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EXAMINATION OF THE ENERGY EFFICIENCY OF CONTAINER SHIP ELECTRIC PROPULSION SYSTEMS

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ABSTRACT

Maritime transport is crucial for global trade, transporting over 10 billion tons of containers annually. Conventional propulsion systems like diesel engines have been used for years, but the International Maritime Organization (IMO) is pushing for alternative solutions due to increasing environmental impacts. In 2019, international shipping, including container ships, accounted for 2.1% of global greenhouse gas emissions. The study aimed to improve the efficiency of the diesel electric propulsion system. To evaluate one such solution, this study simulated an offshore container ship's diesel-electric (DE) propulsion system, assessing fuel consumption and emissions across three scenarios. The load profile was created using the ship's navigation data, and the simulation aimed to build configurations for generators to run at maximum load and batteries to contribute to power balance. Unlike prior works limited to port or coastal vessels, the proposed approach evaluates three distinct propulsion scenarios, including battery-assisted operation and zero-emission port adaptation, within a unified methodological structure. This study selected the container ship type because it frequently performs maneuvering operations and operates under variable engine load conditions during these periods. The results of three scenarios indicate fuel consumption reductions of 2.9%, 5.3%, and 10.38% respectively

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KONTEYNER GEMİLERİNİN ELEKTRİK TAHİRİK SİSTEMLERİNİN ENERJİ VERİMLİLİĞİNİN İNCELENMESİ

ÖZET

Deniz taşımacılığı, küresel ticaret için kritik öneme sahiptir ve yılda 10 milyar tondan fazla konteyner taşımaktadır. Dizel motorlar gibi geleneksel tahrik sistemleri yıllardır kullanılmaktadır, ancak artan çevresel etkiler nedeniyle Uluslararası Denizcilik Örgütü (IMO) alternatif çözümler için baskı yapmaktadır. 2019 yılında, konteyner gemileri dâhil uluslararası deniz taşımacılığı, küresel sera gazı emisyonlarının %2,1'ini oluşturmuştur. Bu çalışmanın amacı, dizel elektrik tahrik sisteminin verimliliğini artırmaktır. Bu tür alternatif çözümlerden birini değerlendirmek amacıyla, bu çalışma bir açık deniz konteyner gemisinin dizel-elektrik (DE) tahrik sistemini simüle ederek üç senaryo kapsamında yakıt tüketimini ve emisyonları değerlendirmiştir. Yük profili, geminin seyir verileri kullanılarak oluşturulmuş; simülasyon, jeneratörlerin maksimum yükte çalışmasını sağlayacak ve bataryaların güç dengesine katkıda bulunacağı yapılandırmalar geliştirmeyi hedeflemiştir. Liman veya kıyı bölgesinde çalışan gemilerle sınırlı önceki çalışmalardan farklı olarak, önerilen yaklaşım; batarya destekli işletme ve sıfır emisyonlu liman uyumunu da içeren üç farklı tahrik senaryosunu, bütüncül bir metodolojik yapı içerisinde değerlendirmektedir. Bu çalışmada konteyner gemi tipi, sık manevra yapması ve bu süreçlerde değişken makine yükleri altında çalışması nedeniyle seçilmiştir. Sonuçlar üç senaryoya göre sırasıyla yakıt tüketiminde 2,9 % , 5,3 % ve 10,38 % azalma olduğunu göstermektedir

Anahtar Kelimeler: *Elektrik Tahrik Sistemi, Gemi Makineleri İşletme Mühendisliği, Enerji Verimliliği, Egzoz Gazı Emisyonları*

1.INTRODUCTION

Sustainability is defined as the process of optimum management of resources to maintain the quality of life of both the current and future generations (Ozispa, 2021) In order to guarantee the sustainable management of resources, authorities have developed regulations through various organizations. Regarding maritime transport, for example, as a member of the UN family, the IMO is actively pursuing the 2030 Agenda in order to achieve the UN's Sustainable Development Goals (SDGs) that aim to end poverty and promote sustainable development (Tay and Konovessis, 2023). According to the revised IMO GHG Strategy, adopted at MEPC 80 in July 2023, international shipping is expected to reach net-zero greenhouse gas (GHG) emissions by or around 2050, with indicative checkpoints of at least a 20–30% reduction by 2030 and a 70–80% reduction by 2040, compared to 2008 levels (IMO, 2023). Decarbonization of shipping is expected to accelerate the electrification of power generation and propulsion systems, which will increase operational flexibility and efficiency, and reduce power consumption and emissions. Novel power generation systems like hybrid diesel-electric or fuel cells are expected to be applied in environmentally sensitive areas (On and Fagan, 2022).

Although an increase in system structure complexity requires new control options, propulsion systems still often use traditional methods. However, the use of such traditional control methods in advanced systems in automotive and maritime research has failed to reduce fuel consumption and emissions, despite increasing system cost and complexity (Sciarretta et al., 2014). Recent studies have shown that incorporating direct current (DC) power distribution and battery optimizations, and smart control strategies can reduce fuel consumption and emissions by 10% to 35% (Zahedi and Norum, 2013) Furthermore, given that ships have multiple main engines, electric motors, generators, fuel cells and a variety of energy storage systems, more diverse propulsion system alternatives are possible (Silvas et al., 2015). In particular, hybrid-electric propulsion systems are gaining popularity in the maritime industry, particularly in offshore support vessels and harbor tugs. These systems provide additional energy on demand, improving reliability, operational efficiency, fuel consumption rates, environmental footprints, and maintenance costs. A fully integrated hybrid system includes energy storage, power generation, and power management systems (On and Fagan, 2022).

Container ships achieve optimum load values during long-distance cruises and design speeds. Hence variable operating profiles, such as frequent maneuvering or slow steaming, result in inefficient load values for diesel engines (Völker, 2015). Conventional propulsion systems struggle with variable operating profiles, making them unsuitable for fuel-

efficient designs, whereas electric propulsion systems offer an alternative for various ship types. However, they cause additional transmission losses of 5-15% of the power produced in electrical components, leading to the emergence of several types of electrical propulsion systems to reduce these losses (Pamik and Nuran, 2021; Viran and Menten, 2021).

These systems include the following (Inal et al., 2022) :

- Hybrid combinations of mechanical and electric propulsion systems
- Separate or hybrid combinations of various power sources, such as diesel engines, steam or gas turbines, fuel cells, or energy storage systems
- Direct current (DC) or alternating current (AC) electricity distribution

Numerous studies have investigated DE propulsion systems. Weinrit and Neumann (2011), assessed one cruise ship's cargo characteristics, revealing that lithium-ion batteries were the most efficient alternative. They also optimized diesel engines, controllers, and batteries to minimize fuel consumption. Their findings highlight the need for an alternative to hybrid propulsion technology on ships. Sakalis et al. (2018) applied the synthesis, design, and operation method to optimize multiple hybrid systems in a model ship. They modeled diesel engines, generator sets, boilers, steam turbines, and waste heat recovery steam turbines to re-evaluating efficiencies and costs. Jeong et al. (2018) conducted a case study on a hybrid propulsion ferry, evaluating its investment cost based on maintenance-attitude, fuel consumption, reliability, safety, and environmental pollution reduction.

In their study of tugboat power systems in India, Kolar et al. (2008) found that fixed speed and variable speed diesel engines meet payload requirements while also having superior fuel consumption, emissions, and conventional propulsion systems. The fixed speed DE drive system was more advantageous (Kolar et al., 2008). Wang et al. (2023) compared battery-free DE and COGES propulsion systems for cruise ships, finding that COGES offers better environmental results but costs 20% more to run (Wang et al., 2023). Zhou et al. (2023) proposed and evaluated a DC hybrid system powered by batteries and diesel generators for a ship in the Northern Sea Route (NSR). Adopting an efficiency-optimization control approach, they analyzed fuel consumption and power source losses in lab-scale experiments conducted at the Shanghai Marine Diesel Engine Research Institute to compare the proposed system with conventional hybrid systems (Zhou et al., 2023).

Although many studies on electric propulsion systems have been carried out in recent years, they are limited to ships operating in the port area or tugboats, and smaller ships in coastal areas, which easily indicates

the advantages of electric propulsion systems. In contrast, our study simulates an offshore container ship's DE propulsion system and assesses its fuel consumption and emissions in three different scenarios. First, the load profile was produced after gathering the ship's 40-day navigation data. To account for electrical conversion losses, this load profile was used for modelling the DE propulsion system. Using a mathematical model for a conventional DE propulsion system, the analysis assumed that a hybrid DE propulsion system using batteries and a DE propulsion system adaptable to zero emission ports can perform the same tasks as the container ship. The goal of the simulation was to identify the configurations required for the generators to run at r maximum load and build a system that allows the batteries to contribute to the power balance.

2.METHODOLOGY

This study aimed to demonstrate the effect of using electric propulsion systems to comply with increasingly stringent regulations on harmful emissions from ships while reducing the need for fossil fuels. A case study design was preferred to simulate the operation of electrical propulsion systems in three different scenarios in one specific container ship, *Gülbeniz A*, owned by Arkas Shipping Co. Figure 1 shows the ship's 40-day cruise route used in our analysis.



Figure 1. *Gülbeniz A*'s Route and Ports of Call

When selecting a ship to implement an electrical propulsion system, it is crucial that it can outweigh the economic disadvantages, increase operational efficiency, and reduce total costs. A crucial factor is the ship's load profile because diesel engines consume more fuel at low loads. Frequent maneuvering is essential for operating at low or variable loads because it requires more controlled and slower movement (Pamuk and Nuran, 2021; Viran and Mentis, 2021).

Ships use slow steaming to save fuel although it causes inefficient main engine operation and higher fuel consumption per unit power. In contrast, electrical propulsion systems enable more efficient operation of diesel engines, thereby reducing fuel consumption without imposing time constraints (Halff, 2017). Figure 2 shows how electric propulsion systems can optimize fuel consumption despite varying loads.

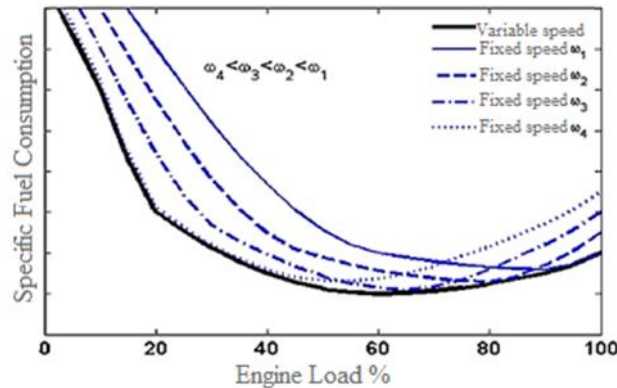


Figure 2. Diesel Engine Load-Specific Fuel-Oil Consumption / Shaft Revolution (Barsali et al., 2004)

As Figure 2 shows, a diesel engine’s minimum fuel consumption depends on whether the engine is operating at fixed or variable speed. For fixed-speed operation, fuel consumption depends on the speed. In all conditions, fuel consumption is lowest at 70–80% load and clearly increases at lower or higher loads. Electrical propulsion systems enable production of the desired power with more than one main power generator, thereby enabling the engines to be operated within their optimum load ranges.

Three different scenarios were simulated for DE or hybrid propulsion system applications for a ship engaged in offshore cargo transportation. The selection of electrical propulsion systems should prioritize cruising at low loads to reveal their advantages, but the instantaneous loads’ values should be accurately determined. As already noted, the container ship *Gülbeniz A*, owned by Arkas Shipping, was selected because it met the above-mentioned specifications. In particular, the ship has a data logger that can receive and record instantaneous machine load values. *Gulbeniz A* has a main engine power of 21,770 kW and a service power of 5,960 kW, including the emergency generator. Table 1 presents the ship’s full technical characteristics.

Table 1: Gülbeniz A Characteristics

Build Completion Date – Location	04 / 2011 – Volkswerft Stralsund GmbH / Germany
Flag	Turkish
GRT / NRT	26,195 / 12,947
DWT	34,973
IMO No	9491850
Class	+100 A5 EP IW NAV – OC BWM DG ERS Container ship + MC AUT / GL
Length	210.54 m.
Breadth	29.80 m.
Summer Draught	11.40 m.
Engine type, power, rotation speed	MAN-Diesel 7L 70 ME-C MCR 21.770 KW / 108 RPM
Speed	21.7 knots
Number of holds	5
Cranes	3 x Liebherr SWL 45/40/36 tons x 23/26/29 mtrs
Reefer capacity	306 reefer plugs (258 plugs on deck + 48 plugs in hold)
Capacity	2,478 TEU
Hold weight and size capacity	992 TEU (310 x 40' + 16 x 20')
Deck weight and size capacity	1,486 TEU (425 x 40' + 43 x 20')
Homogeneous cargo weight	1,868 TEU

M/V Gülbeniz A's engine load values were converted into numerical data at five-minute intervals to ensure high accuracy. These data were then converted into power values corresponding to the specified load, using catalog data prepared by MAN, the main engine manufacturer. These instantaneous power (P_{GA}) values are produced by the main engine and transmitted to the ship's propeller. Figure 3 shows the main engine load during two voyages totaling 40 days of cruising.

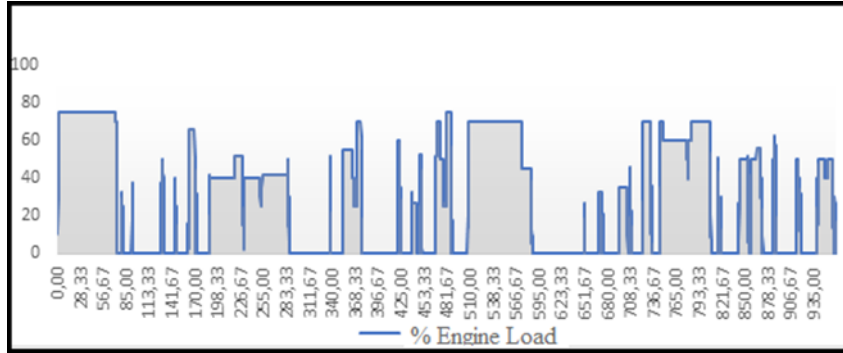


Figure 3. Gülbeniz A main engine load over 40-day cruise

In order to achieve more realistic results, the time intervals of the transferred data were kept as short as possible as five-minute intervals, resulting in 11,520 numerical data entries covering 960 hours. The most important finding revealed in Figure 3 is that, overall, the ship's engine only operated for a short time within the 70-80% load range, which, as already explained, is the range in which a ship's main engine works most efficiently with the lowest fuel consumption values per kilowatt hour. This indicates that this case is appropriate for the study's focus, in which the prime movers already provide optimum operating performance and reduce fuel consumption and harmful emissions.

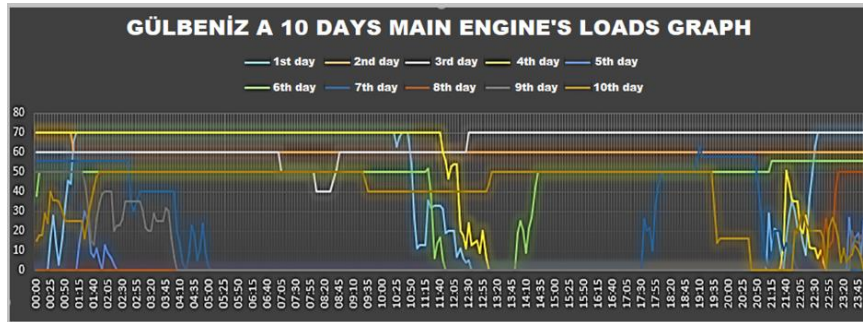


Figure 4. Gülbeniz A's Main Engine Daily Load Graph Over the Final 10 Days of 40-Day Cruise

Figure 4 shows the same engine loads as Figure 3 but presents them for the last 10 days of the cruise to show how Gülbeniz A's engine load varied frequently. Load fluctuations during arrival and departure maneuvers, strait crossings, and in areas with heavy ship traffic can cause the main prime movers to operate inefficiently, resulting in higher fuel consumption. The 5-minute engine load figures were obtained, then utilized in the MATLAB program for further analysis (Table 2).

Table 2: Main Engine Load Figures by Time and Day

Day / Time	28	29	30	31	32	33	34	35	36
00:30	0	0	35	28	70	60	70	0	50
00:35	0	0	35	14	70	60	70	0	50
00:40	0	0	35	3	70	60	70	0	50
00:45	0	0	35	17	70	60	70	0	50
00:50	19	0	35	33	70	60	70	0	50
00:55	25	0	35	46	70	60	70	0	50
01:00	23	0	35	44	70	60	70	0	50
01:05	6	0	35	66	60	60	70	0	50
01:10	27	0	35	70	60	60	70	0	50
01:15	19	0	35	70	60	60	70	13	50
01:20	24	0	35	70	60	60	70	22	50
01:25	7	0	35	70	60	60	70	30	50
01:30	3	0	35	70	60	60	70	24	50
01:35	0	0	35	70	60	60	70	9	50
01:40	0	0	35	70	60	60	70	7	50
01:45	0	0	35	70	60	60	70	11	50
01:50	0	0	35	70	60	60	70	5	50
01:55	0	0	35	70	60	60	70	0	50

The data shown in Table 2 was used for all scenarios to simulate one ship (Gülbeniz A) operating with the same load requirements using electrical propulsion systems. In compliance with the IMO sulfur regulations, Gülbeniz A is required to switch from heavy fuel oil (HFO) to marine gas oil (MGO) while at European ports and in emission control areas (ECAs). Since January 2020, a global sulfur cap of 0.50% m/m has been in force, with a stricter limit of 0.10% m/m in ECAs (IMO, MARPOL Annex VI, Regulation 14). In the present simulations, it was not feasible to model two separate fuel types simultaneously, so MGO consumption

was converted into its HFO equivalent by adjusting the calorific value. This approach enabled the total fuel consumption to be presented consistently based on a single fuel type, without affecting the comparative analysis of different propulsion scenarios.

Simulations are crucial for researchers because it is challenging to conduct real-world experimental studies of high-cost machinery like ship propulsion systems. Our study compared three scenarios: traditional DE propulsion systems, hybrid power systems with batteries, and hybrid power systems that can adapt to zero emission ports due to their high battery capacity.

The Wartsila 6L46 diesel engine with a power of 5,850 kW, commonly used in DE propulsion systems, was selected as the generator for all three scenarios, using its catalog data for data collection (Wärtsilä, 2019).

The electrical propulsion system was simulated for Gülbeniz A's load characteristics using MATLAB. Finally, the electrical propulsion system equipment was specified in order to create the simulation. It was given the following basic elements:

- AC /DC circuit
- Generator
- Energy storage device (EDC)
- Converters, rectifiers
- Electric motors- Propellers

2.1. Scenario 1

Scenario 1 modeled a conventional DE(Diesel Engine) propulsion system without batteries, aiming to maintain the load shared by four generators at minimum fuel consumption for diesel engines. A typical DE propulsion system diagram is shown in Figure 5.

Instead of a single large main engine in a conventional propulsion system, power from multiple smaller power capacity diesel generator sets feeds a fixed-frequency, high-voltage electrical grid. In most cases, this network feeds the electric motor driver and other electrical loads outside the propulsion system by means of a transformer. In fixed-blade-angle propeller systems, the electric motor driver includes electronic power converters to control propeller shaft speed and, in turn, the ship's speed.

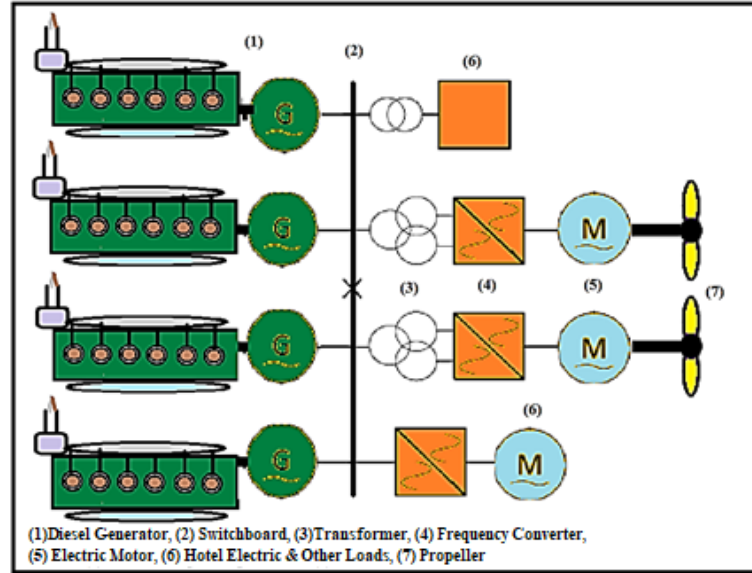


Figure 5. Conventional DE Propulsion System Layout

While fuel consumption values may vary by engine manufacturer, the equation for the specific fuel consumption is as follows:

$$SFOC = C_0 + aP_m + bP_m^2 \quad (1)$$

The five-minute load values of Gülbeniz A's main engine, represent instantaneous power, P_{Gi} . These power values should also be produced by the generator set group used in the simulation so that they result in the same shaft power. However, it should be acknowledged that generators in electrical propulsion systems result in larger power losses by the time power is transmitted to the propeller (Sofras and Prousalidis, 2014). Therefore, in order to transfer an equal amount of power to the propeller in the simulation, the power produced by the generators (P_g) was calculated as follows:

$$P_g = P_{Gi} \frac{\eta_c}{\eta_g * \eta_{dd} * \eta_d * \eta_{EM}} \quad (2)$$

where η_g is generator efficiency, η_{dd} is diode rectifier efficiency, η_d is converter efficiency, η_{EM} is electric motor efficiency, and η_c is conventional system direct transmission efficiency.

However, because the instantaneous power (P_i) to be used in the simulation is still not equal to P_g , the power produced by the auxiliary machines (P_a) used to meet the conventional system's electricity need should be added to this value.

$$P_i = P_g + P_a \quad (3)$$

It was not possible to obtain all the instant auxiliary engine load values of *Gülbeniz A*. Instead, data were obtained for total working hours (h_{GT}), total fuel consumption (FC_{GT}), and specific fuel consumption ($SFOC_G$). The P_a value, which is assumed to affect the value of P_i in the simulation with the available data, was calculated formulas follows:

$$P_a = \frac{FC_{GT}}{h_{GT} * SFOC_G} \quad (4)$$

Applying the algorithm in MATLAB, it was possible to determine how many generators should be run according to the P_i values. In the first scenario, the aim was to calculate total fuel consumption (FC_{T1}) by selecting the minimum SFOC (g/kwh) ($SFOC_{min}$) values for each P_i value, as follows:

$$FC_{T1} = \sum_{k=1}^n P_{ik} * SFOC_{min} / 12$$

where the value 12 is due to the P_i values being taken every 5 minutes..

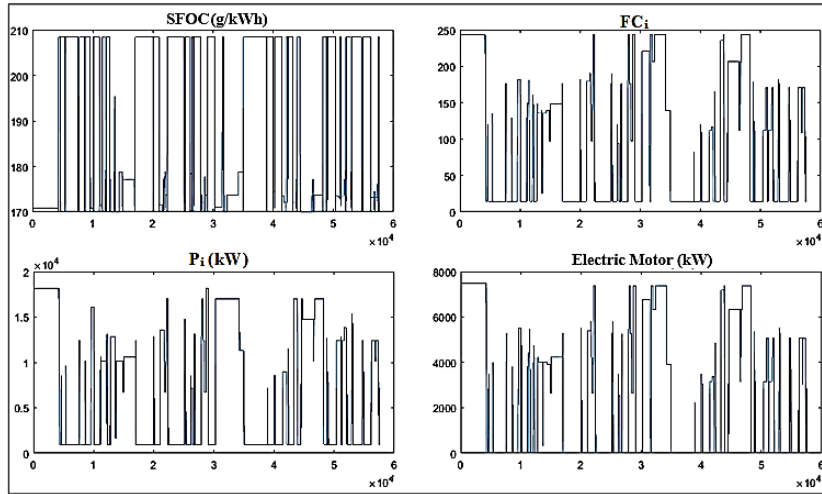


Figure 6. MATLAB simulation graphs (Scenario 1)

Figure 6 presents the findings from the DE simulation conducted in MATLAB, specifically the generators' FC_{T1} values operating for power generation, their instantaneous fuel consumption, the power produced, and output power during *Gülbeniz A*'s 40-day cruise. Figure 6 shows the SFOC values at variable loads, instantaneous fuel consumption (FC_i) values, the

P_i values, and the power values given to the electric motor (P_{EO}) to be transferred to the propeller.

The difference (ΔFC_1) between the official total fuel consumption of Glbeniz A (FC_{GA}) reported by the ship's crew during the same 40-day cruise and the FC_1 calculated in the simulation can be determined as follows:

$$\Delta FC_1 = FC_{GA} - FC_1$$

The change in emissions was calculated using the IMO's fuel-based emission factors (EF_f) (IMO, 2018) while the IMO's carbon emission factor (EF_{fCO_2}) (IMO 2018) was used to measure the reduction (ΔE_{CO_2}) in carbon dioxide (CO_2) emissions.

$$\Delta E_{CO_2} = \Delta Y T_1 * EF_{fCO_2}$$

Sulfur oxide (SO_x) emissions depend on fuel consumption, fuel sulfur content, and use of exhaust gas cleaning systems if fitted. The fuel-based SO_x emission factor (EF_{fSO_x}) was calculated as follows:

$$EF_{fSO_x} = 2 * 0,97753 * S$$

This equation reflects the assumption that 97.753% of the sulfur in the fuel is converted to SO_x (the remainder is converted to sulfate/sulfide aerosol and classified as part of particulate matter), the value 2 represents the ratio of the fuel's molecular weight. Because the vast majority of SO_x in ship emissions is SO_2 , the reduction in SO_x (ΔE_{SO_x}) was calculated as follows:

$$\Delta E_{SO_x} = \Delta Y T_1 * EF_{fSO_x}$$

NO_x emissions were calculated using the IMO's energy-based emission factor (EF_e). The IMO classifies diesel engines into three groups according to the number of revolutions (n), with a specific NO_x emissions equation for each. The following formula for medium-speed diesel engines (EF_{eNO_x}) was appropriate for our model (IMO 2018):

$$EF_{eNO_x} = 9 * n^{-0.2}$$

In its third and fourth GHG study, the IMO used 500 as the n value for medium-speed engines, which was taken as the reference for the present study. Because Glbeniz A has a slow-speed engine, the IMO's NO_x emission factor (EF_{eNO_x}) value (3.4 g/kWh) was used and the difference between the two (ΔE_{NO_x}) was calculated to make a comparison (IMO, 2018).

2.2. Scenario 2

This scenario aimed, by using batteries, to ensure that the ship's generators can operate within the optimum load range as much as possible. That is, the generators produce extra energy for energy needs below the optimum load range that can be stored by the batteries, which can then provide additional energy to the system for energy needs above the generators' optimum load. The batteries can also meet some small loads in line with their capacities without requiring any generator to work. Figure 7 presents the hybrid propulsion system simulated in Scenario 2.

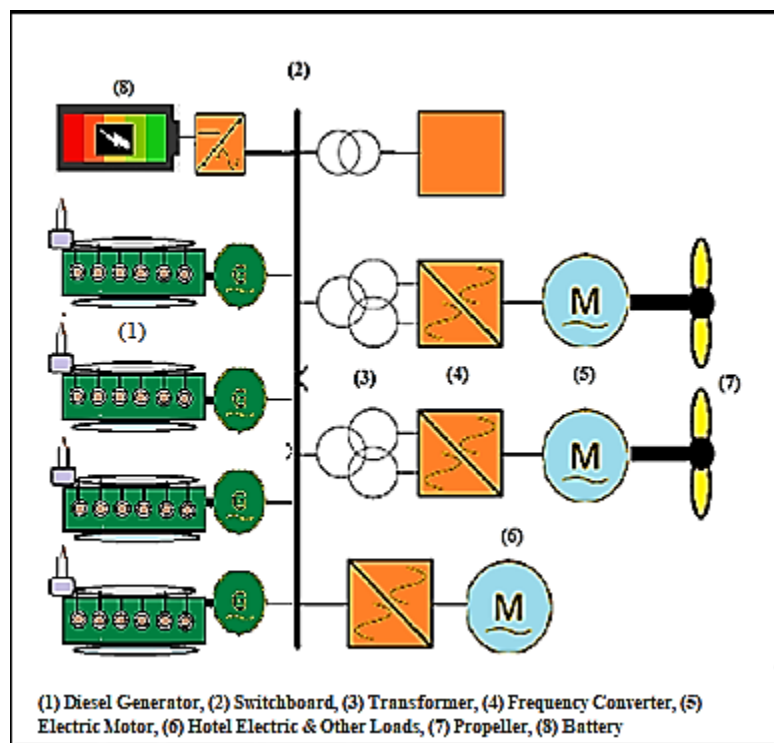


Figure 7. Hybrid propulsion system layout

The hybrid propulsion system shown in Figure 7 was created by adding batteries to the DE propulsion system in Scenario 1 (Figure 5). Some limitations were defined in the proposed energy management system to ensure safe battery operation. The first is state of charge (SOC). Discharging a battery to low SOC values is not recommended because it shortens battery life cycle. Therefore, the lowest SOC value simulated in Scenario 2 was 20% while the highest SOC value was 100% to prevent overcharging. The total energy capacity (E_{BT}) of the batteries was simulated as approximately one generator capacity, or 5,000kWh. The

battery capacity (Q_B) was 100Ah while the nominal voltage (V_{nom}) was 3.2 V, which is generally used for lithium-ion batteries.

Each lithium-ion battery cell (B_c) was quadrupled in parallel (n_p) to form a battery set at the same nominal voltage (V_{Bnom}). Two parallel groups, with 1954 serial connection (n_s) were made so that the batteries' voltage value met the DC bus power requirement. This was calculated as follows:

$$DC_b = V_{Bnom} * n_s$$

Battery pack energy capacity (E_{BS}):

$$E_{BS} = V_{Pnom} * Q_B * n_p$$

Total battery energy output (E_{BT}):

$$E_{BT} = (E_{BS} * n_s)n_p$$

To determine when to charge and discharge batteries, there must be a power limit value (P_{glim}) supplied by the generator, which should be set to the operating range that maximizes the diesel engine's fuel efficiency. If battery power (P_B) is insufficient or cannot meet the power consumed while operating the generators, the power limitation should be ignored by allowing additional generators to be connected to the power grid if necessary, as in the following equation:

$$FC_{T2} = \sum_{k=1}^n (P_{ik} - P_{Bk})SFOC_{mink}/12$$

Figure 8 presents the results of the simulation using the above formulas.

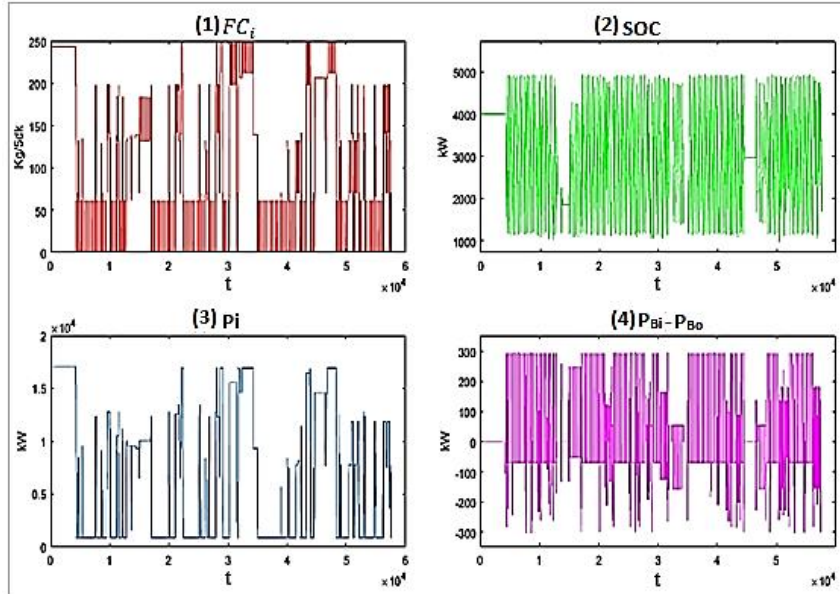


Fig. 8. MATLAB simulation graphs (Scenario 2)

Figure 8 shows four key outputs from Scenario 2: the indicated fuel consumption (FC_i), SOC, P_i , and the batteries' charge (P_{Bi})-discharge (P_{Bo}) status. Because Figure 8 presents 11,520 data points covering the whole 40-day cruise period, it is not possible to identify small changes in fuel consumption. Accordingly, Figure 9 compares the results over a shorter interval (36 hours) between Scenario1 and Scenario 2.

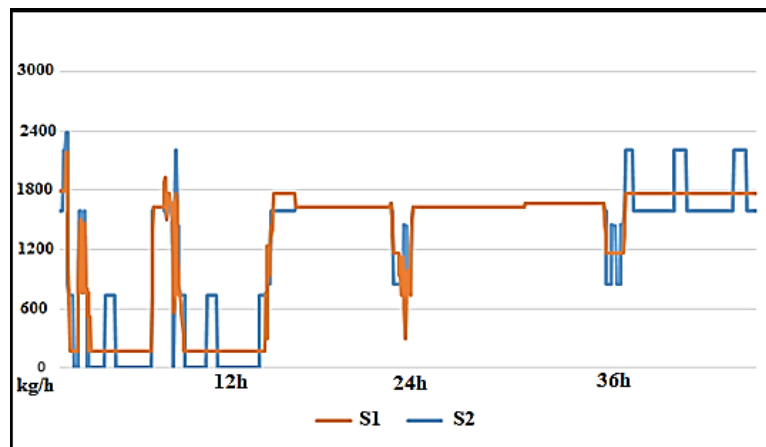


Figure 9. Comparison of FC_i between S1 and S2 (g/kWh)

As Figure 9 shows, the FC_i line varied over shorter time intervals in S2 than S1. The value of FC_i was high in S2 due to the P_{Bi} state, whereas, in Scenario 2, it was low in the P_{Bo} state and even appears to be zero at certain times. These results suggest that the HPS that incorporated batteries (S2) provided a more fuel-efficient system than the DE propulsion system (S1). Figure 10 compares the power produced by the generators (P_n) and P_i , and the power difference covered by the batteries.

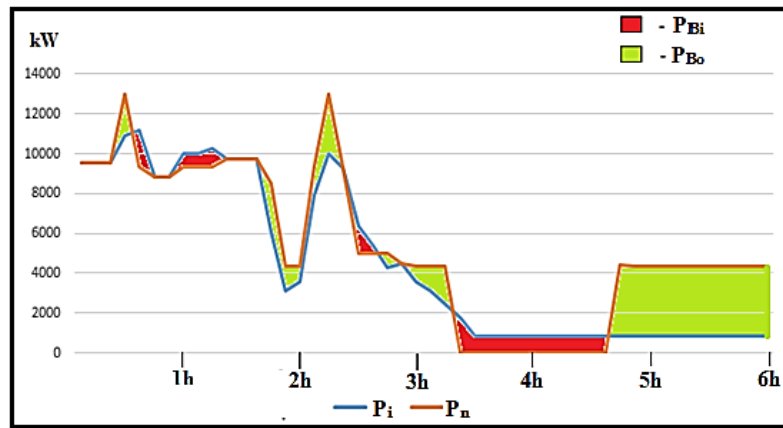


Figure 10. Six-hour trend in $P_i - P_n$ and $P_{Bi} - P_{Bo}$ (kW)

In Figure 10, which shows the changes in $P_i - P_n$ and $P_{Bi} - P_{Bo}$ over a 6-hour period, the green area between the two curves indicates that the batteries were being charged—that is, the generators were producing more power than needed. Conversely, the red area indicates that the batteries were discharging, that is, the generators were producing less power than needed, so the remaining power was provided by the batteries. Indeed, the generators sometimes were not working at all, so that the batteries provided the ship's entire energy load.

2.3.Scenario 3

Scenario 3 (S3) modeled an approach to adapt to zero-emission ports that have emerged, as a result of efforts to reduce ship-borne emissions in ports, specifically by meeting the ship's energy needs from land-based energy sources while in port. The propulsion system was modeled in the same way as in Scenario 2. The scenario assumes that, from the moment the ship berths, it switches off all its generators and receives power from the shore. Hence, it consumes no fuel while in port and therefore produces no exhaust emissions.

Total fuel consumption in this scenario (FC_{T3}) was calculated as in S2, while the cost of the electrical energy (C_e) consumed by the ship was calculated from the unit electricity fee for the port where it was berthed. In order to make a comparison, the amount of fuel purchased was calculated with (C_e) and added to FC_{T3} :

$$FC_{T3} = \sum_{k=1}^n (P_{ik} - P_{Bk}) SFOC_{mink} / 12$$

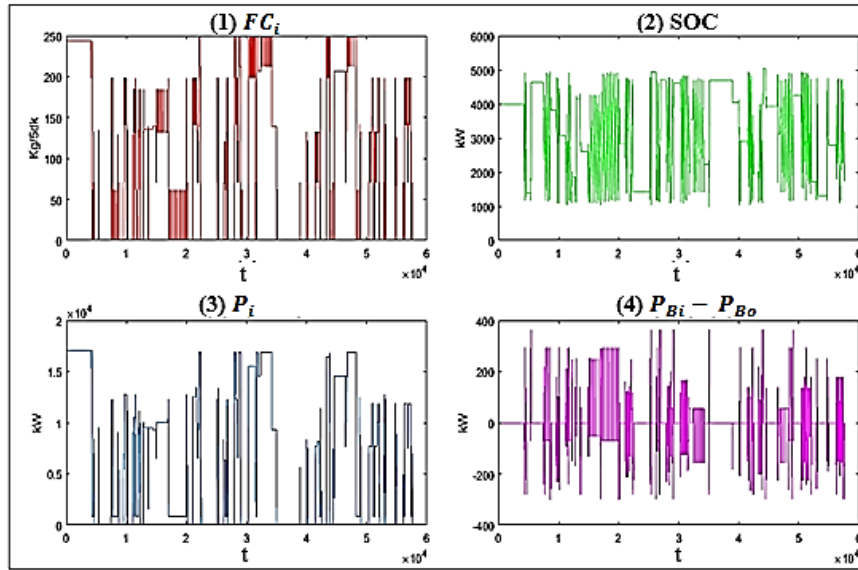


Figure 11. MATLAB simulation graphs (Scenario 3)

Figure 11 presents the results for Scenario 3. Figure 11.1 shows that FC was often zero, which can be expected because the ship’s generators were not working while in port. This reduces the FC_{T3} value and reduces FC-related exhaust emissions. Figure 11.2 and 11.4 show that the batteries were used much less in S3 than S2, thereby reducing the number of charge-discharge cycles, which increases the batteries’ life cycle. As expected, the P_i values in Figure 11.3 were not different to those in S2.

Given that none of the ports on *Gülbeniz A*’s route had appropriate infrastructure for cold ironing (CI), Scenario 3 was aiming to predict the future. Table 3 presents the estimated CI costs for S3.

Table 3. Duration of port stays, electrical energy needs, and energy unit costs for *Gülbeniz A*

Port	Time		Energy (kWh)	Electrical Energy Unit Cost (Cent)
	Hours	Minutes		
Valencia	126	40	105,766.7	21.21
Castellon	34	-	28,390	21.21
Barcelona	28	50	24,075.8	21.21
Fos	17	10	14,334.1	11.17
Piraeus	36	10	30,199.1	19.12
Ambarlı	69	20	57,893.3	13.61
Gemlik	25	50	21,570.8	13.61
Yarımca	37	-	30,895	13.61
Aliğa	20	15	16,978.3	13.61

Table 3 presents the unit electrical energy prices for 2022 (Statista, 2023) used to calculate the CI costs for each port where *Gülbeniz A* docked and the duration of its stay in each port. The unit costs for the Turkish ports were converted into cents (Investing, 2023; TUIK, 2022). Fuel prices were taken from the Global 20 Ports Average on July 22, 2022 (Ship and Bunker, 2023).

3. EVALUATION OF THE FINDINGS

Comparison of *Gülbeniz A*'s actual values with the simulation results revealed important differences for each of the three scenarios. Table 5 compares *Gülbeniz A*'s actual FC_T and NO_x values with those in the three scenarios, as well as the changes in fuel-based emissions for each scenario based on the IMO calculation method.

Table 5. Comparison of Simulation Results and Actual Values for *Gülbeniz A*

	Gülbeniz A	S1	S2	S3
FC_T (T)	1102.03	1,070.07	1,044.23	987.62
ΔFC_T (T)	-	31.96	57.8	114.41
ΔFC(%)	-	2.9	5.25	10.38
CI(T)	-	-	-	69.2
ΔCO_2 (T)	-	99.52	179.99	356.27
ΔSO_x (T)	-	31.24	56.5	111.84
NO_x (T)	19.872	15.872	15.872	15.017

Table 5 shows that, over the 40-day cruise, the ship consumed 2.9%, or 31.96 tons, less fuel in S1 than in the actual data. S1 produced the

smallest ΔFC value while reducing CO_2 , SO_x , and NO_x emissions by 99.52T, 31.24T, and 4T, respectively. S2 produced an ΔFC value of 57.8T while reducing CO_2 , SO_x , and NO_x emissions by 179.99T, 56.5T, and 4T, respectively. S3 produced the largest ship-based ΔFC value of 114.41. This indicates that the cost of CI was high, so it would be more economical for the ship to produce its own electricity in ports under current conditions. However, countries can provide some funds to put forward the idea of environmentally friendly ports. Additionally, efforts can be made to ensure that ports use renewable sources of electricity. While S3 imposed a high cost disadvantage, it produced the largest reductions in ship-based fuel-based emissions of 356.27T, 111.84T, and 4.86T for CO_2 , SO_x , and NO_x respectively. Several studies report around ~5% fuel/SFOC improvements when batteries are used mainly for peak shaving and generator loading optimization, which aligns closely with this study (Chin,et al.,2022 ; Choi, et al.,2024; Peixoto,et al.,2023)

4. CONCLUSION

This simulation study showed that electric propulsion systems can contribute to reducing ship fossil fuel consumption and related exhaust emissions. In the first scenario, in which a conventional diesel-electric (DE) propulsion system was simulated, fuel consumption was reduced by 2.9%. In particular, S1 produced promising results regarding the DE propulsion system, which has a more economical and simple design. In the second scenario, the use of batteries was considered to further reduce fuel consumption and the associated emissions, and the results indicate that total fuel consumption was reduced by 5.2%. S2 achieved much better results by including batteries into the system. In the third scenario, a system in which the vessel does not generate its own energy in ports and instead meets its energy demand through shore-side power supply was simulated. It has been demonstrated that a vessel operating with such a system could reduce its fuel consumption by 10.38%. S3, which simulated a hypothetical future scenario, suggested that electric propulsion systems can be an effective method for reducing emissions, whose harmful environmental effects are frequently discussed and which require urgent amelioration measures. Only one or more of these scenarios may be applicable across all shipping companies when initial investment and operating costs are taken into account.

Future studies can take into account the current costs of the components used in propulsion systems. This study demonstrates, with decreasing costs and increasing efficiencies of electrical equipment and batteries, sufficient cost savings can be achieved. Considering that battery costs are expected to decline further in the near future, the payback periods of the initial investments can be periodically reassessed. The methodology

adopted in this study can be systematically applied to various ship types and operational routes, allowing for a comprehensive assessment of energy efficiency improvements and fuel consumption reduction potentials under different operational conditions.

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