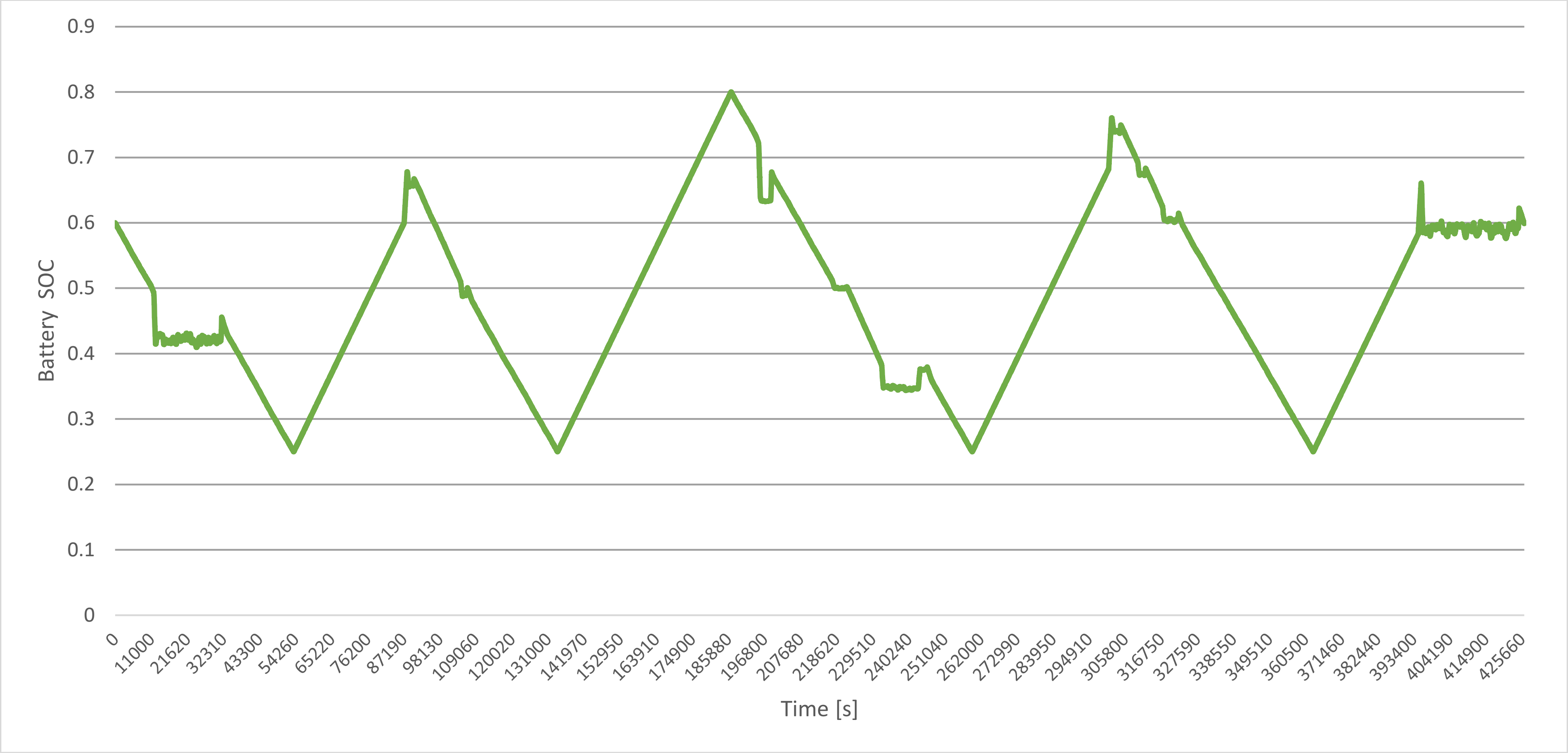


Figure 94. Battery SOC of Configuration 5/Scenario 1.

- Total fuel consumed

$$Fuel\ Consumption = 14.0961\ tons$$

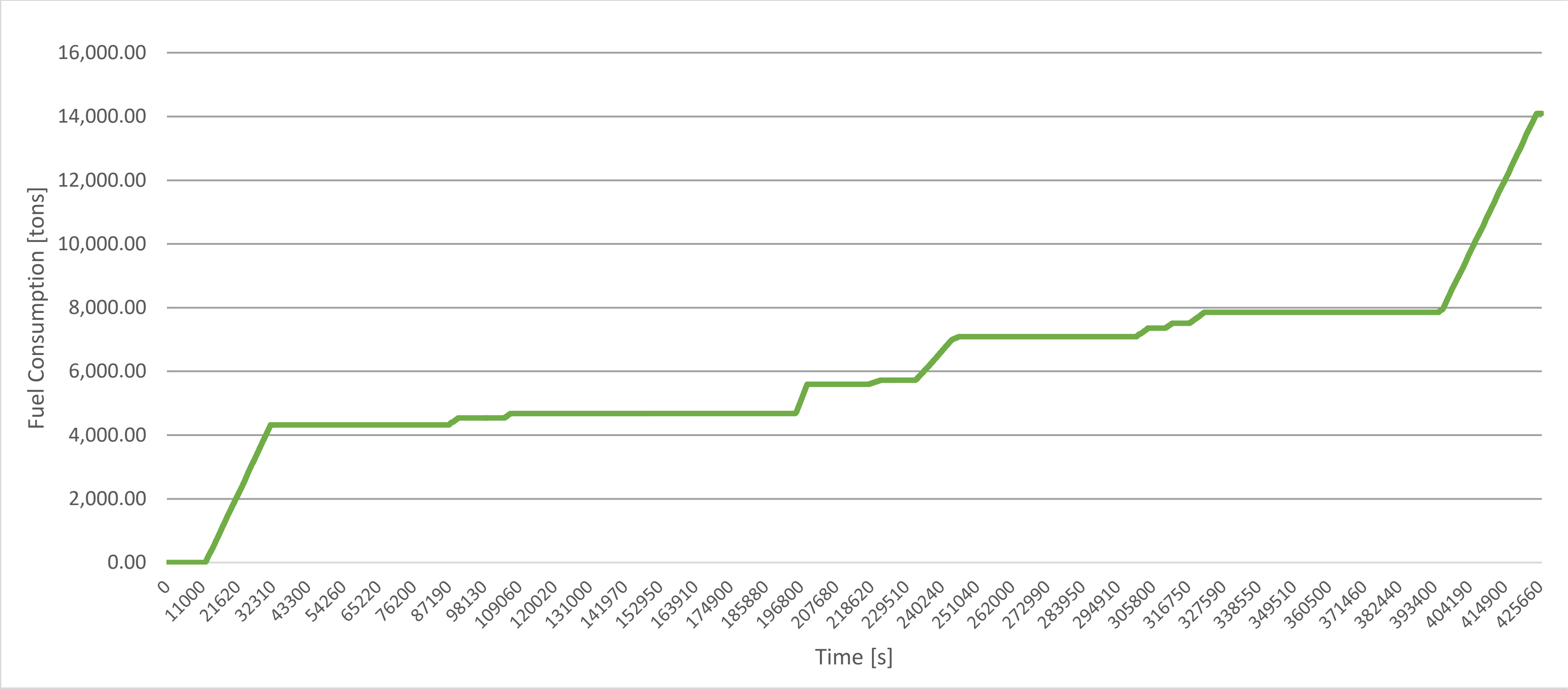


Figure 95. Fuel Consumption for Configuration 5/Scenario 1.

- CO_2 Emissions

$$CO_2\ Produced = 45.192\ tons$$

8.1.2. Results for Scenario 2 (Italy).

This subsection shifts focus to the findings of Scenario 2, presenting a comprehensive analysis of its distinct results for the selected propulsion configurations.

8.1.2.1. Scenario 2: Configuration 1 - Mechanical.

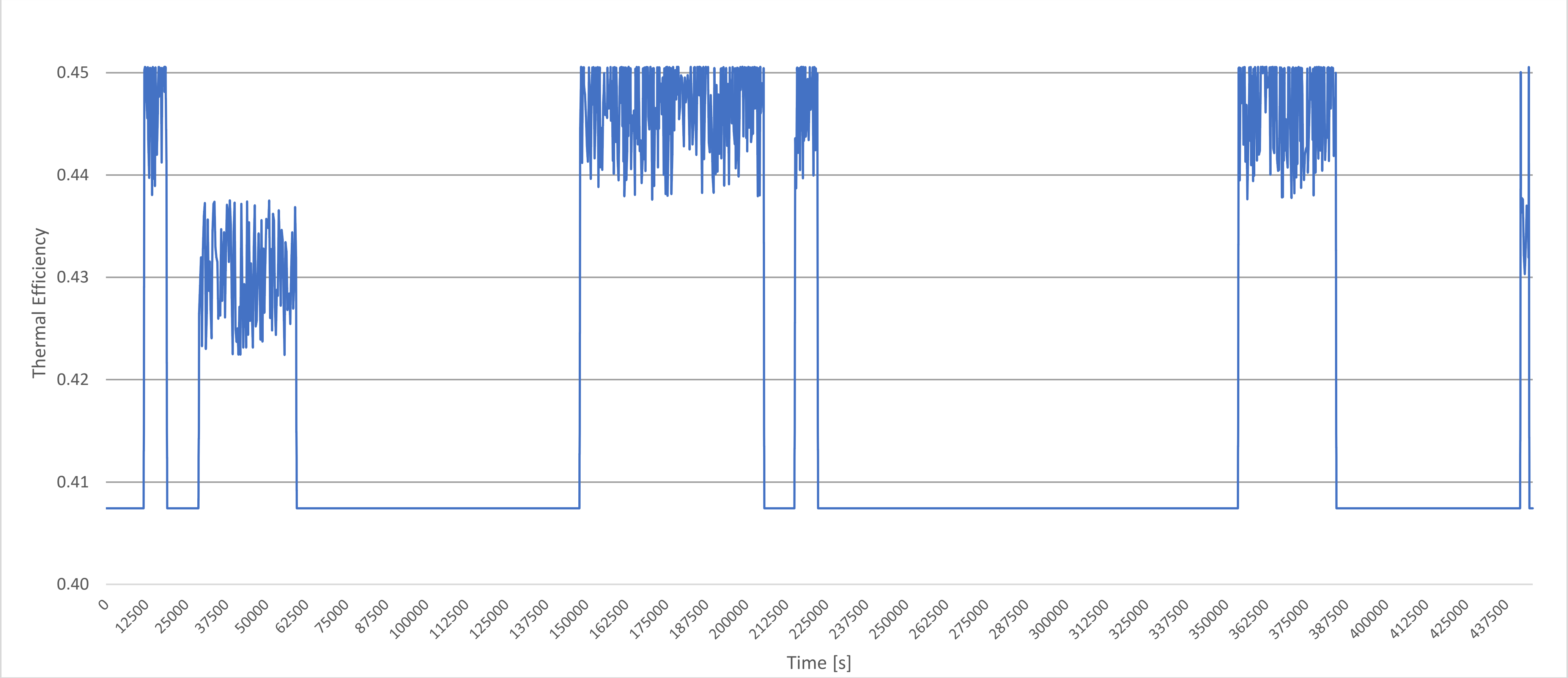


Figure 96. Thermal efficiency of the main engines of Configuration 1/Scenario 2.

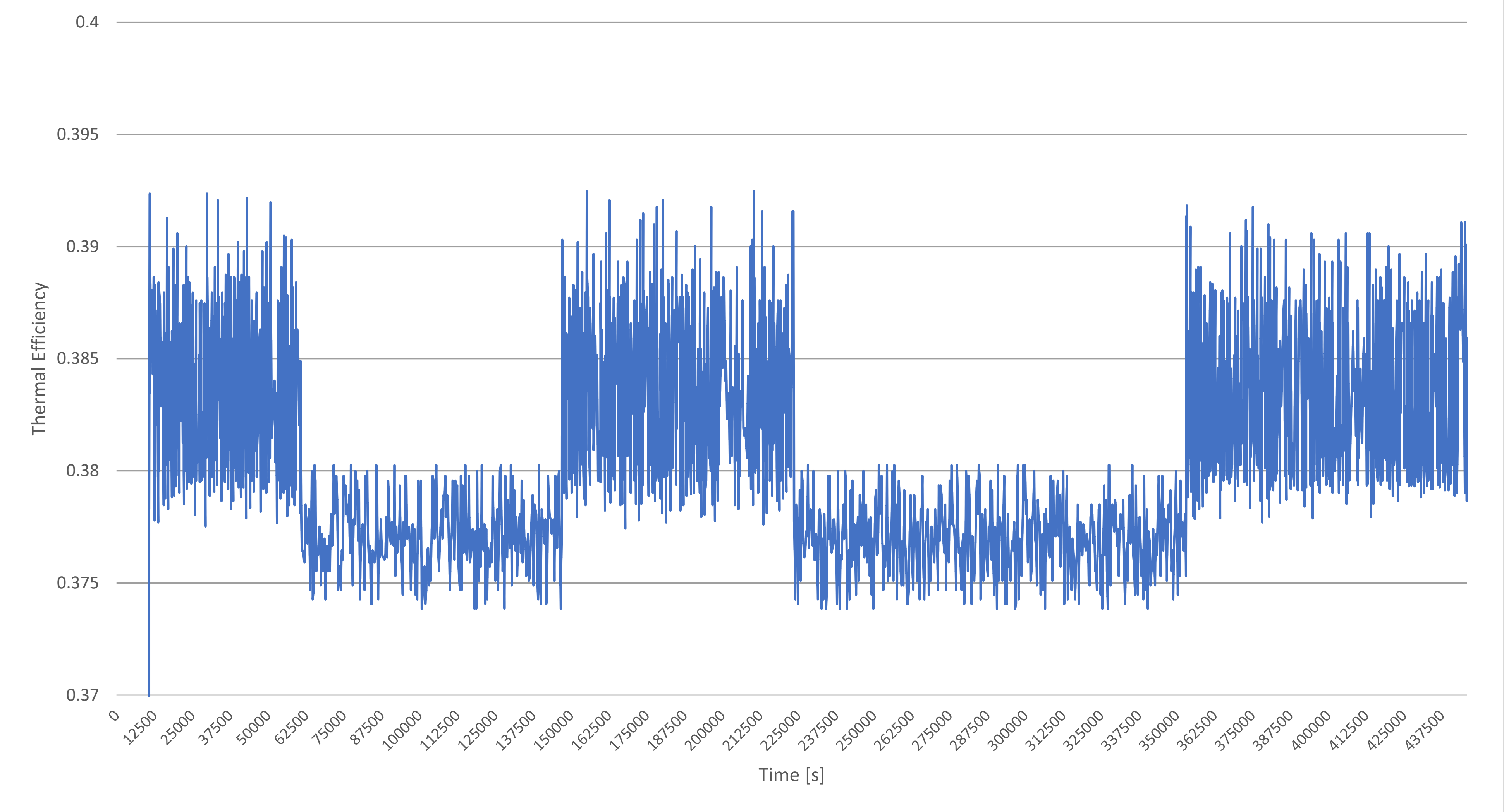


Figure 97. Thermal efficiency of the generator sets of Configuration 1/Scenario 2.

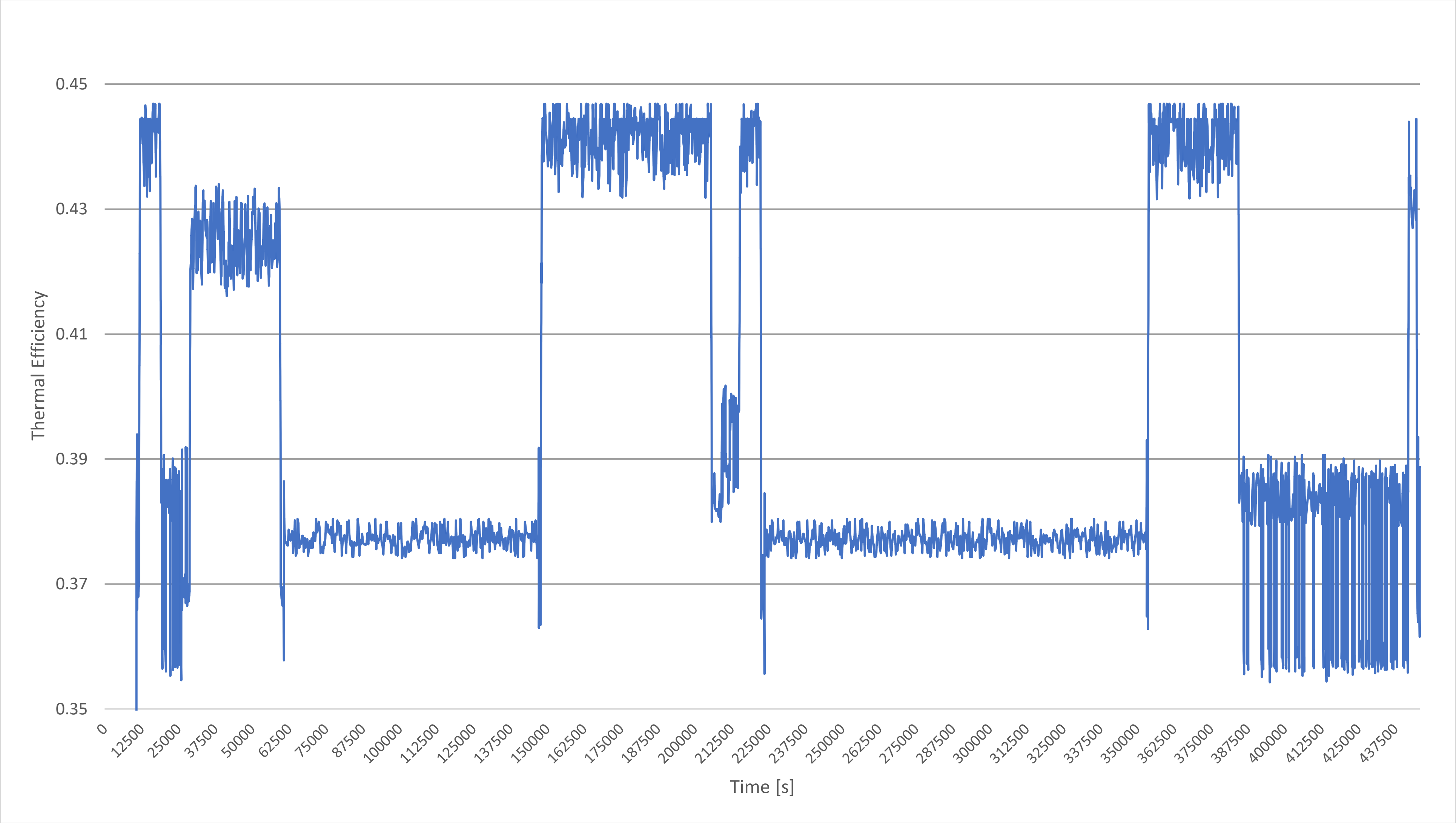


Figure 98. Overall thermal efficiency of Configuration 1/Scenario 2.

- Total fuel consumed

Fuel Consumption = 27.1955 tons

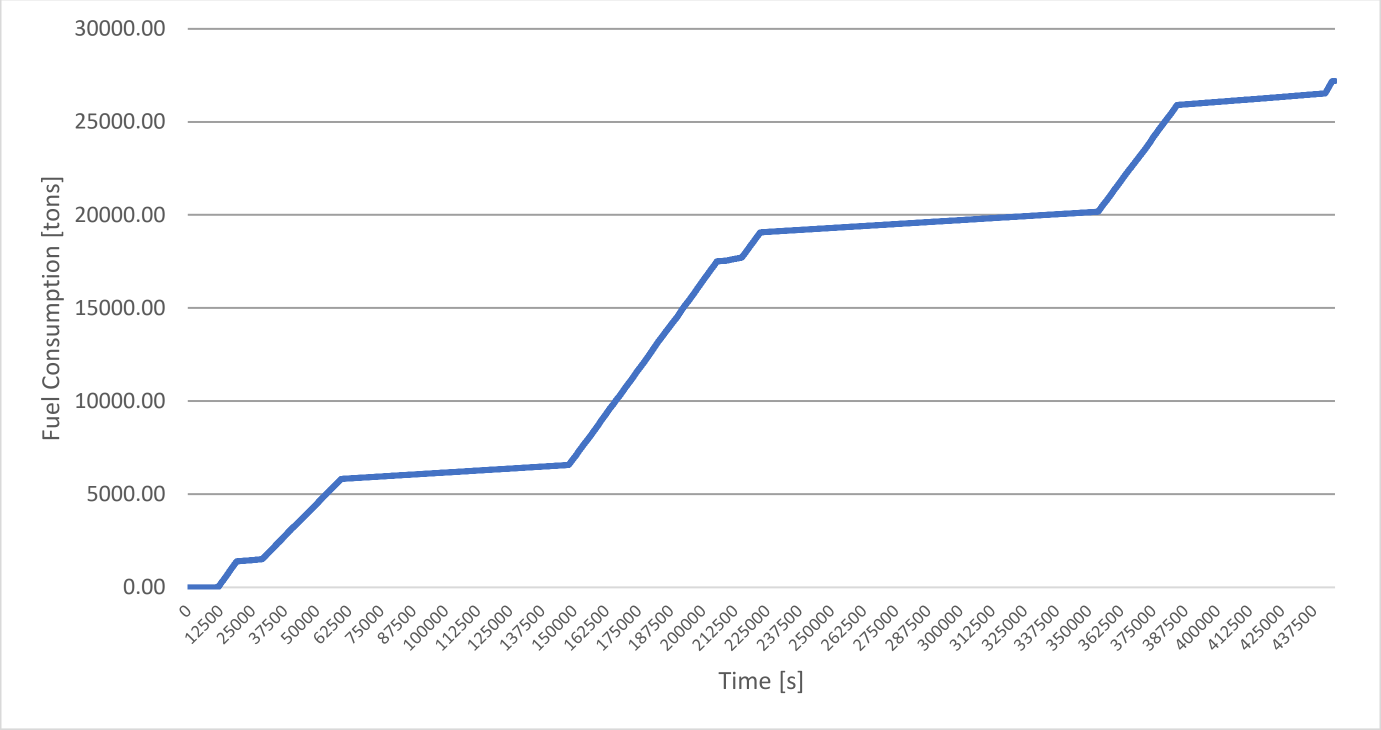


Figure 99. Fuel Consumption for Configuration 3/Scenario 2.

- CO_2 Emissions

CO_2 Produced = 87.189 tons

8.1.2.2. Scenario 2: Configuration 2 - Hybrid.

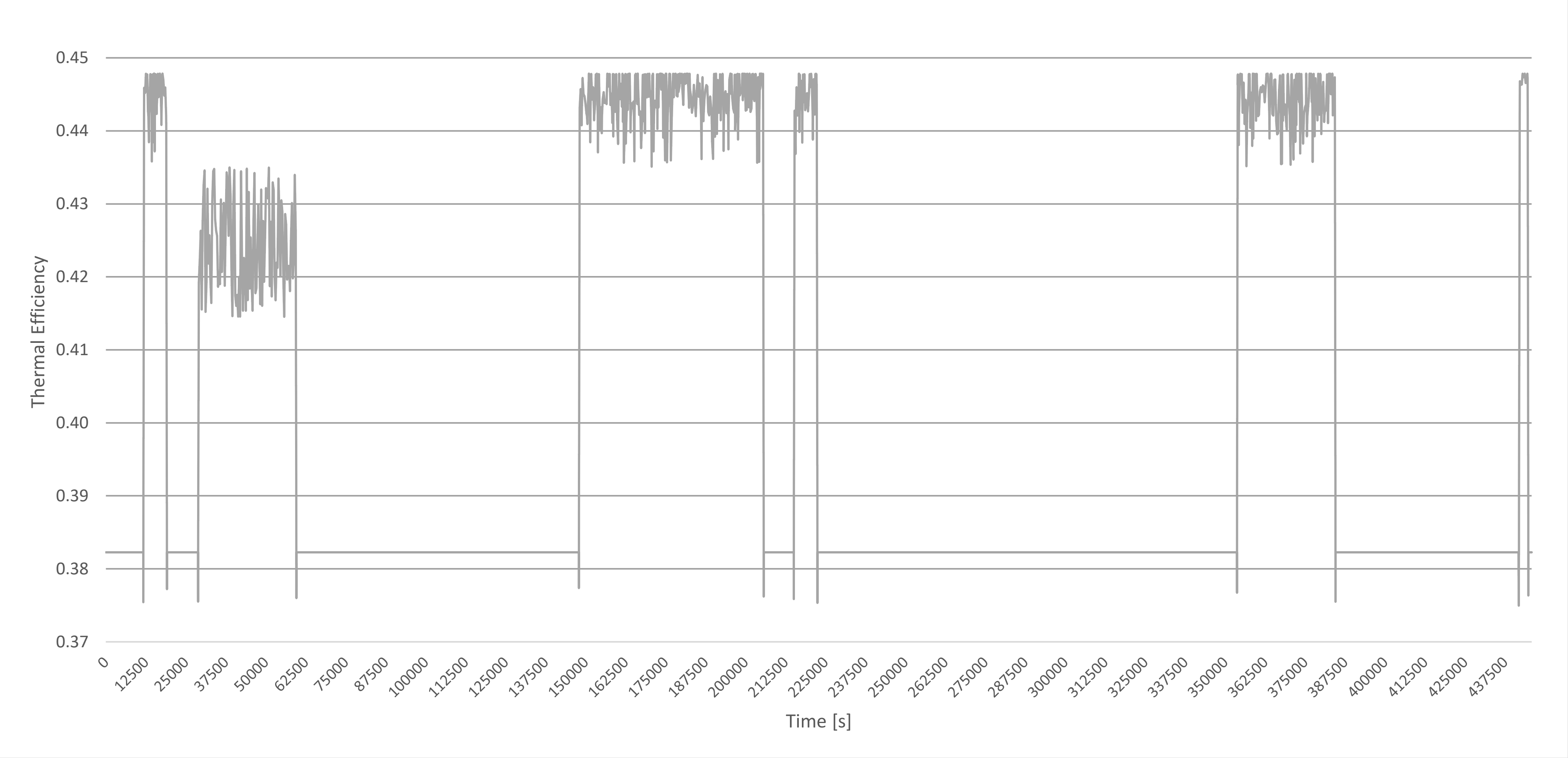


Figure 100. Thermal efficiency of the main engines of Configuration 2/Scenario 2.

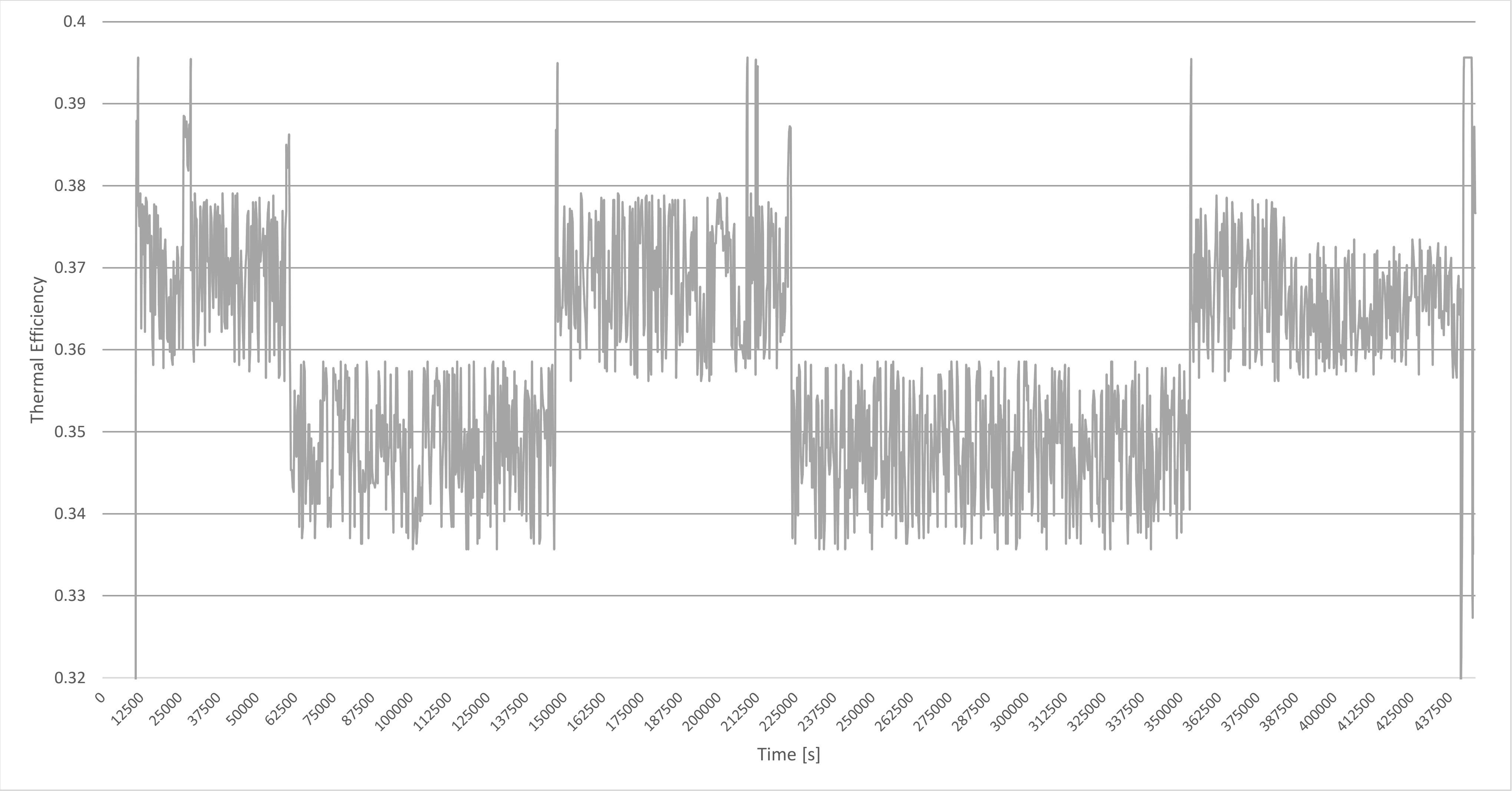


Figure 101. Thermal efficiency of the generator sets of Configuration 2/Scenario 2.

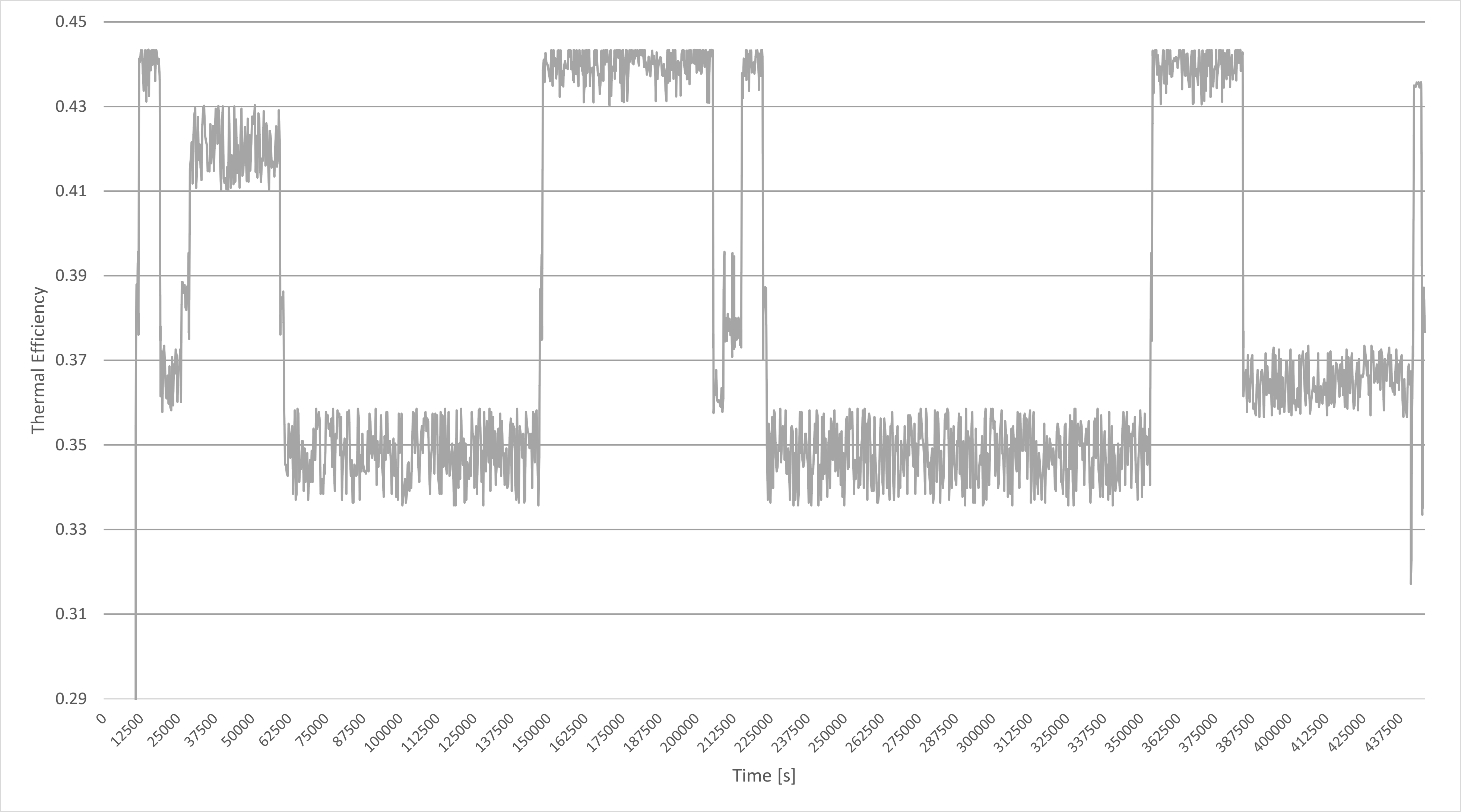


Figure 102. Overall thermal efficiency of Configuration 2/Scenario 2.

- Total fuel consumed

Fuel Consumption = 27.4956 tons

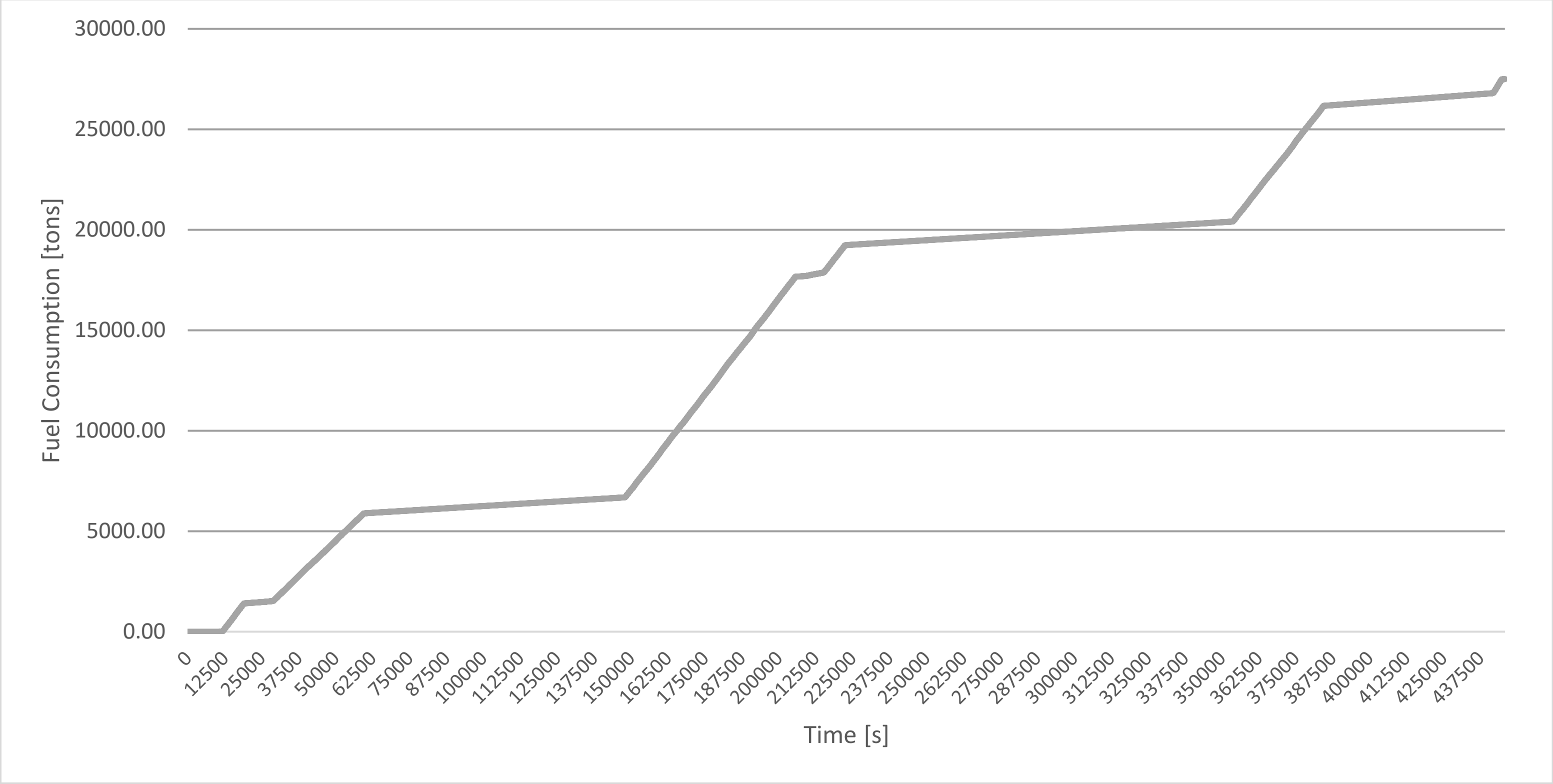


Figure 103. Fuel Consumption for Configuration 2/Scenario 2.

- CO_2 Emissions

CO_2 Produced = 88.151tons

8.1.2.3. Scenario 1: Configuration 3 – Hybrid with batteries.

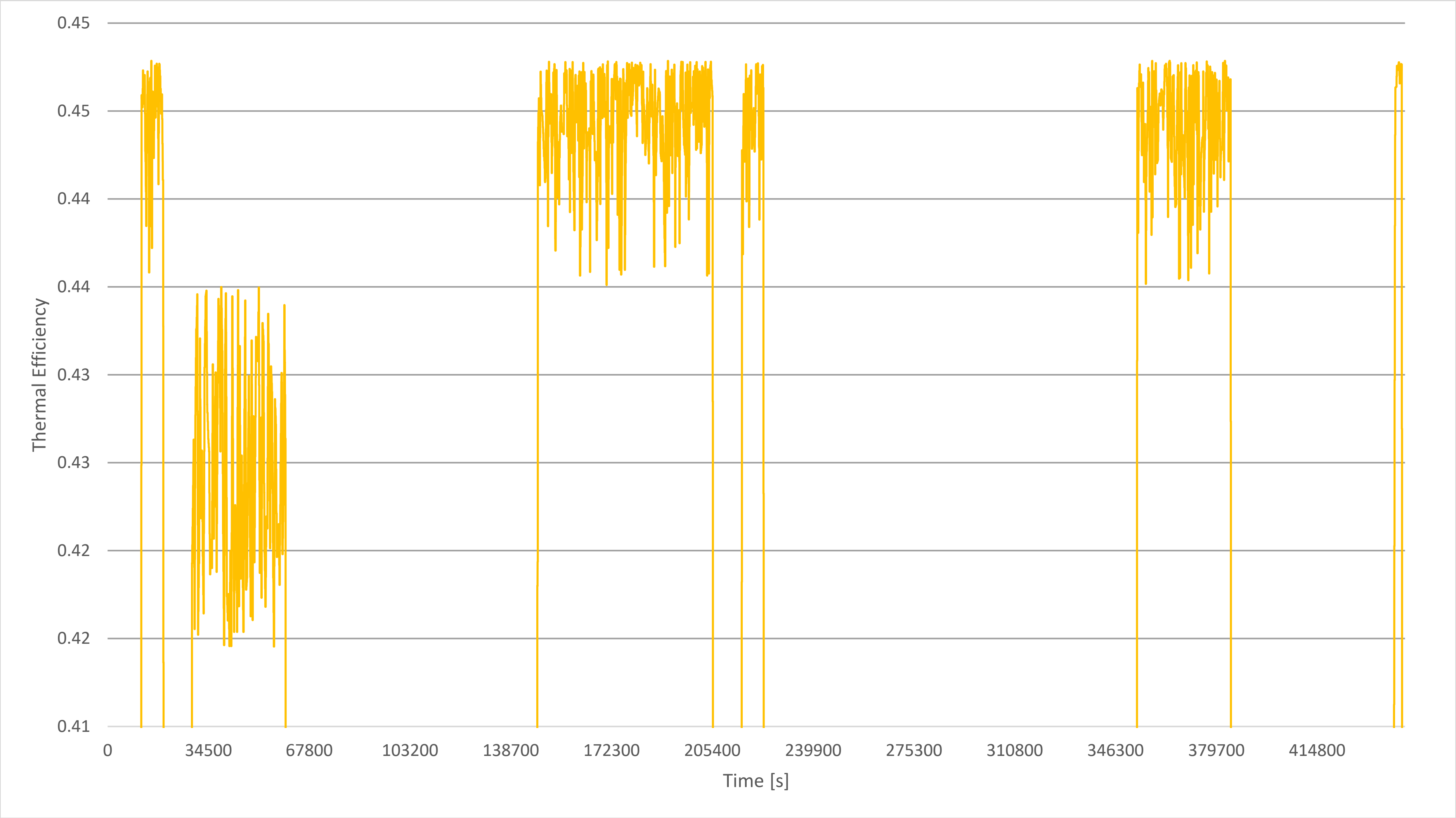


Figure 104. Thermal efficiency of the main engines of Configuration 3/Scenario 2.

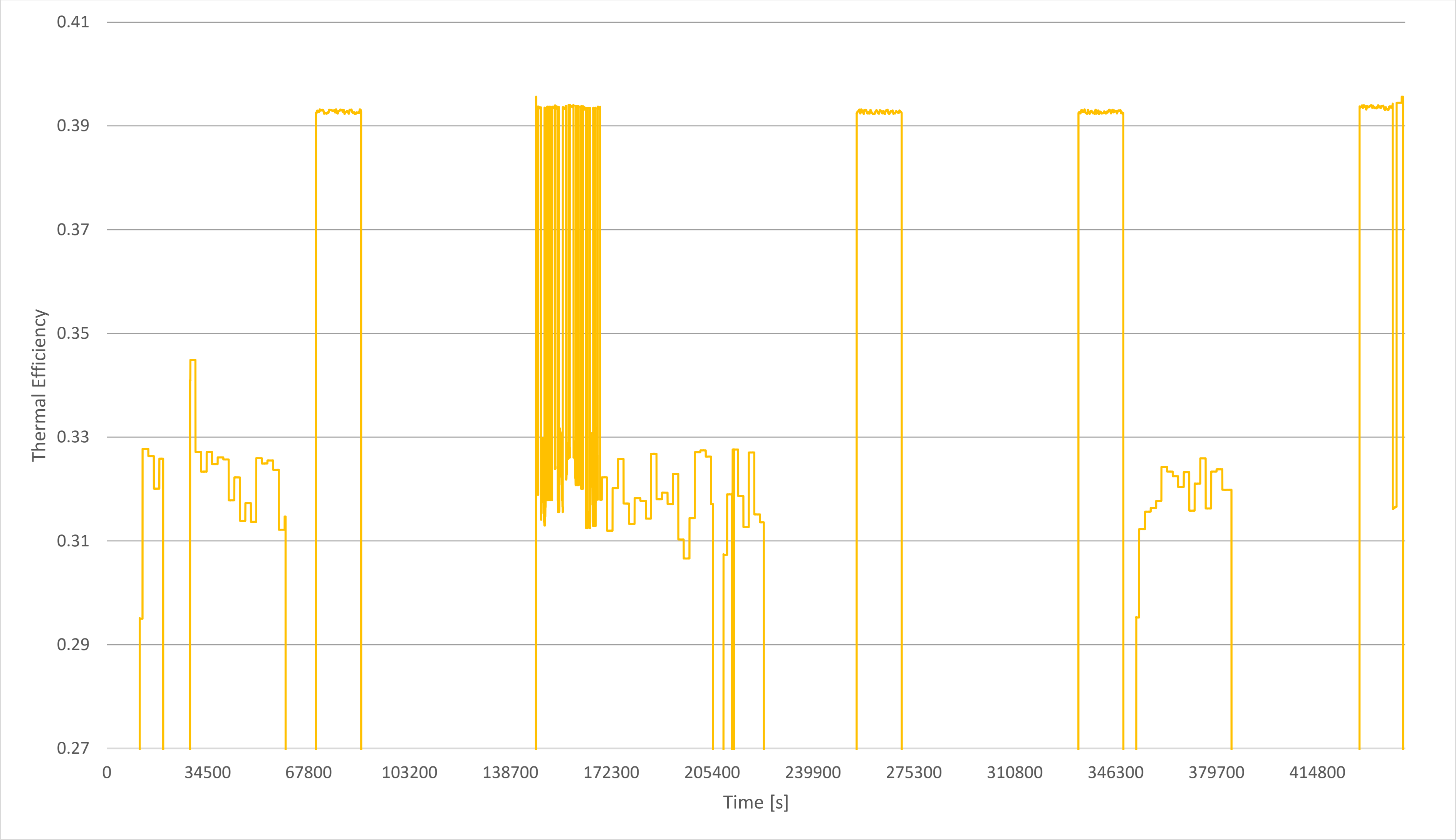


Figure 105. Thermal efficiency of the primary generator set of Configuration 3/Scenario 2.

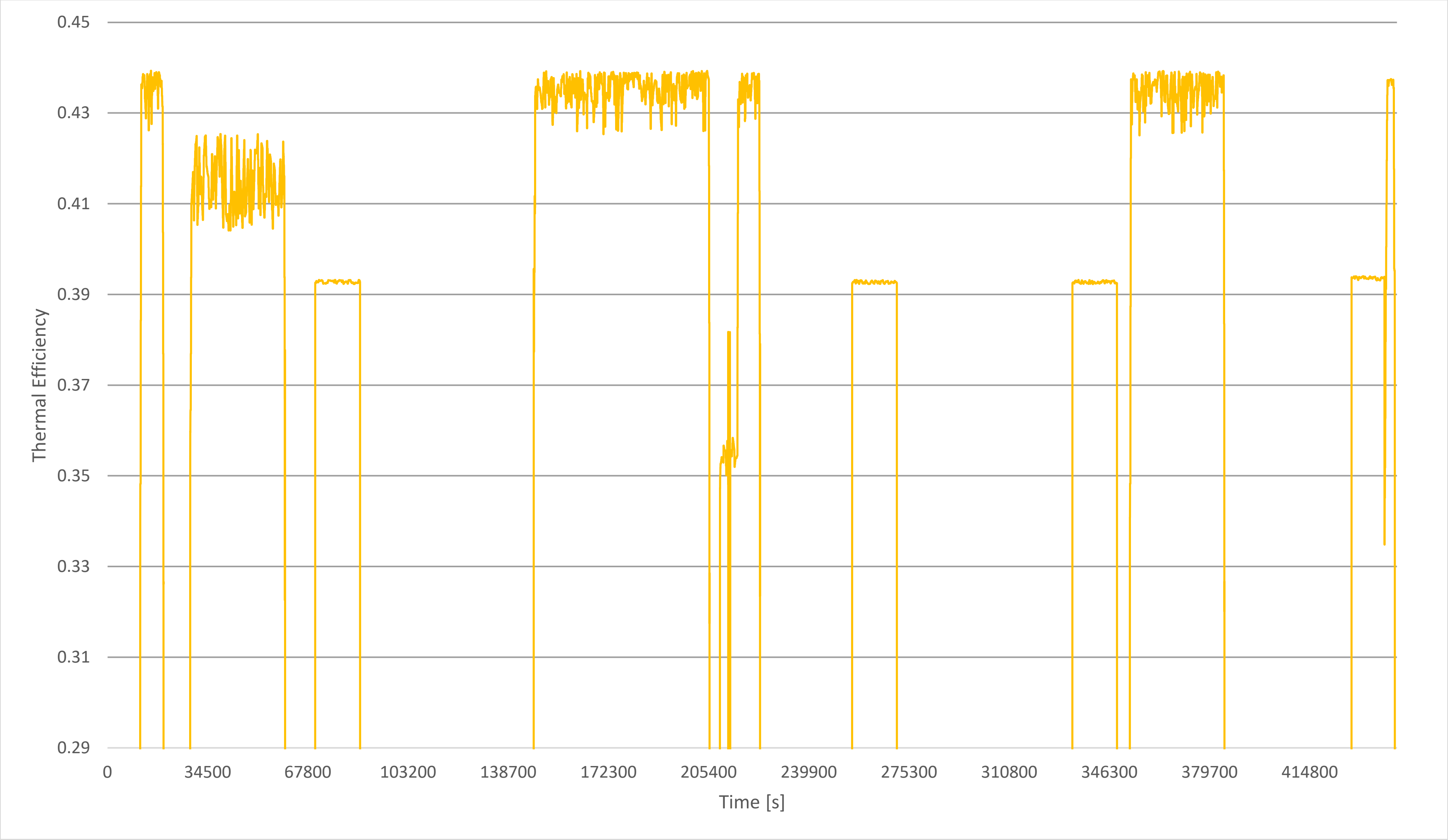


Figure 106. Overall thermal efficiency of the Configuration 3/Scenario 2.

Figure 107. Battery SOC of the Configuration 3/Scenario 2.

- Total fuel consumed

Fuel Consumption = 27.6491 tons

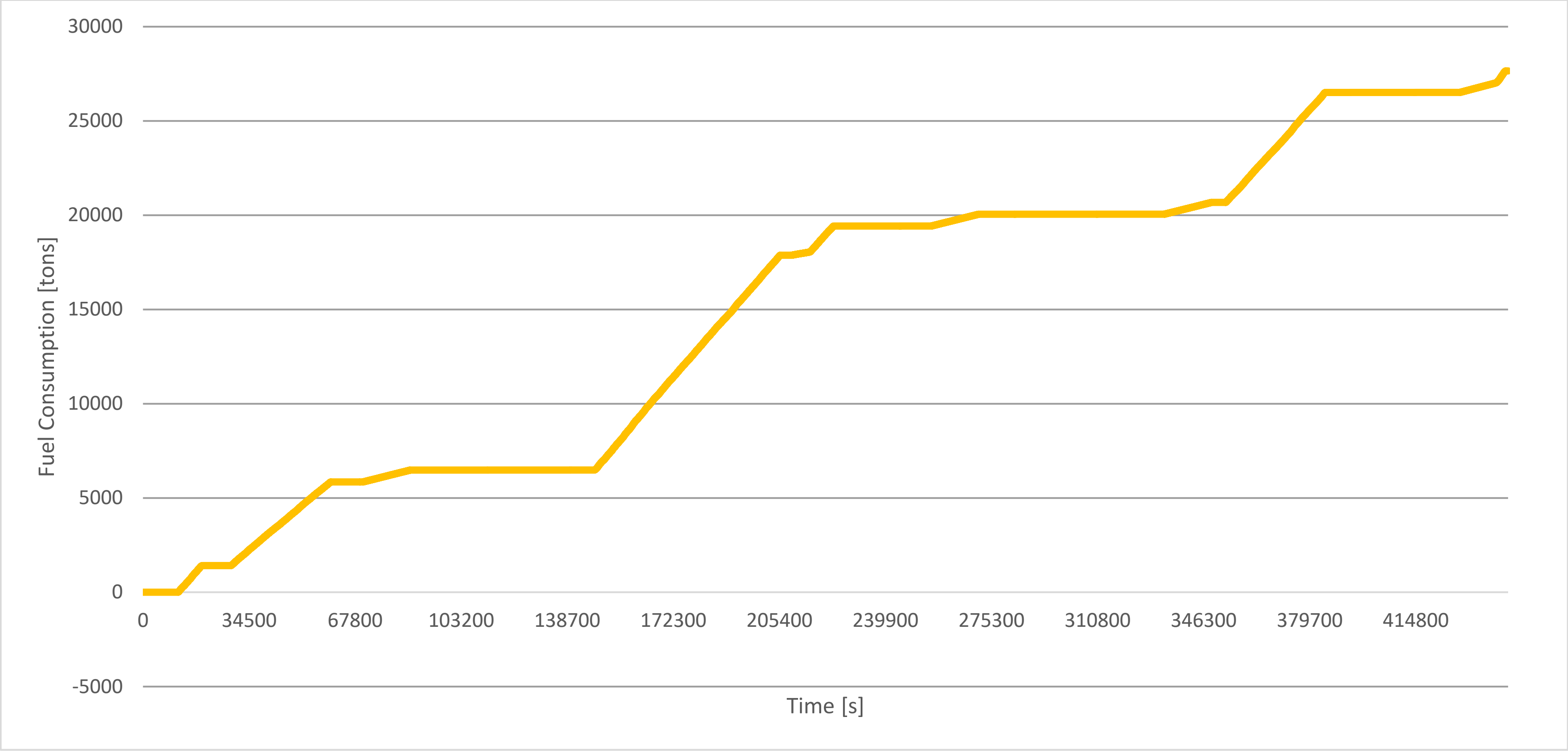


Figure 108. Fuel consumption of the Configuration 3/Scenario 2.

- CO_2 Emissions

$$CO_2\ Produced = 88.643\ tons$$

8.1.2.4. Scenario 2: Configuration 4 - Diesel-Electric.

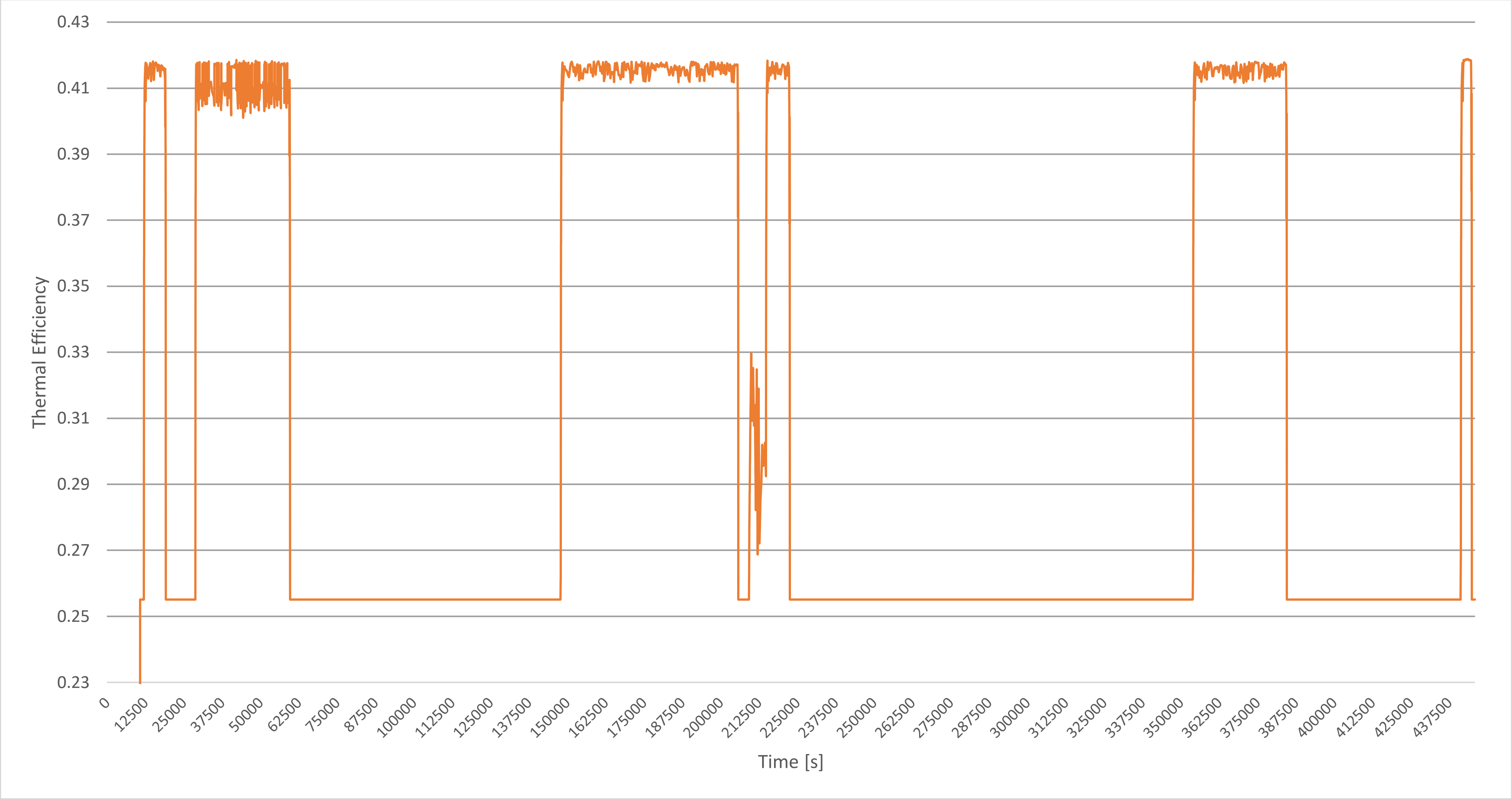


Figure 109. Thermal efficiency of the primary generator sets of Configuration 4/Scenario 2.

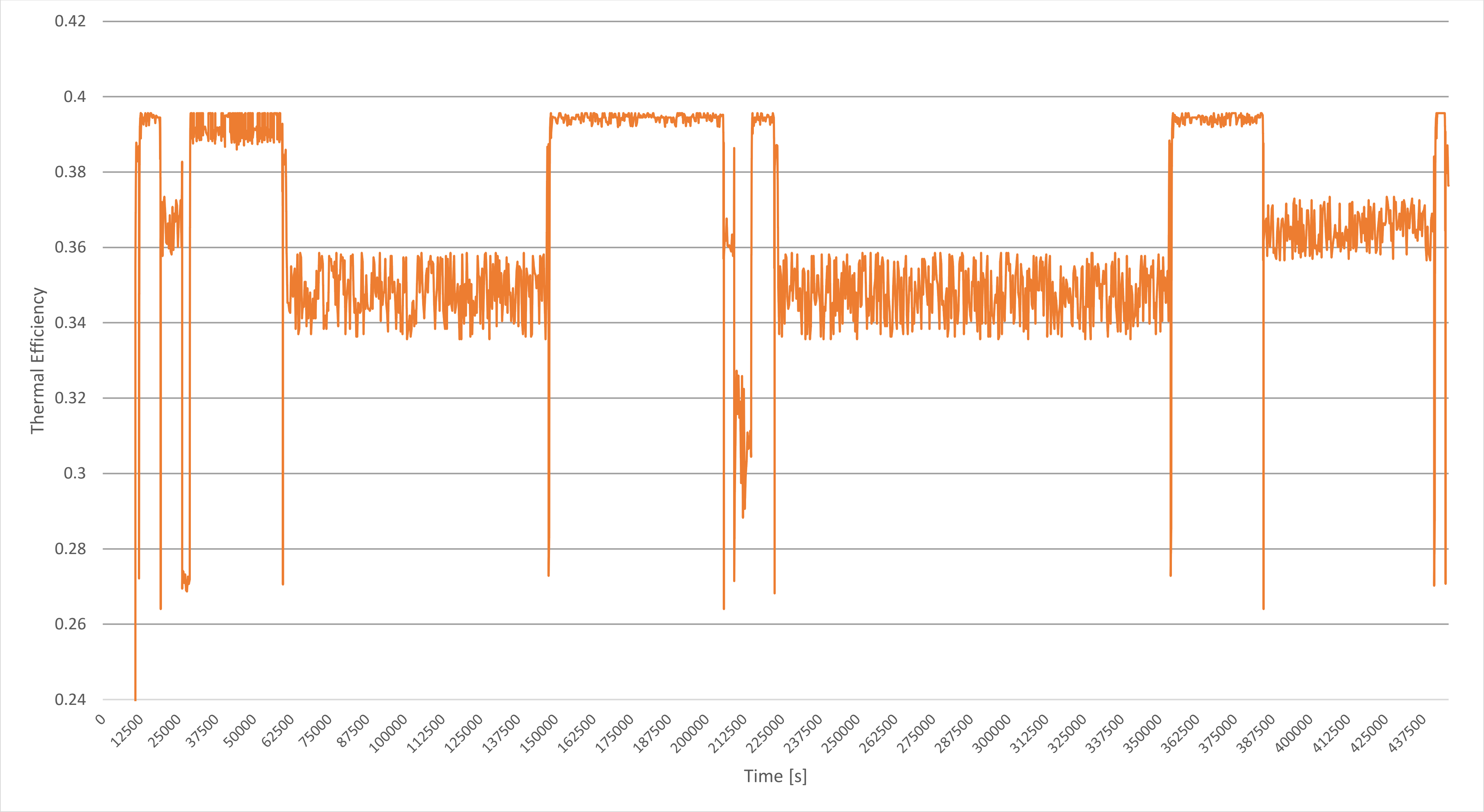


Figure 110. Thermal efficiency of the secondary generator set No. 1 of Configuration 4/Scenario 2.

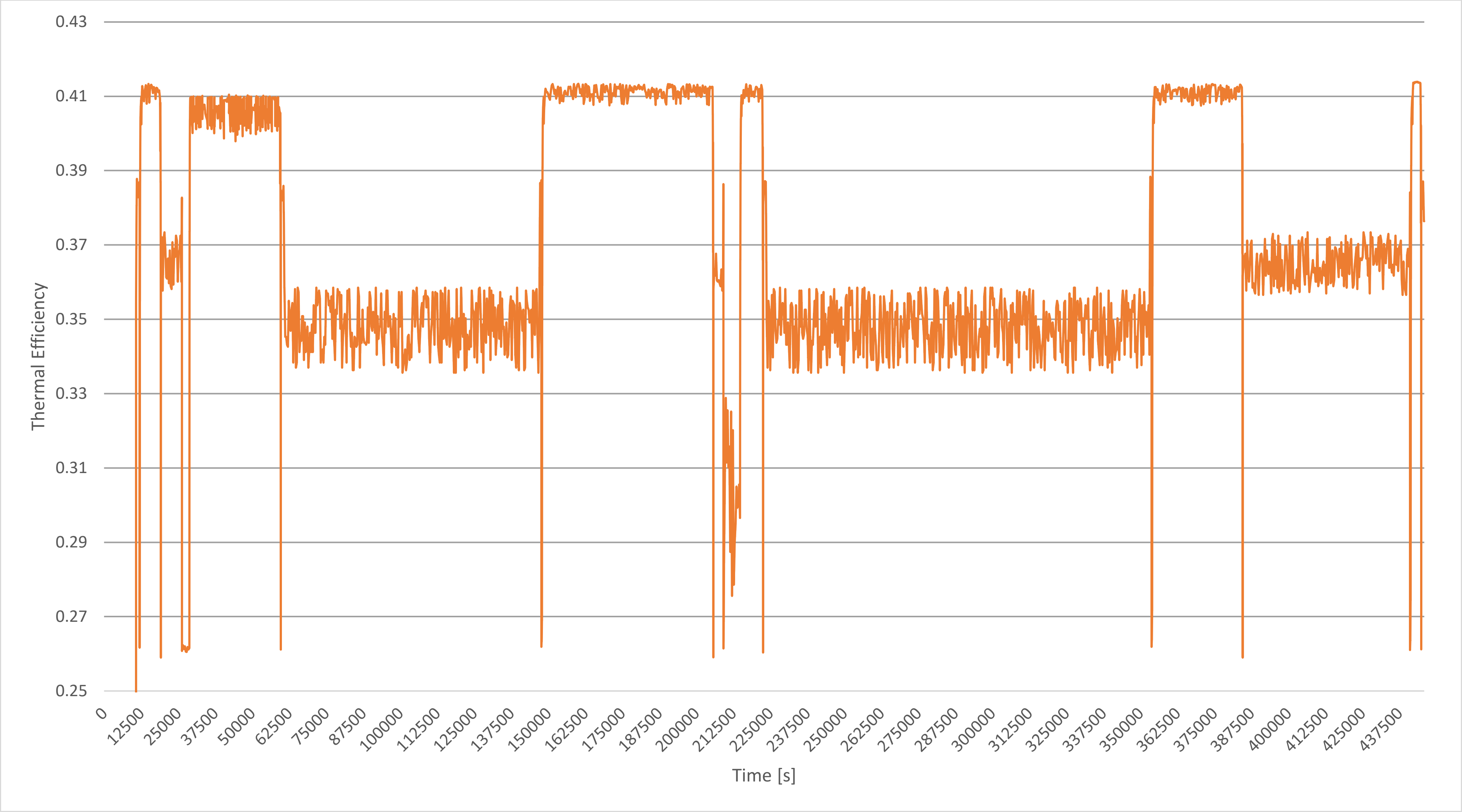


Figure 111. Overall thermal efficiency of Configuration 4/Scenario 2.

- Total fuel consumed

Fuel Consumption = 30.8061 tons

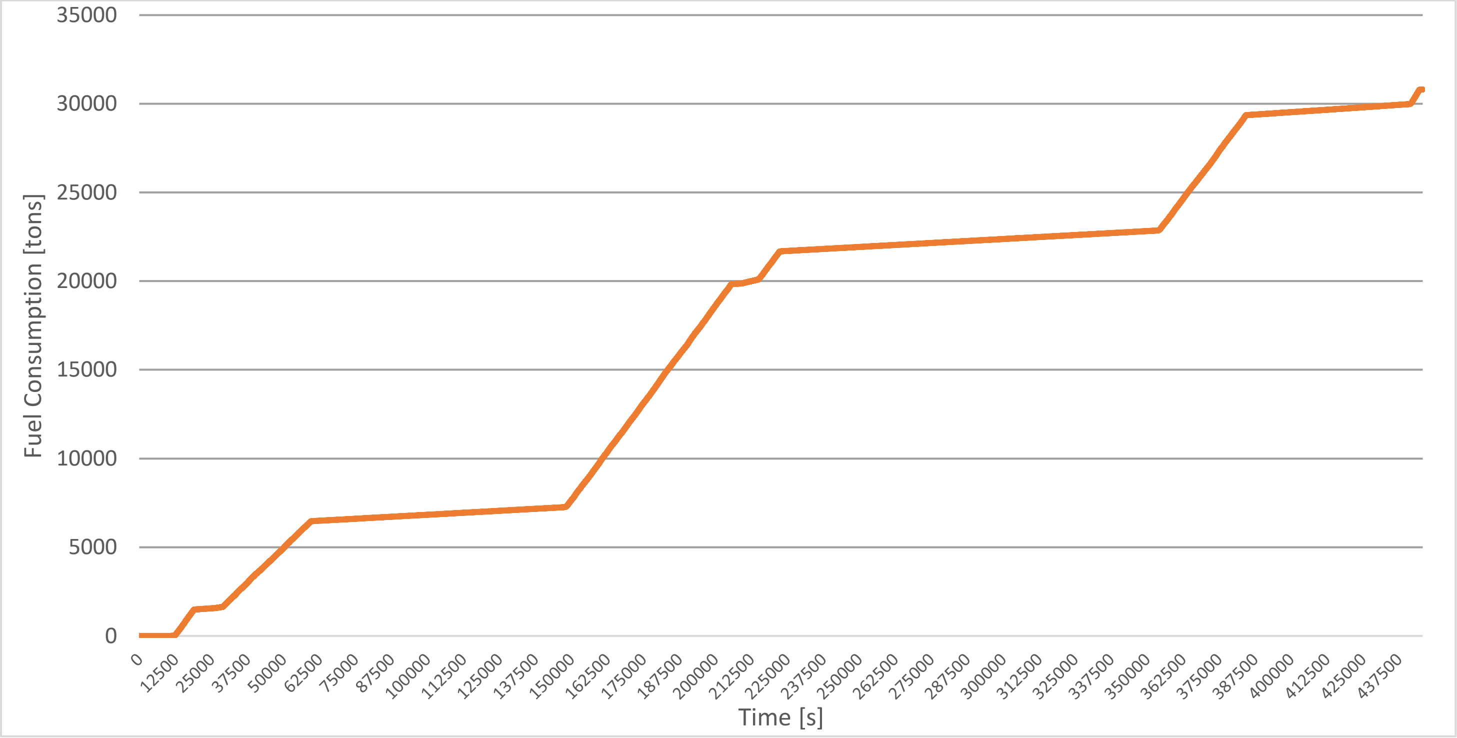


Figure 112. Fuel Consumption for Configuration 4/Scenario 2.

- CO_2 Emissions

CO_2 Produced = 98.764 tons

8.1.2.5. Scenario 2: Configuration 5 - Diesel-Electric with batteries.

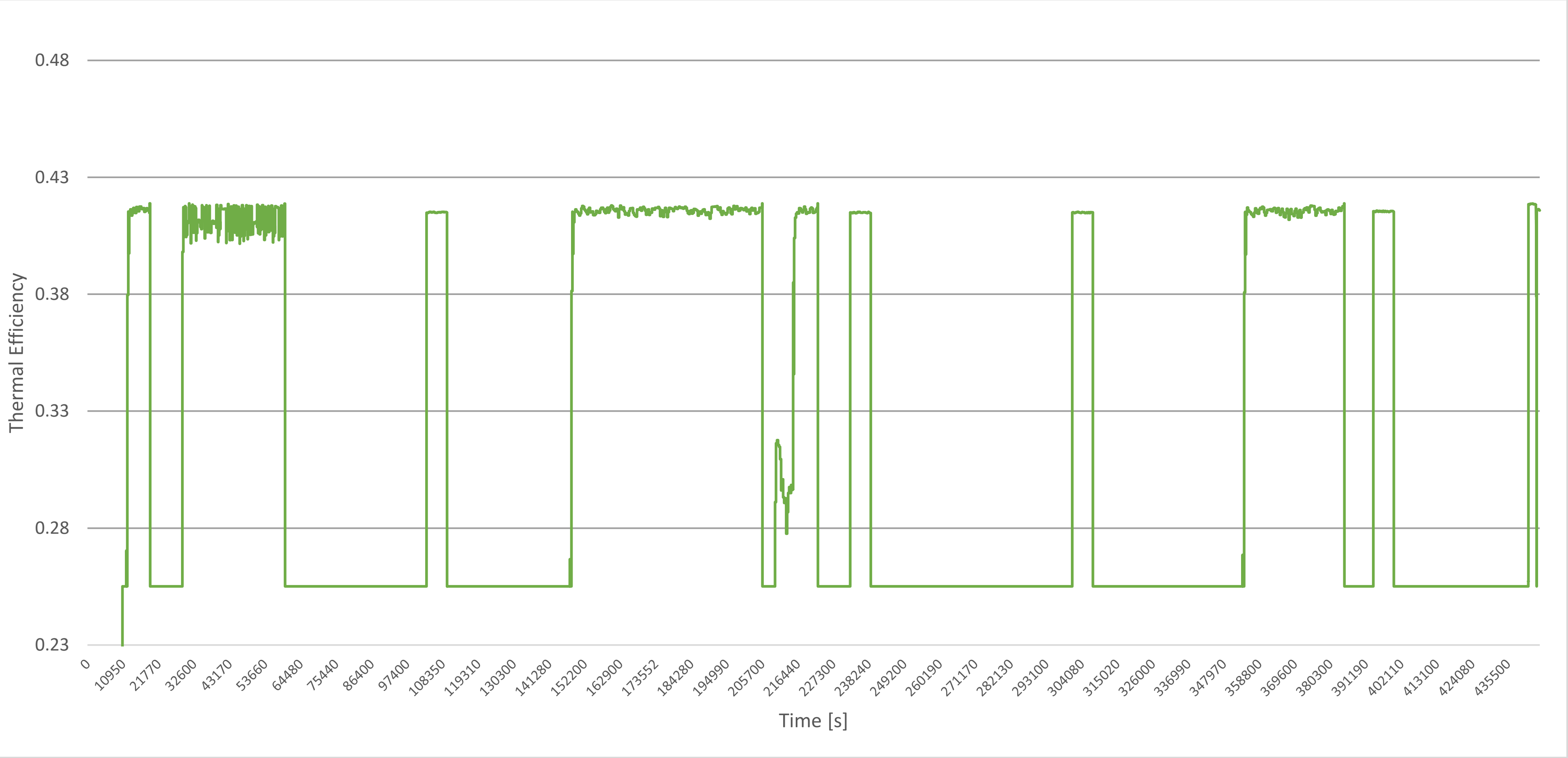


Figure 113. Thermal efficiency of the primary generator sets of Configuration 5/Scenario 2.

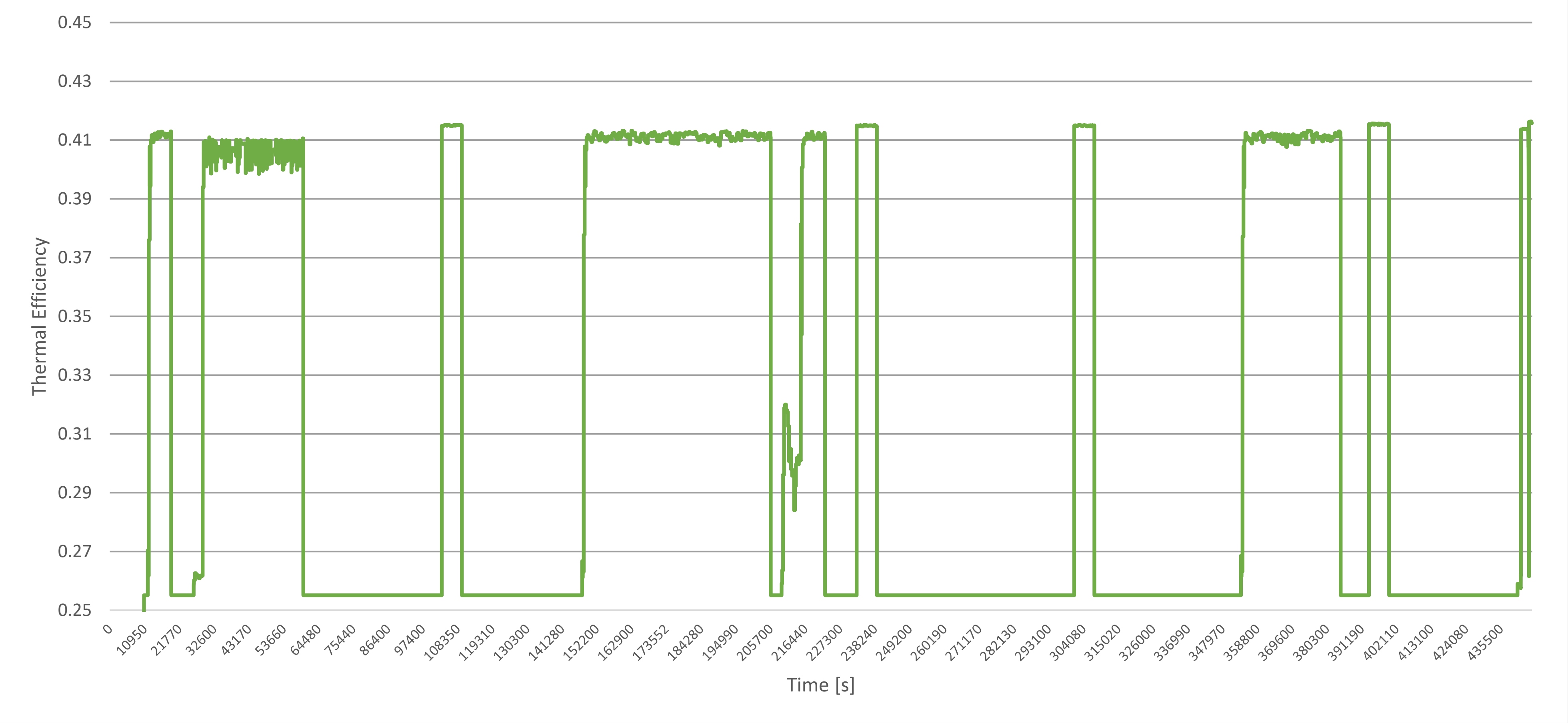


Figure 114. Thermal efficiency of the secondary generator sets of Configuration 5/Scenario 2.

Figure 115. Battery SOC of Configuration 5/Scenario 2.

- Total fuel consumed

$$Fuel\ Consumption = 29.9680\ tons$$

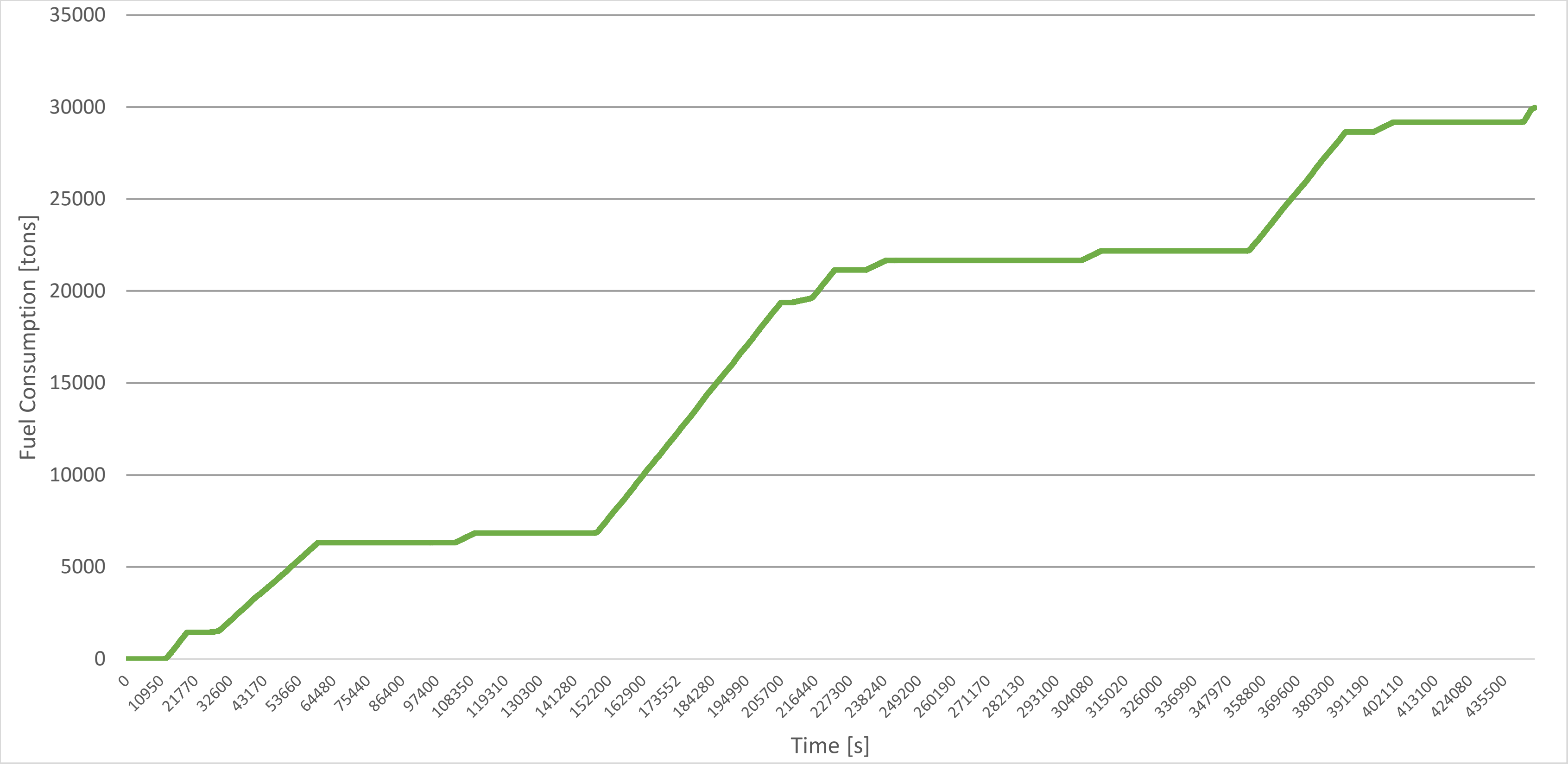


Figure 116. Fuel Consumption for Configuration 5/Scenario 2.

- CO_2 Emissions

$$CO_2 \text{ Produced} = 96.077 \text{ tons}$$

8.2. Overview and comparative analysis.

In this section, the comparative analysis is primarily centered on evaluating fuel consumption and thermal efficiency across distinct operational modes, with a keen focus on their implications for environmental sustainability. This examination compares various propulsion configurations, assessing not only their fuel efficiency and energy utilization but also their potential environmental impact. By understanding the variations in fuel consumption and thermal efficiency, we can draw insights into the ecological footprint of each configuration.

This analysis is key to identifying propulsion solutions that strike an optimal balance between operational efficiency and environmental responsibility, a crucial consideration in the design and selection of sustainable propulsion systems for mega-yachts. Additionally, this analysis also serves as a vital component in addressing environmental sustainability, highlighting which configurations minimize ecological impact while maintaining operational efficiency, thereby contributing to the development of more eco-friendly propulsion alternatives in the maritime industry.

8.2.1. Energy Analysis.

This first section of the analysis involves presenting an overall thermal efficiency comparison for both operational scenarios. These indexes will encapsulate the efficiency with which each propulsion configuration converts fuel into usable energy across all operational modes. This comparison aids in identifying the most energy-efficient systems, providing a basis for further detailed examination when comparing configurations' overall performance.

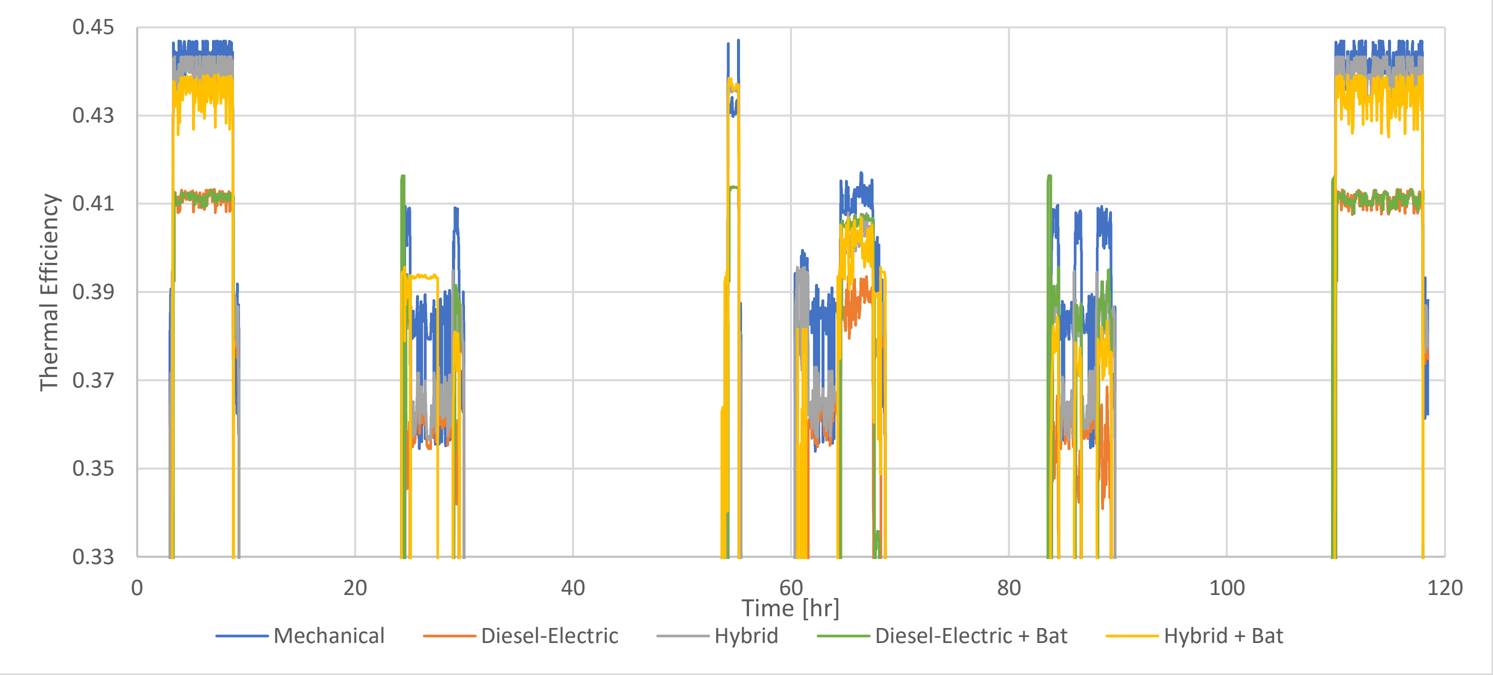


Figure 117. Thermal efficiency comparison chart for Scenario 1.

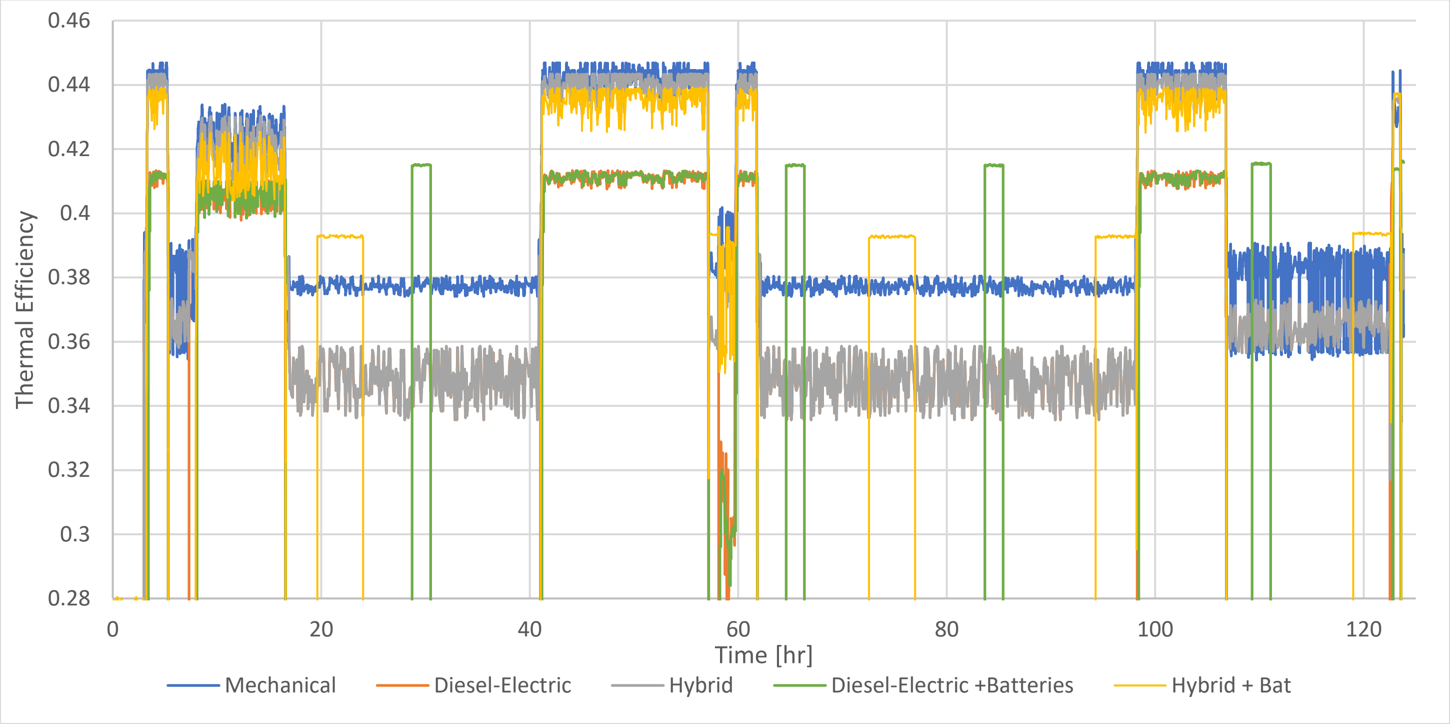


Figure 118. Thermal efficiency comparison chart for Scenario 2.

The thermal efficiency graphs offer a vivid illustration of how different propulsion configurations perform across various operational modes. A key observation from these graphs is the notably lower efficiency of the diesel-electric configuration (Configuration 4) across all modes, especially while cruising. This lower efficiency stems from the necessity for diesel-electric gen sets to simultaneously address both electric and propulsion demands, necessitating a higher generator sets minimum nominal power. Consequently, this leads to a reduced load percent, and thereby, diminished efficiency compared to other configurations (see Section 6.3.).

The incorporation of batteries into the diesel-electric setup (Configuration 5) marks a significant improvement in efficiency. Firstly, batteries can autonomously supply hotel loads when sufficiently charged. Secondly, through peak shaving, they facilitate generator sets operation at more optimal load levels. This strategic utilization of battery support not only balances the load on gen sets but also harmonizes power provision with efficiency, showcasing the benefits of integrating battery technology.

Comparatively, the hybrid (Configuration 2) and mechanical (Configuration 1) systems display closely matched thermal efficiencies, with the mechanical configuration edging ahead slightly, particularly at cruising speeds below 17 knots (cruising speed). This similarity indicates that both configurations achieve a high level of efficiency in transforming fuel into propulsion and electrical power. On the other hand, during the time periods that the yacht is berthed and is not powered through shore connection (see Scenario 2), we can observe that the hybrid (Configuration 2) has the exact same thermal efficiency as the Diesel-Electric (Configuration 4). This is due to the fact that they both have the same generator sets running at this point of time. However, all other configurations perform better while berthed either because of the more balanced loads or as a result of the ON-OFF running circles of the batteries.

Noteworthy is the superior efficiency of Configuration 5 during maneuvering operations, attributed to the batteries' capability to fully power these operations independently, assuming they are sufficiently charged. This highlights the strategic advantage of battery inclusion, providing a cleaner and more efficient operation without engaging the gen sets. Furthermore, the operation on battery power alone while maneuvering and docked as well presents a pivotal aspect of environmental and operational efficiency. This practice contributes to significant fuel savings, but also promotes the concept of zero emissions marinas, underlining the critical role of batteries.

It is important to point out that the effectiveness of battery-equipped configurations, especially in terms of enhancing thermal efficiency, is significantly influenced by how the batteries are utilized within the operational framework of the vessel. Strategies that optimize battery charging and discharging cycles, manage peak shaving effectively, and ensure batteries are deployed strategically during key operational phases can lead to substantial efficiency gains. Thus, the adoption of advanced battery management systems (BMS) that can dynamically adjust to changing operational needs, environmental conditions, and battery health status further enhances the potential for efficiency improvements.

Although thermal efficiency graphs serve as a valuable instrument for comparing the performance across configurations, it's observed that during the discharging states of battery-equipped configurations, thermal efficiency may exceed 1.0. This anomaly occurs as the power delivered by the batteries to the system can surpass the fuel heat input. Consequently, we advance by computing an average thermal efficiency index, providing a metric for comparing the configurations. Following this, a fuel consumption graph will be introduced, offering enhanced clarity on which configuration stands out in terms of efficiency.

To enhance the comparative analysis, a calculated average thermal efficiency index for each propulsion configuration is introduced. This index offers a concise measure of energy efficiency across varied operational scenarios, allowing for an immediate comparison of the systems' effectiveness.

$$Average\ Thermal\ Efficiency\ Index = \frac{Energy\ Converted}{Energy\ provided\ by\ fuel}$$

Equation 7. Average thermal efficiency index.

Where:

I. **Energy Converted** refers to the total output energy, including both electrical and mechanical energy produced by the system.
II. **Energy provided by fuel** is calculated as the product of the Fuel Consumed and the Fuel Calorific Value, representing the total potential energy input from the fuel.

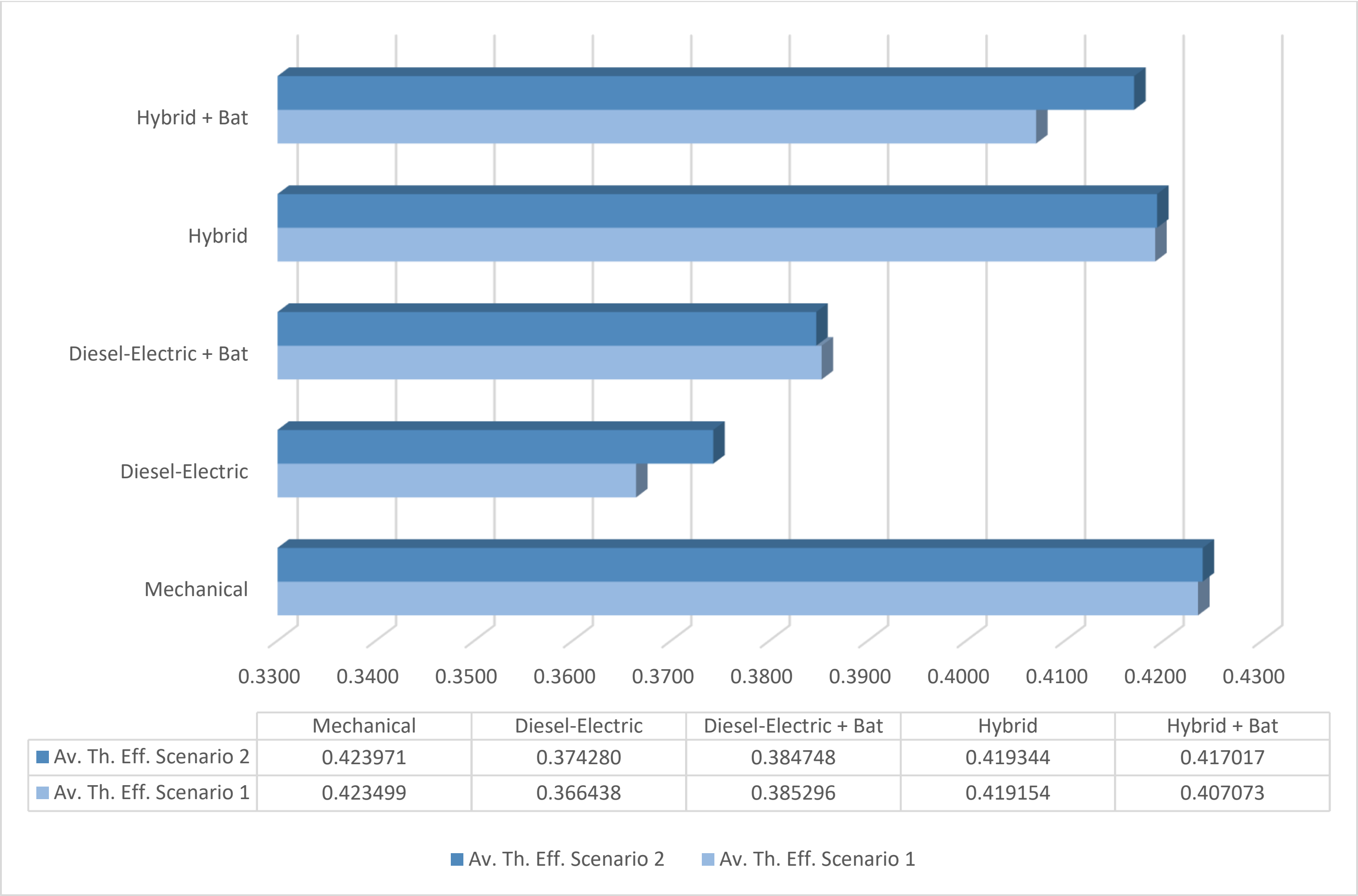
Given that:

- **Fuel Consumed** is measured during the operation.
- **Fuel Calorific Value** is specified as 42,700 kJ/kg for the fuel used in our scenarios.

Thus, the formula incorporates these values as:

$$Energy\ provided\ by\ Fuel = (Fuel\ Consumed\ kg)\ x\ (42{,}700\frac{kJ}{kg})$$

Equation 8. Energy provided by fuel.



	Mechanical	Diesel-Electric	Diesel-Electric + Bat	Hybrid	Hybrid + Bat
■ Av. Th. Eff. Scenario 2	0.423971	0.374280	0.384748	0.419344	0.417017
■ Av. Th. Eff. Scenario 1	0.423499	0.366438	0.385296	0.419154	0.407073

Figure 119. Average thermal efficiency comparison for both Scenarios.

This efficiency index is instrumental in identifying the most energy-efficient propulsion configuration, condensing multifaceted performance data into a single, comparative value. It stands as a crucial tool in the analysis, streamlining the process of evaluating the relative merits of each configuration based on their overall energy efficiency.

Based on the figure above, we conclude that the Mechanical propulsion (Configuration 1) is the best when asking which configuration has the best thermal efficiency in both scenarios. The second most consistent configuration is the Hybrid (Configuration 2) which is slightly behind the Mechanical in terms of average thermal efficiency. Moreover, it is important to point out the addition of batteries in Diesel-Electric propulsion can be crucial in increasing the thermal efficiency of the system as it can clearly observed. On the other hand, the same cannot be stated for the Hybrid configurations as the results show that the performance of Configuration 5 highly depends on the Scenario requirements.

- Fuel Consumption in Cruising Mode

Following the overview above, the analysis narrows down to a chart specifically dedicated to comparing the thermal efficiency of the propulsion configurations under cruising operation. This focused comparison will highlight how each configuration performs in terms of energy conversion during steady-state travel, where consistent speed and operational efficiency are paramount.

Additionally, the analysis then focuses on fuel consumption specifics during cruising mode, where the vessel operates at an average speed of 17 knots as the variability in power requirements influenced by weather and sea conditions has been accounted in order to provide insights into the fuel required per nautical mile. Such a comparison is vital for understanding the efficiency and environmental impact of each configuration under consistent operational conditions, providing a metric for evaluating performance where fuel efficiency directly correlates with reduced emissions.

The comparison between Mechanical (Configuration 1) and Hybrid (Configuration 2) configurations shows them to be nearly parallel in terms of fuel consumption, with the Hybrid configuration edging slightly ahead. On the other hand, the Diesel-Electric (Configuration 4) and Diesel-Electric with Batteries (Configuration 5) configurations present a different profile. These configurations exhibit similar efficiency patterns, yet the introduction of batteries in Configuration 5, particularly when operated in Peak Shaving mode, introduces a noticeable modification to the thermal efficiency trend.

The curves of the battery-equipped configurations tend to display a more "squared" profile. This distinctive shape results from the Battery Management System's (BMS) efforts to maintain as stable a load on the generators as possible, leveraging the batteries to absorb or supply power as needed to smooth out fluctuations in demand. This stabilization is particularly beneficial during cruising, where power needs can vary due to changing sea conditions, speed adjustments, and other operational factors. By minimizing load fluctuations, the BMS helps ensure that the generators operate within their most efficient load range for extended periods, enhancing overall fuel efficiency and reducing operational costs.

As for the Hybrid with Batteries solution (Configuration 5) the peak shaving cannot be that easily observed in the fuel consumption graph. This is due to the fact that the main fuel consumers in this configuration are the main engines and the peak shaving mode is utilized by the batteries which power the generator sets. Thus, although, the generator sets manage to keep a steady load through peak shaving, this does not result in an observable reduction of fuel consumption.

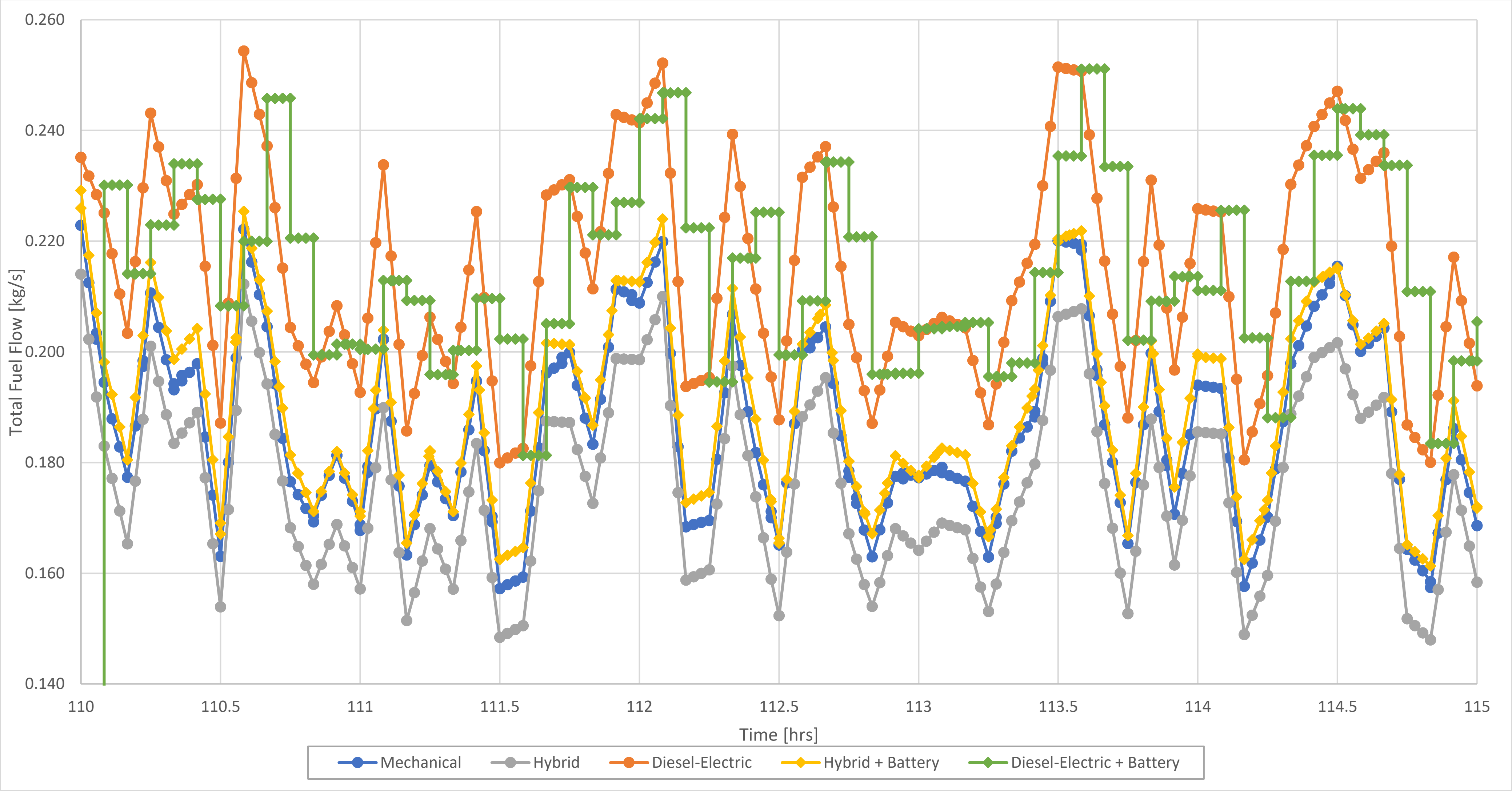


Figure 120. Fuel Consumption under cruising speed comparison chart.

8.2.2. Economic Analysis.

In the comparative analysis of fuel consumption across different propulsion configurations, a key factor considered is the cost implications associated with the use of Marine Gas Oil (MGO). For this purpose, the total fuel consumption for each configuration has been meticulously calculated per schedule, providing a basis for evaluating the economic impact of operational choices.

To ensure accuracy and relevance in this assessment, the average price of MGO during the summer period, spanning from 1st May to 30th October, has been utilized. Notably, in the Port of Piraeus, this price stood at an average of 873.5 USD per metric ton [21]. This price point serves as a critical reference in estimating the operational costs associated with the fuel consumption of the various propulsion configurations under consideration.

Scenario 1: Cyclades

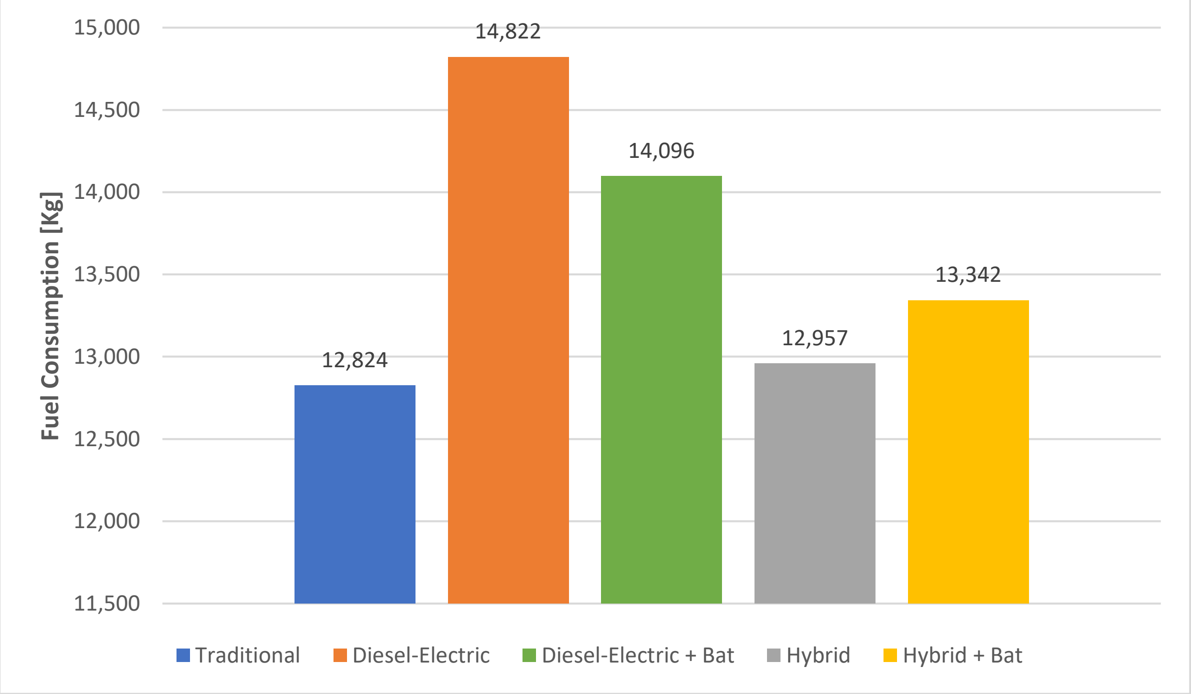


Figure 121. Fuel consumption comparison for Schedule no. 1.

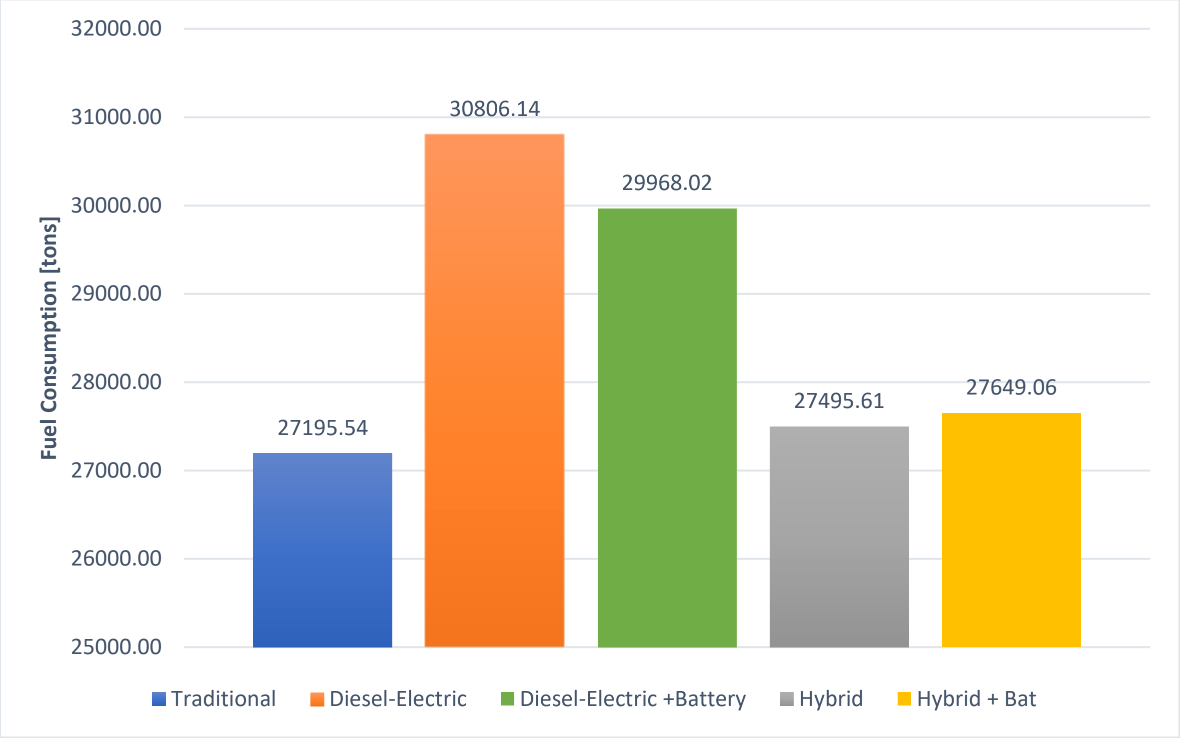


Figure 122. Fuel consumption comparison for Schedule no. 2.

Configurations 1 (Mechanical) and 2 (Hybrid) display remarkably similar fuel consumptions, reflecting their close thermal efficiency as highlighted in the energy analysis section. This near parity in fuel costs between the Mechanical and Hybrid configurations suggests that the slight thermal efficiency advantage of the Mechanical setup translates into comparably minor economic benefits in terms of fuel expenses.

On the other hand, the Diesel-Electric configuration (Configuration 4) emerges as the worst in terms of fuel consumption. This outcome aligns with expectations set by its lower thermal efficiency.

However, the addition of batteries to the Diesel-Electric configuration (Configuration 5) introduces a significant dynamic to the economic analysis. The implementation of batteries, particularly through strategic management such as Peak Shaving, results in approximately a 5% reduction (Scenario 1) in fuel costs. This cost-saving effect is attributed to the batteries' role in stabilizing generator load, allowing for more consistent operation within the efficient load range and reducing the total fuel consumed.

For Configuration 3 (Hybrid with Batteries), there's a slight rise in fuel consumption when compared to Configuration 2 (Hybrid), a consequence attributed to the cycles of battery charging. This increase might initially seem counterproductive, yet further examination will demonstrate that the "extra" fuel utilized for battery substantially curtails expenses related to shore power connection. This interplay between fuel consumption for battery charging and the economization on shore power utilization underscores a strategic approach to operational cost management within the context of hybrid propulsion systems equipped with battery support.

To comprehensively assess the cost-effectiveness of various propulsion configurations, it's important to extend the economic comparison beyond fuel consumption to include the cost of electricity for battery charging, especially when utilizing shore connection. The significance of this comparison is based on potential high costs associated with charging batteries through shore power, which can impact the overall economic viability of a configuration.

Given the fact that the exact values of the shore connection power at each point of time are known, calculating the cost for power consumption in marinas becomes an easy task. It's important to note that the power consumed from shore remains consistent across all three non-battery configurations (Mechanical, Diesel-Electric, and Hybrid).

The initial step involved gathering data on electricity costs incurred while moored in the marinas designated in our vessel's operational schedule [22] [23] [24].

Subsequently, the total power consumption from shore connection for each marina was multiplied by the corresponding cost (Euros/kWh) to derive the total electricity cost for each configuration.

Table 18. Shore connection cost analysis for non-battery configurations (Scenario no. 1).

Non-Battery Propulsion Configurations

	Location	Rate kWh (Euros)	Consumption (kWh)		Cost (Euros)
1	Flisvos	0.37	377.58	€	139.70
2	Mykonos	1.00	1912.19	€	1,912.19
3	Mykonos	1.00	3059.74	€	3,059.74
4	Naxos	0.50	626.56	€	313.28
5	Santorini	0.75	1907.10	€	1,430.32
6	Santorini	0.75	2525.46	€	1,894.10
	Total		10408.63	**€**	**8,749.33**

Table 19. Shore connection cost analysis for Configuration 5 (Scenario no. 1).

Diesel-Electric with Batteries

	Location	Rate kWh (Euros)	Consumption (kWh)	Cost (Euros)	
1	Flisvos	0.37	0.38	€	0.14
2	Mykonos	1.00	2601.09	€	2,601.09
3	Mykonos	1.00	4080.12	€	4,080.12
4	Naxos	0.50	0.63	€	0.31
5	Santorini	0.75	3207.76	€	2,405.82
6	Santorini	0.75	2471.64	€	1,853.73
	Total		12361.61	**€**	**10,941.21**

Table 20. Shore connection cost analysis for Configuration 3 (Scenario no. 1).

Hybrid with Batteries

	Location	Rate kWh (Euros)	Consumption (kWh)	Cost (Euros)	
1	Flisvos	0.38	0.38	€	0.14
2	Mykonos	1.00	1040.68	€	1,040.68
3	Mykonos	1.00	2553.78	€	2,553.78
4	Naxos	0.50	0.63	€	0.31
5	Santorini	0.75	1329.32	€	996.99
6	Santorini	0.75	1329.32	€	996.99
	Total			**€**	**5,588.89**

However, given the considerable variation in electricity prices across marinas, an average price per kWh was calculated to facilitate a fair comparison. This approach ensures that configurations relying more heavily on shore connection, particularly those with battery systems, are not unfavorably compared to non-battery configurations solely due to high electricity rates in certain marinas. This average cost offers a balanced basis for evaluating the economic implications of shore power use across different propulsion systems.

Table 21. Unified shore connection cost analysis for non-battery configurations (Scenario no. 1).

Non-Battery Propulsion Configurations/ Rates Unified

	Location	Rate kWh (Euros)	Consumption (kWh)	Cost (Euros)	
1	Flisvos	0.66	377.58	€	247.31
2	Mykonos	0.66	1912.19	€	1,252.48
3	Mykonos	0.66	3059.74	€	2,004.13
4	Naxos	0.66	626.56	€	410.40
5	Santorini	0.66	1907.10	€	1,249.15
6	Santorini	0.66	2525.46	€	1,654.18
	Total		10408.63	**€**	**6,817.65**

Table 22. Unified shore connection cost analysis for Configuration 5 (Scenario no. 1).

Diesel-Electric with Batteries / Rates Unified

	Location	Rate kWh (Euros)	Consumption (kWh)	Cost (Euros)
1	Flisvos	0.66	0.38	€ 0.25
2	Mykonos	0.66	2601.09	€ 1,703.71
3	Mykonos	0.66	4080.12	€ 2,672.48
4	Naxos	0.66	0.63	€ 0.41
5	Santorini	0.66	3207.76	€ 2,101.08
6	Santorini	0.66	2471.64	€ 1,618.92
	Total		12361.61	**€ 8,096.85**

Table 23. Unified shore connection cost analysis for Configuration 3 (Scenario no. 1).

Hybrid with Batteries / Rated Averaged

	Location	Rate kWh (Euros)	Consumption (kWh)	Cost (Euros)
1	Flisvos	0.66	0.38	€ 0.25
2	Mykonos	0.66	1040.68	€ 684.25
3	Mykonos	0.66	2553.78	€ 1,679.11
4	Naxos	0.66	0.63	€ 0.41
5	Santorini	0.66	1329.32	€ 874.03
6	Santorini	0.66	1329.32	€ 874.03
	Total			**€ 4,112.07**

By integrating the data previously discussed, a series of graphs are generated, providing an analytical overview of the total costs associated with each configuration. These graphs visualize the economic impact of each propulsion configurations, with both fuel consumption and shore connection costs encapsulated within the defined operational schedules.

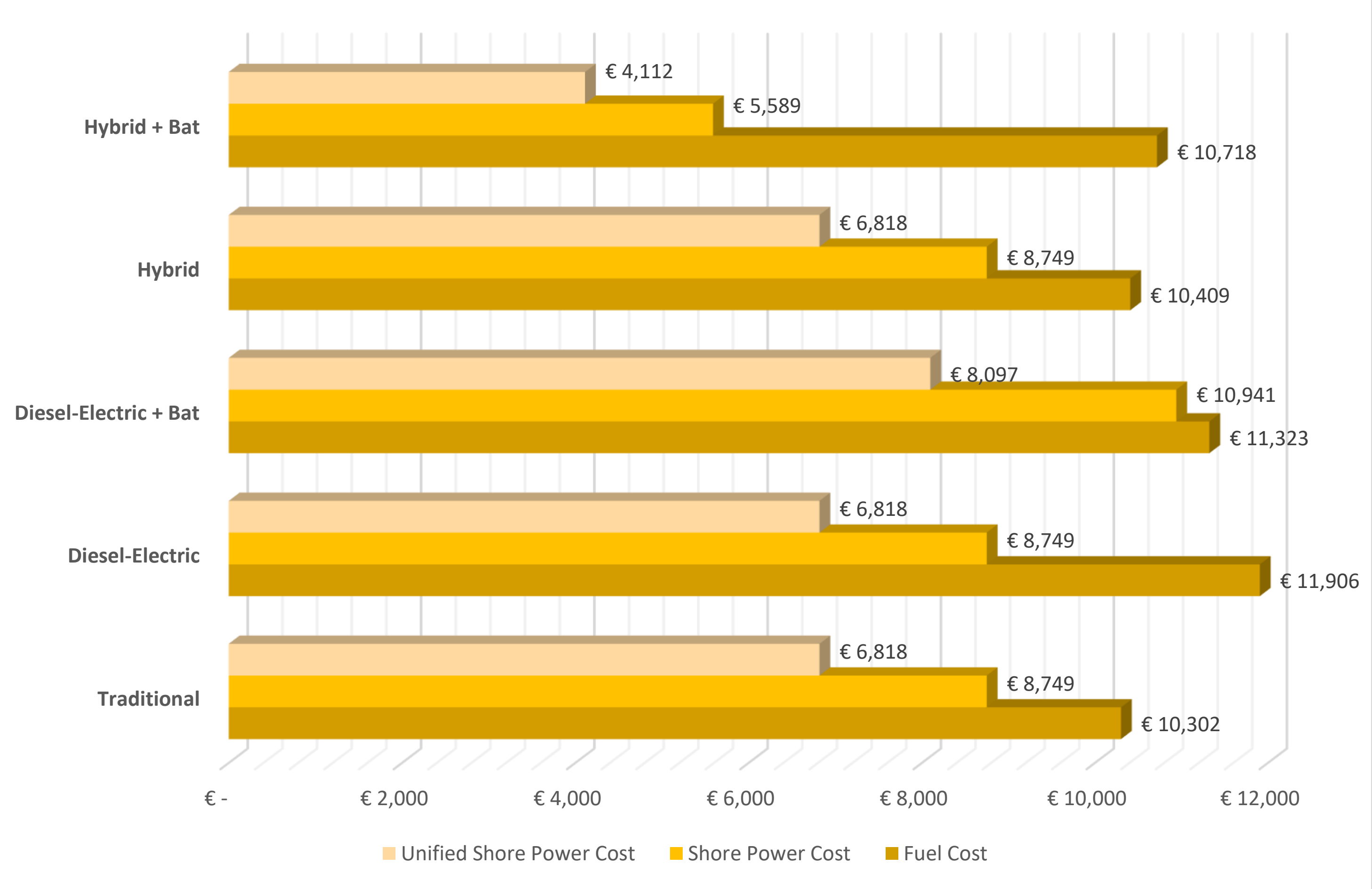


Figure 123. Total cost analysis for Scenario no. 1.

As previously noted, the costs for configurations without batteries (Scenario 1: Configurations 1, 2, and 4) remain the same due to identical consumption patterns when connected to shore power for their electrical needs. For configuration 5, an increase in shore connection cost is observed, a consequence of the substantial energy required to charge the batteries. This increased cost reflects the higher demand placed on shore power resources to replenish battery stores, an essential process for ensuring the batteries are adequately charged to meet operational demands. On the other hand, the analysis of Configuration 3 shows a significant decrease in shore connection costs (40% for unified costs in Schedule no. 1), which is a result of the utilization of batteries.

Moreover, regarding Schedule number 1, from a cost-per-voyage perspective, the integration of batteries into diesel-electric propulsion systems (Configuration 5) incurs higher expenses compared to the non-battery configuration, primarily due to the elevated kWh prices prevalent in many marinas. On the contrary, Configuration 3 provides the most affordable solution. Key to this performance is the highly reduced costs of shore connection.

As for the shore connection costs for Schedule No. 2, the analysis is considerably more straightforward due to the presence of a single mooring interval within the schedule. This simplification is primarily attributed to the size constraints of the marinas, which are unable to accommodate yachts of our specified dimensions. In the following, table the total cost of each propulsion configuration is presented.

Table 24. Shore connection cost analysis for Scenario 2.

Non-Battery Propulsion Configurations

Location	Consumption (kWh)	Rate kWh (Euros)	Cost (Euros)
Flisvos	377.58	0.37	€ 139.70

Diesel-Electric with Batteries

Location	Consumption (kWh)	Rate kWh (Euros)	Cost (Euros)
Flisvos	2424.26	0.37	€ 896.98

Hybrid with Batteries

Location	Consumption (kWh)	Rate kWh (Euros)	Cost (Euros)
Flisvos	0.37	0.37	€ 0.14

As we can observe, the shore connection costs during Scenario 2 are vastly different from those encountered in Scenario 1. Consequently, the cost analysis presented below offers a summation of the total costs, rather than dividing between fuel and shore power expenses.

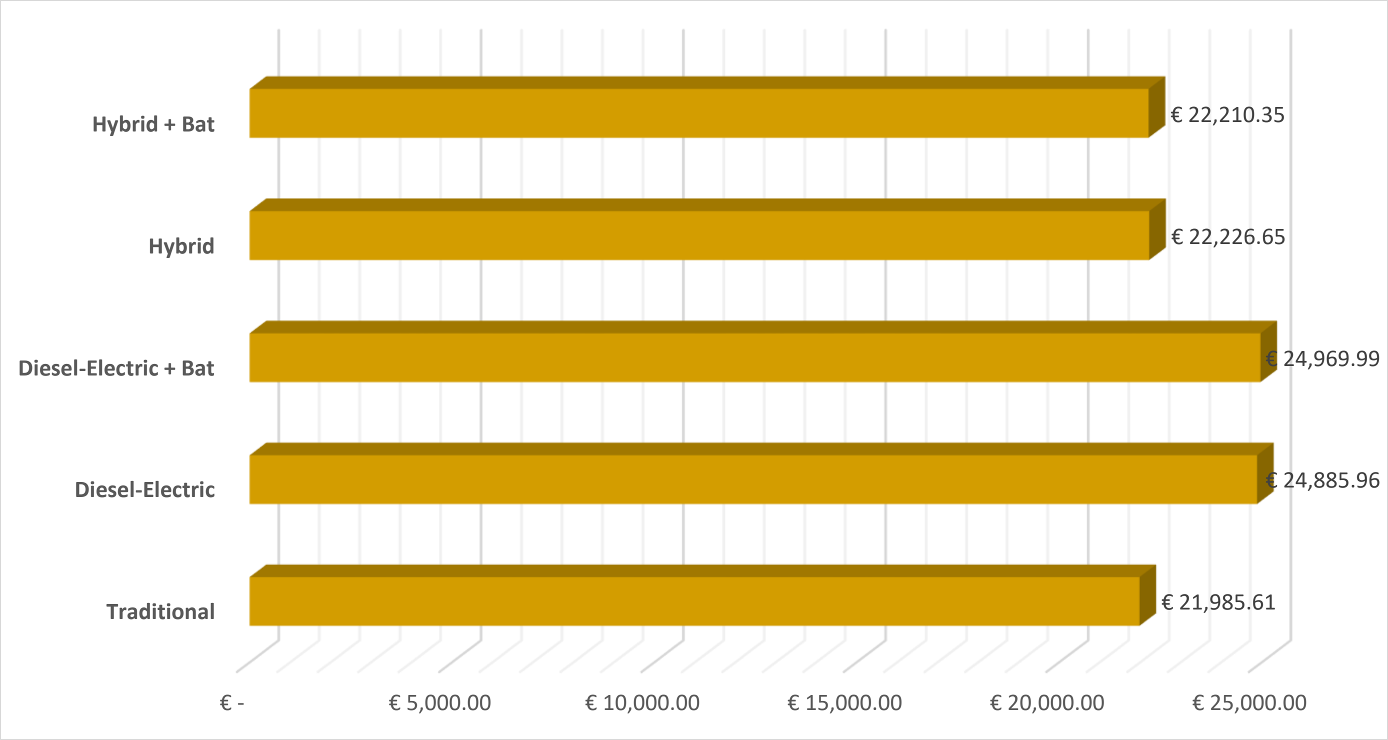


Figure 124. Total cost analysis for Scenario no. 2.

During Scenario 2, the cost analysis shows some slight differences and similarities with the previous one. First of all, since the yacht is not able to moor in any marina, except

Flivos (starting position) Configuration 3 cannot take advantage of its batteries the same way as in Scenario 1. As a result, Configurations 1, 2 and 3 have almost identical total costs. On the other hand, similar to Scenario 1, the Diesel-Electric configurations (4 and 5) present the highest costs

However, an essential consideration in this economic analysis is the broader operational and maintenance implications of battery use. Through strategic charging and energy management, batteries can substantially reduce the running hours of a yacht's machinery, including both propulsion engines and generator sets. Moreover, by enabling these systems to operate under more consistent and optimal loads, batteries contribute to a reduction in wear and tear, potentially lowering maintenance costs over time. Operating machinery within its efficient load range not only enhances fuel efficiency but also minimizes the mechanical stress and operational strains that can accelerate component degradation. This reduction in maintenance requirements, resulting from less variable operational loads and fewer running hours, represents a significant long-term cost-saving aspect that can possibly offset the higher immediate costs associated with shore power charging.

Transitioning from the analysis of operational and maintenance costs, it becomes crucial to delve into the market trends, particularly focusing on sales and resale values of yachts. This aspect of the discussion offers insight into how the broader market perceives and values different propulsion configurations, highlighting the impact of technological advancements and environmental considerations on yacht investment and ownership dynamics.

The appeal of hybrid and full electric systems extends beyond their operational and environmental benefits. These technologies are perceived as indicators of innovation and forward-thinking design, attributes that resonate with buyers looking to invest in vessels that stand at the cusp of maritime evolution. This perception significantly contributes to the potential for higher resale values for yachts equipped with such propulsion systems. Environmentally conscious buyers, motivated by the desire to minimize their ecological impact while enjoying the luxury and autonomy that yachting offers, are more likely to value the advanced technology and reduced emissions of hybrid and electric configurations. This demand, in turn, can translate to a premium in the resale market, where such yachts are seen as not only more sustainable but also as a smarter long-term investment.

However, it's important to acknowledge the persistence of traditional perceptions among many yacht owners regarding propulsion systems. The belief that traditional mechanical propulsion systems offer unparalleled reliability is a testament to this old-fashioned perspective. This viewpoint underscores a preference for proven, time-tested technologies over newer, perhaps less familiar alternatives.

8.2.3. Environmental and Sustainability Analysis.

The importance of environmental criteria in evaluating these configurations cannot be overlooked, particularly in light of the International Maritime Organization's (IMO) ongoing commitment to steering the maritime industry towards a greener future. This commitment underlines the necessity of integrating environmental considerations into the assessment of propulsion technologies, ensuring that the maritime sector aligns with broader sustainability goals and regulatory frameworks aimed at reducing the environmental footprint.

- Fuel Consumption Overview

A foundational aspect of this environmental analysis is the examination of fuel consumption across the different propulsion configurations. By presenting overall data for fuel consumption, we establish a baseline understanding of each system's fuel efficiency and its implications for environmental impact (see Figure. 121 and Figure. 122)

As expected, these graphs mirror the patterns observed in both the fuel costs and thermal efficiency analyses, reflecting a consistent relationship between fuel consumption and propulsion system efficiency across the configurations.

- CO2 Production Comparison

Concluding the environmental analysis, the comparison of CO2 production for each propulsion configuration draws upon previously presented data, offering a quantifiable measure of each system's contribution to greenhouse gas emissions. This comparison not only highlights the direct environmental impacts of the configurations but also aligns with the IMO's objectives for emission reductions, providing a clear indication of which propulsion technologies are more conducive to achieving a sustainable maritime future.

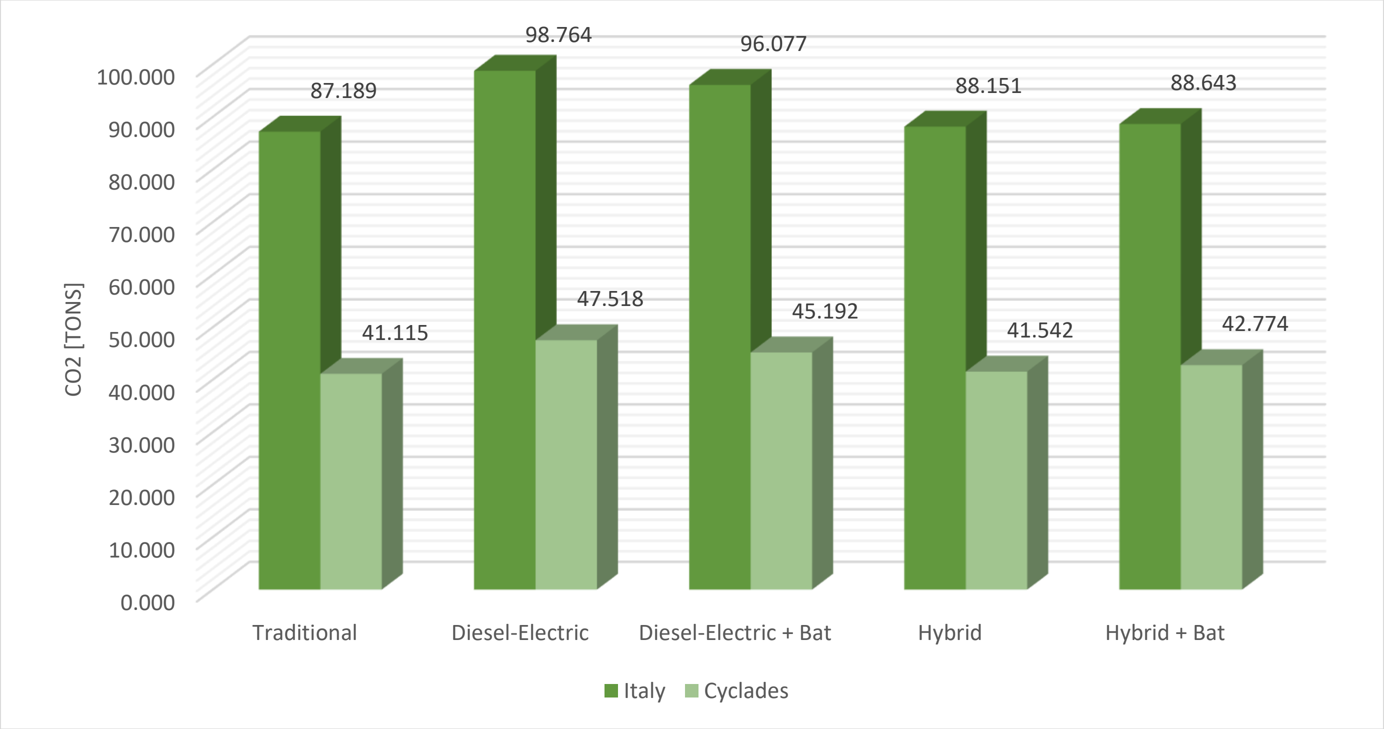


Figure 125. CO2 production comparison chart for both Scenarios.

Transitioning from discussions on fuel consumption and CO2 production, it's vital to highlight the environmental benefits of zero-emission marina modes and the ability of battery-equipped configurations to traverse sensitive areas, such as the Corinth Canal, without running the engines. This not only results in zero emissions during such operations but also contributes significantly to creating zero-emission areas. The ability of battery-powered systems to maintain operations silently and cleanly, especially in ecologically sensitive or regulated zones, underscores the potential for greener maritime practices. Embracing these technologies promotes a more sustainable and environmentally responsible approach to yachting, aligning with broader efforts to reduce the maritime industry's ecological footprint and lead the shift towards greener maritime operations.

In luxury yachting, the emphasis on an exceptional onboard experience cannot be overstated, with quiet operation and minimal vibration being crucial components of this experience. Hybrid and full electric propulsion systems are ideal at providing these benefits. The use of electric motors in these configurations leads to significantly reduced noise and vibration levels compared to traditional diesel engines, directly contributing to a more serene and comfortable environment onboard. This reduction in noise is not just a byproduct of electric propulsion but a deliberate design feature that enhances the luxury yachting experience.

Moreover, the inclusion of batteries in these systems introduces the capability for completely silent operation. When the yacht is powered solely by batteries, it can operate without any engine noise, creating an unparalleled atmosphere of tranquility. This feature is especially valuable during mooring or slow cruising through sensitive or scenic areas, where the absence of engine noise allows passengers to fully enjoy the surroundings without disturbance.

This advanced capability of hybrid and full electric systems to merge silent operation with the luxury demands of yacht owners represents a significant evolution in yachting. It not only meets the high standards for comfort and luxury but also aligns with the increasing desire for environmentally conscious boating solutions, offering a perfect blend of sustainability and tranquility.

9. Conclusion

9.1. Summary of the analysis.

In this thesis, the objective was to construct accurate and realistic simulation models for five distinct propulsion configurations of a reference yacht under two different operational scenarios. This endeavor was guided by an analysis of prevailing market trends and projections regarding the future landscape of the maritime industry, ensuring that the selected configurations reflect both current preferences and anticipated shifts in demand.

A foundation for creating these well-structured models was the use of real test data and the construction of a detailed and realistic timetable simulated two potential voyages that a yacht of similar specifications might undertake during the summer high season. This crucial data was acquired through private communication with engine manufacturers and providers, enriching the simulations with authentic performance parameters. Furthermore, the construction of a detailed and realistic timetable simulated two potential voyages that a yacht of similar specifications might undertake during the summer high season. This simulation effort extended beyond propulsion needs, incorporating the yacht's electricity consumption for auxiliary machinery and hotel loads, providing a comprehensive view of the yacht's operational demands.

Employing the gPROMS platform and premade libraries such as “LIBARIES NAME” we managed to create detailed models that serve as “digital twins” of the equivalent yacht’s propulsion configurations. Moreover, by properly developing power management plans for each propulsion configuration, we aimed to achieve the best possible thermal efficiency in each model in order to achieve a fair comparison between the different configurations.

The thesis concludes with the analytical comparison of results, focusing on crucial factors such as thermal efficiency, fuel consumption, gas emissions and the costs associated with fuel and electricity. This all-rounded analysis examined the propulsion configurations under energy, environmental, and economic criteria, providing a well-balanced evaluation of the configurations under study.

9.2. Key outcomes

After analyzing the outcomes of the simulations conducted, several key findings emerge, underscoring the nuanced interplay between propulsion configurations, operational strategies, and their implications in the yachting industry.

Traditional mechanical propulsion continues to stand out as a highly reliable and efficient option among the various propulsion solutions available in the yachting industry. Even amidst the introduction of newer technologies, mechanical systems demonstrate a level of consistency and performance efficiency that keeps them competitive for yacht owners and designers.

Hybrid propulsion emerges as closely rivaling traditional mechanical systems in terms of efficiency and cost. It is safe to say that with the right configurations and adjustments, especially the strategic integration of batteries, hybrid systems have the potential to outperform in the future. This proposition underscores the importance of fine-tuning and innovation within hybrid configurations to unlock their full efficiency and economic benefits.

Battery-equipped configurations demonstrate distinct operational advantages through two primary modes: peak-shaving and on-off operation. Peak-shaving enables a stable load on the engines, which can notably extend the machinery's lifespan by minimizing wear and tear. Conversely, the on-off mode significantly reduces the engines' operational hours, contributing to lower maintenance requirements.

The incorporation of batteries into propulsion systems, like hybrid or diesel-electric configurations, significantly enhances both efficiency and cost savings. However, the utilization of these advantages is influenced by multiple factors, including the voyage's nature (access to charging stations and intervals between marinas), the batteries' specifications, and the battery management system's strategy. These considerations are crucial in determining how effectively battery can improve the performance and reduce operational costs of the propulsion system.

Furthermore, the direct correlation between CO2 production and fuel consumption brings to light the mechanical configuration's superiority in minimizing emissions. This finding suggests that while the development of new, greener technologies is imperative, there is also a substantial opportunity for advancements in traditional propulsion methods. Enhancing the environmental performance of mechanical systems could serve as a viable pathway to achieving greater sustainability in the yachting industry, indicating that innovation within conventional propulsion technologies remains a critical area for future research and development.

Lastly, a direct correlation is found between CO2 emissions and fuel consumption, underscoring the environmental impact of operational choices in propulsion systems. This relationship emphasizes the need for continuous innovation and improvement across all propulsion technologies, including the performance of traditional solutions, which could serve as a viable pathway to achieving greater sustainability in the yachting.

9.3. Proposals for future work.

In the concluding section, we outline directions for future research, building upon the groundwork established in this thesis. A primary recommendation involves broadening the dataset from engine manufacturers, which would enable a more precise matching of propulsion systems to the vessel's specific requirements. Additionally. enhancing the precision of data related to the (Required Propulsion – Velocity) curve and electrical consumption in various operational modes could significantly improve the realism and accuracy of our simulations.

In enhancing the accuracy of our simulations, a pivotal focus would be on capturing the impact of environmental conditions, such as weather, on propulsion and electricity demands. Instead of relying on randomization, developing a methodology that incorporates predictive models or historical data analysis could offer a broader understanding of how specific weather conditions influence operational efficiency. This approach aims to bridge the gap between simulated scenarios and the dynamic challenges presented by real-world maritime environments, ensuring that the models reflect the true complexity of navigating under varied environmental conditions.

Lastly, the formulation of comprehensive power management plans for each propulsion configuration emerges as essential for maximizing efficiency. While the detailed development of these plans is beyond this thesis's current scope, it represents a critical path for future research. Investigating a wider spectrum of operational scenarios and power requirement fluctuations further would illuminate the efficiency and adaptability of different propulsion systems across a full range of operational conditions. Such explorations promise to evolve the maritime industry towards more efficient, environmentally friendly, and operationally effective propulsion technologies.

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