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Original article

# Effects of transportation of electric vehicles by a RoPax ship on carbon intensity and energy efficiency

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ABSTRACT

Electric vehicle (EV) transportation aboard RoPax vessels presents several technical, safety, and regulatory challenges that must be carefully addressed for effective implementation. This study investigates the integration of an EV charging facility on a RoPax vessel, focusing on its impact on operational carbon dioxide emissions and compliance with maritime energy efficiency regulations. Motivated by the need for sustainable maritime transport, the research aims to evaluate various battery charging configurations for 200 EVs, assessing the total electrical energy required and the additional loads on the ship's electrical system. A scenario-based analysis is conducted using three engine configurations powered by different marine fuels. Key findings reveal a carbon intensity variation of up to 5.3% based on fuel choice during an eight-hour round-trip voyage. The dual-fuel engine using liquefied natural gas meets Energy Efficiency Existing Index (EEXI) requirements, achieving an 8.121 Carbon Intensity Indicator (CII) value without charging, thus ensuring an A rating until 2026. Even in the worst-case charging scenario, the carbon intensity of this configuration increases by only 2.26%, still complying with EEXI and CII metrics. This research offers a comprehensive evaluation of EV charging impacts on RoPax vessels, providing insights for adapting and optimizing ship power systems.

## Introduction

Maritime shipping passageways play a vital role in facilitating global trade. According to the International Maritime Organization (IMO), it is estimated that almost 90 % of global trade relies on the maritime transport of commodities [1]. Each of the types of shipping routes serve crucial roles in the shipping industry, with some routes being more heavily navigated and important because of the trade routes they provide [2].

The transport of electric vehicles (EVs) via Roll-on/Roll-off Passenger (RoPax) ships presents important consequences for carbon intensity and energy efficiency. With the rising demand for sustainable transport solutions, it is essential to comprehend the environmental impact of maritime operations. Contemporary RoPax vessels are designed to carry both passengers and vehicles, including EVs, which can play a role in lowering carbon emissions in comparison to conventional transport methods [3]. The incorporation of sustainable ships into maritime transport systems has the potential to reduce overall carbon intensity, especially when these vessels employ cleaner energy sources [4]. For example, the electrification of the ferry service and the provision of onshore power supply are recognized as effective strategies to improve energy efficiency and decrease emissions in short-sea shipping operations [5]. The integration of hybrid technologies and low-carbon electricity sources can enhance the energy efficiency of these vessels [6]. The operational efficiency of RoPax vessels is influenced by factors such as speed, load, and route planning, which can be optimized through advanced modeling techniques [7].

The environmental advantages of transporting EVs using RoPax ships go further than just reducing direct emissions. Shifting freight from road to sea has the potential to reduce traffic congestion and lower roadside

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pollution, both of which are major factors affecting urban air quality [8]. This change is especially significant in areas where road infrastructure faces challenges, and where maritime transport can provide a more sustainable option [9]. Moreover, employing RoPax vessels for the transportation of EVs is in harmony with wider sustainability objectives, such as the European Union's (EU) dedication to decreasing greenhouse gas emissions within the transport sector [10] (Haas & Sander, 2020). Incorporating shipping into emissions trading schemes, like the EU Emissions Trading System (EU ETS), highlights the necessity for maritime operators to adopt more efficient practices and technologies [11]. This regulatory framework encourages the adoption of cleaner technologies and operational efficiencies, which can further improve the sustainability of RoPax shipping.

In today's world, the prevalence of the use of ferries and RoPax ships to transport individuals with their vehicles is remarkable; this can be supported by the fact that approximately 16,000 of the world's trade fleet of approximately 119,000 ships are Ferries and RoPax used for passenger and vehicle transportation [12]. In this alternative form of transport, the currently widespread EVs, as reported by the European Automobile Manufacturers' Association (ACEA), show that the new electric car market comprises approximately 47.5 % (with battery-electric cars at 10.9 %, hybrid-electric cars at 28.8 %, and plug-in hybrid electric cars at 7.8 %), alongside vehicles powered by internal combustion engines [13].

Given the current circumstances, it is imperative to address the requisite infrastructure for EV charging stations [14]. Presently, charging facilities for EVs are established in various locations, including roadways, gas stations, shopping malls, and residential areas [15]. To enhance the diversity of available options, initiatives are underway to manufacture or retrofit cruise ships and ferries with integrated charging infrastructure for EVs [16].

Establishing legislative and technological regulations is vital to enable EV charging while cruising at sea A solid legal framework is necessary to define the obligations of all parties involved. Additionally, integrating several costly components is required to provide charging capabilities on the vessel [17]. These components include charging station installation, personnel recruitment/training, and ship electrification system modifications [18].

While the installation of an EV charging point on the vehicle deck of a ship represents a fundamental technical measure, enhancing or optimizing the capacity and operational parameters of the external or shaft generator responsible for generating electricity on the ship poses a more complex technical challenge. Additionally, the business management must consider several factors, such as the client pricing for this service and the profit margin compared to initial investment costs. Additionally, these parameters ought to have a competitive dimension. Another technological infrastructure concern pertains to the necessity of equipping vehicles transporting electric cars with fire suppression systems capable of effectively combating various types of fires [19].

Marine transportation has set standards and regulations for EV charging and transportation on maritime vessels. Implementing these on RoPax ships requires a comprehensive risk assessment. This evaluation must address threats posed by alternative fuel vehicles (AFVs) that could compromise passenger safety, environmental integrity, and ship safety [20]. Hazard management should comply with International Safety Management (ISM) code criteria, ensuring that all operations related to AFVs undergo risk assessments, leading to ship-specific procedures for fire prevention [21]. Compliance with International Convention for the Safety of Life at Sea II-2/15.2.3 Training manuals, II-2/16.2 Fire Safety operational booklets, and the ISM code is essential. Additionally, electrical connections must adhere to the Annex to the Interim Guidelines and MSC.1/Circ.1615 paragraphs 1.1 to 1.6 to prevent ignition [22]. It is crucial to document and justify these exclusions to guarantee transparency and concentrate on the most significant risks, all while adhering to established maritime safety standards.

In recent years, maritime shipping has been responsible for approximately 1.0 Gt carbon dioxide ($CO_2$) per year, which represents about 2.8 % of global $CO_2$ emissions [23]. Notably, around 70 % of this total emissions figure came from international shipping activities [24]. The IMO has established specific objectives to mitigate carbon emissions in the maritime sector, and these objectives entail a minimum reduction of 40 % in $CO_2$ emissions from ships by the year 2030 and a more substantial reduction of 70 % by the year 2050 [25].

To accomplish the objectives, the Marine Environment Protection Committee (MEPC), which is one of the main committees of the IMO which is responsible for addressing environmental issues related to international shipping, enacted the regulations of the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) in June 2021, and these regulations became effective in January 2023 [26]. The EEXI provides a framework for assessing the energy efficiency of existing vessels, ensuring adherence to energy efficiency standards, and facilitating the reduction of greenhouse gas emissions. Conversely, the CII functions as an operational metric that evaluates and monitors a vessel's carbon intensity during its operations, incentivizing ship operators to lower carbon emissions by improving operational efficiency and embracing more sustainable practices [27]. Therefore, the implementation of $CO_2$ emission controls on ships is anticipated to have a substantial impact on the reduction of $CO_2$ emissions within the context of international shipping [28].

The literature on EV charging aboard ships is limited, primarily focusing on charging station design for fully electric marine vessels. These studies have focused on charging station designs [29,30], economic evaluation of charging stations [31] and the site selection for charging stations [32]. Full electric ferries and roll-on roll-off (RoRo) ships have also been evaluated within this concept [33,34].

Among the limited studies strictly focusing on EV transportation and onboard charging, Dean et al. [18] provided a model framework and requirements for the transportation and charging the EVs. Range, charging protocols, weather, and EV owners charging preferences were determined as the modelling criteria. Wu et al. [35] conducted a Bayesian Network to assess the affecting parameters and possible outcomes of the electrical vehicle transportation in RoPax ships. The risk of explosion was highlighted in their findings.

Given the decarbonization concerns, marine diesel generators must operate within energy efficiency standards to meet the energy needs of auxiliary machinery and equipment alongside the main engine. The literature review revealed a gap in examining the environmental impacts of EV vehicle charging onboard and its effects on EEXI and CII metrics, depending on fuel type and different EV charging levels.

This research focuses on a RoPax ship transporting both cars and passengers. The study investigates various battery charging configurations for 200 EVs aboard the vessel aiming to determine the total electrical energy required for charging. This situation increases the ship's electrical energy demands during navigation. Consequently, this study evaluates the impact of installing EV charging stations on a RoPax ship, specifically examining the additional loads these stations introduce to the existing electrical system. Different electrical load scenarios are considered, and the analysis also addresses the resulting changes within the framework of EEXI and CII regulations.

The analysis contributes to the literature by providing a comprehensive evaluation of the total electrical energy required for charging 200 EVs on a RoPax ship, assessing the additional loads introduced by EV charging stations, and examining the implications of EEXI and CII regulations. It offers insights into optimizing the ship's electrical system for reliability during navigation, informs operational strategies for integrating charging infrastructure, and evaluates the sustainability impacts of adopting EVs in maritime transport.

## Case study description

This section delineates the ship design parameters and specifications, operational profile and propulsion/electrification system assessed in the case study.

*Specifications of the case study ship*

The initial calculations for the case ship including the determination of some particulars such as the total engine power and type. The required power was determined based on predictions of the general weight groups, hydrostatic and stability, and resistance-power values. In the context of determining stability and resistance power, it is assumed that the vessel is buoyant at a draft of 9.00 m, while the vessel was on an even keel. As a result, the main characteristics of the vessel are outlined in Table 1. This ship was designed by considering the hull form of the Ro-Ro ship used in Göksu and Bayramoglu [3] and was arranged to have two propellers. The schematic representation of the ship's design, as examined in this study can be found in Appendix A.

The concept design marks the initial stage of the design process, emphasizing the development and exploration of innovative ideas. The RoPax ship, comprising 14 decks, offers extensive capacity for passenger transport and vehicle carriage. It accommodates 2,000 passengers, a crew of 200, and up to 1,000 automobiles, including 800 conventional vehicles and 200 EVs. This allocation aligns with the global trend, where approximately 20 % of vehicles transported through ports are electric, reflecting the growing adoption of EVs in urban areas linked to shipping routes [36].

To support EVs, the ship is equipped to charge 200 vehicles during navigation, utilizing either 50 charging units at 22 kW each or 100 units at 11 kW each. These charging systems adhere to commercial manufacturer guidelines, ensuring compliance with industry standards and reliable performance [37].

The batteries of EVs are charged up to 80 % on board. Starting from a state of charge (SoC) of 10 %, the required power and charging times have been calculated parametrically, assuming all vehicles begin with the same SoC. This range captures most real-world charging needs [38]. The charging curve, or rate of charging, tends to be linear or follows predictable behavior within this range, facilitating easier parametrization and modeling [39]. Additionally, many EVs recommend charging up to 80 % during fast charging to avoid stressing the battery and to maintain long-term battery health and navigational safety [38,40].

The design incorporates a diesel-electric propulsion (DEP) system featuring a twin-propeller setup powered by a combination of generators. The number of internal combustion engines varies depending on the specific engine type and fuel used to satisfy the propulsion and electrification demands described in Section 2.3.

The determination of weight groups for the ship was conducted by employing empirical formulas sourced from existing literature. The practice of estimating values using empirical formulas is commonly employed throughout the initial stages of ship construction for preliminary design purposes. Table 2 presents a comprehensive compilation of weight categories, empirical weight estimation approaches, and their respective values.

The total displacement of a ship is determined by its weight groupings, distributions, and general features. The consideration of this element holds paramount importance in the computation of resistance-power and stability, providing it a vital facet of ship design.

During maritime expeditions, vessels encounter diverse variable environments [48]. A limited understanding of how these factors impact ships necessitates adherence to stability requirements set by international conventions and classification societies, ensuring safety. Inadequate cargo handling and failure to monitor ship equilibrium can lead to sinking or damage resulting in casualties, material losses, and significant environmental harm [49]. Regardless of a vessel's specific characteristics, determining hydrostatic values is essential in the ship design process [50]. Table 3 presents the hydrostatic values used in the concept design calculations.

The Holtrop-Mennen method is utilized to calculate the resistance of the hypothetical ship form constructed for this study. Accurate resistance calculations are crucial during the design phase, as they heavily influence the determination of the engine type and power requirements for the ship [51]. These calculations are often used to estimate the cruising speeds attainable under specific conditions with the existing main engine. The data presented in Table 4 is employed to determine the power required from the main engine for propulsion, along with the corresponding speeds and resistances.

The computations in this study assume a maximum propulsion efficiency of 48 %. This efficiency is composed of 90 % hull efficiency, 60 % propeller efficiency, 95 % relative rotative efficiency, and 95 % transmission efficiency [52]. Accounting for a 15 % loss due to sea margin and an additional 5 % loss from fouling effects, the overall propulsion efficiency is reduced to 40 % [3]. This data corresponds to the evaluated conditions at a specified draft of 9.00 m.

**Table 1**
The specifications of the case ship.

| Particulars | Values | Units |
|---|---|---|
| Length overall (LOA) | 230.0 | m |
| Draft amidships (T) | 9.00 | m |
| Displacement | 43,680 | t |
| Gross tonnage | 85,000 | – |
| Waterline (WL) length | 218.95 | m |
| Beam max extents on WL | 32.00 | m |
| Wetted area | 8,222.30 | $m^2$ |
| Waterplane area | 5,972.65 | $m^2$ |
| Prismatic coefficient ($C_p$) | 0.731 | – |
| Block coefficient ($C_b$) | 0.676 | – |
| Max section area coefficient ($C_m$) | 0.936 | – |
| Waterplane area coefficient ($C_{wp}$) | 0.852 | – |

**Table 2**
The weight groups, methodologies, and weight values.

| Weight group | Reference | Weight [t] |
|---|---|---|
| | | T = 9.00 *m* |
| Construction | [41] | 20,000 |
| Main engine | [42] | 1,800 |
| Auxiliary engines | [43] | 1,000 |
| Outfitting | [41] | 4,500 |
| Engine car cargo load | [44] | 1,200 |
| Electrical car cargo load | [45] | 400 |
| Service requirements | [46] | 14,280 |
| Passenger and Crew belongings | [47] | 500 |
| Total displacement | | 43,680 |

**Table 3**
Hydrostatic values of the concept ship [3].

| Draft amidships [m] | 8.50 | 9.00 | 9.50 | 10.00 | 10.50 |
|---|---|---|---|---|---|
| Displacement [t] | 40,644 | 43,680 | 46,763 | 49,877 | 53,031 |
| Heel [deg] | 0 | 0 | 0 | 0 | 0 |
| Draft at FP [m] | 8.50 | 9.00 | 9.50 | 10.00 | 10.50 |
| Draft at AP [m] | 8.50 | 9.00 | 9.50 | 10.00 | 10.50 |
| Trim (+by stern) [m] | 0 | 0 | 0 | 0 | 0 |
| WL length [m] | 218.78 | 218.95 | 219.40 | 218.91 | 219.99 |
| Beam max extents on WL [m] | 32.00 | 32.00 | 32.00 | 32.00 | 32.00 |
| Wetted area [$m^2$] | 7,965.99 | 8,222.30 | 8,486.68 | 8,731.17 | 8,991.05 |
| Waterplane area [$m^2$] | 5,895.76 | 5,972.65 | 6,046.66 | 6,116.79 | 6,189.96 |
| Prismatic coefficient ($C_p$) | 0.724 | 0.731 | 0.737 | 0.745 | 0.748 |
| Block coefficient ($C_b$) | 0.666 | 0.676 | 0.684 | 0.695 | 0.700 |
| Max section area coefficient ($C_m$) | 0.932 | 0.936 | 0.939 | 0.942 | 0.945 |
| Waterplane area coefficient ($C_{wp}$) | 0.842 | 0.852 | 0.861 | 0.873 | 0.879 |

**Table 4**
The concept ship resistance-power values.

| Speed [knot] | Fn | Resistance [kN] | Power ($P_B$) [kW] |
|---|---|---|---|
| 3.0 | 0.033 | 29.3 | 113 |
| 6.0 | 0.066 | 115.6 | 892 |
| 9.0 | 0.100 | 250.6 | 2,900 |
| 12.0 | 0.133 | 428.9 | 6,620 |
| 15.0 | 0.166 | 661.3 | 12,757 |
| 18.0 | 0.199 | 983.8 | 22,775 |
| 21.0 | 0.233 | 1,451.2 | 39,195 |
| 24.0 | 0.266 | 2,078.6 | 64,159 |

*Ship operational profile*

Notable European ports serving ferries and RoPax vessels include Dover, Calais, Dublin, Rotterdam, Livorno, Trieste, Gothenburg, Genoa, London, Helsinki, and Tallinn, which facilitate the movement of passengers, wheeled vehicles, and diverse cargo types [53]. These terminals support efficient loading and unloading services, while current technological advancements indicate a rising trend in EVs among passenger transport. The desire for increased mobility drives the transport of EVs alongside individuals [54]. In consideration of the prominent routes and the specifications of operational RoPax vessels provided as Supplementary Material in Appendix A, the case study will focus on a specific route identified in the analysis of Huttunen [55].

The operational hours and required power for hotel demand and thrusters are also determined by using the sample driving cycle for the same type of vessel presented by Huttunen [55]. Table 5 indicates operation duration distributions for one navigation assumed to be eight hours. The operational power distributions, corresponding to the data points and operational profiles, are available as the supplementary figure in the Appendix A.

In Table 5, the power demand ratios from the sample vessel have been used to detect the power requirements of our case study vessel. The duration and route of the case study vessel also align with those of the sample vessel. The operational power demands are divided into three sections and calculated considering the required equipment used in the operation. In the maneuvering operation, it is assumed that the engines perform at 30 % load [56]. Four different case scenarios have been developed to assess the impact of EV charging on fuel consumption (FC) and carbon emissions. Table 6 depicts the case scenarios used in the analysis.

In Table 6, the number of entering EVs has been assessed in four ways, resulting in various scaled power needs. For instance, certain vehicles may start with a higher SoC, allowing them to complete the charging process more quickly. Due to the lack of real-time data, the effects have been observed through cases related to SoC and EV number distributions.

Case-1 is the most power-demanding scenario (worst-case scenario), while Case-2 represents a medium level of demand with an equal distribution across 20 %–50 % SoC. Case-3 is the least power-demanding, featuring an equal distribution across 30 %–70 % SoC. In Case-4, the number of EVs has been distributed according to a normal distribution to diversify the load demand and simulate real-world applications. The base scenario, denoted as Case-0, represents the scenario with no EV charging.

**Table 5**
Operation duration distributions for one voyage

| Operation | Duration (h) | Demand | Power (kW) |
|---|---|---|---|
| Navigation | 6.36 | Propulsion + Hotel | 42,159.977 |
| Port | 1.44 | Hotel | 2,964.7059 |
| Maneuvering | 0.21 | Propulsion*0.3 + Hotel + Thruster | 18,496.549 |

adapted from Huttunen [55].

**Table 6**
Charging cases employed in the study.

| Cases | Initial SoC | 10 % | 20 % | 30 % | 40 % | 50 % | 60 % | 70 % |
|---|---|---|---|---|---|---|---|---|
| 1 | **Number of EVs** | 200 | – | – | – | – | – | – |
| 2 | | 40 | 40 | 40 | 40 | 40 | – | – |
| 3 | | – | – | 40 | 40 | 40 | 40 | 40 |
| 4 | | 12 | 25 | 38 | 50 | 38 | 25 | 12 |

The primary purpose of these cases is to examine diverse charging scenarios, ranging from uniform conditions in Case-1 to varied distributions in Case-4. This analysis enhances understanding of the impact of different charging behaviors on power demand. Moreover, the cases provide insights into infrastructure design, illustrating how charging stations and power grids can accommodate various charging profiles and usage patterns, which is vital for effective planning. By integrating both uniform and realistic SoC distributions, these cases reflect actual EV charging behaviors, contributing valuable insights into system performance under diverse conditions and facilitating informed decision-making for future EV infrastructure.

*Propulsion and electrification systems*

DEP has been used in the case study RoPax ship since it represents a significant opportunity for enhancing energy efficiency and mitigating $CO_2$ emissions. The DEP approach especially benefits passenger and cruise vessels, effectively lowering FC while minimizing vibration and noise levels. Furthermore, it offers rapid responsiveness to load fluctuations and improved reliability, collectively leading to a diminished need for spare parts [57]. The electrification and propulsion requirements of the vessels are effectively addressed by a single system, providing an additional operational advantage [58].

The system functions through an integrated configuration that encompasses load-sharing generators, electric motors, and, potentially, battery systems. Four-stroke marine diesel generators serve as prime movers, providing mechanical energy to electrical generators that produce power in the diesel-electric system. The number of diesel generators in a system depends on the power requirements and the power of a single engine. Designs featuring multiple smaller engines as opposed to fewer larger engines have been utilized for RoPax, cruise ships, and RoRo vessels [59]. This power is transmitted to the main switchboard, controlling all energy flow. Transformers enhance power capacity or meet voltage needs for various equipment. Frequency converters convert alternating current to direct current and vice versa, enabling motor drive control. Electric motors are powered by variable frequency drives fed by transformers [60].

Three distinct four-stroke main engine configurations have been assessed for the diesel-electric propulsion of the reference vessel. The investigated fuels are Heavy fuel oil (HFO), light fuel oil (LFO), liquefied natural gas (LNG), and methanol. Table presents the technical specifications of the evaluated marine engines.

Engine-1 is a diesel engine, while Engines 2 and 3 are dual-fuel (DF) engines that can operate on both gas and conventional fuels. The number of units in Table 7 reflects the marine diesel engines needed to fulfil the vessel's propulsion, thruster, and hotel load requirements. The engine selection considers the vessel's navigational speed of 21 knots, necessitating a propulsion power of 39.195 MW, as indicated in Table 4. Additionally, the total design propulsion power is calculated to be 43.662 MW when the engines operate at maximum output.

The power demand dictates the number of operational generators. If the required power exceeds the output of a single generator operating at 85 % of its maximum continuous rating, an additional generator is activated. The power range for a single unit has been determined by analyzing existing RoPax vessels with comparable specifications. The selection of other diesel and LNG-DF engines has been made with this

**Table 7**
Technical specifications of the examined engine types [61].

| Specification | Engine-1 | Engine-2 | Engine-3 |
|---|---|---|---|
| Product Name | Wärtsilä 10 V31 | Wärtsilä 9L32 | Wärtsilä 12V31DF |
| Number of cylinders | 10 | 9 | 12 |
| Engine Speed (rpm) | 720 | 720 | 720 |
| Engine Output (kW) | 6,300 | 5,400 | 6,960 |
| Fuel | HFO/LFO | Methanol/ LFO | LNG/LFO |
| Mean Effective Pressure (Mpa) | 3.24 | 2.9 | 2.96 |
| Fuel Flow to Engine ($m^3$/h) | 2.34 | 5.02 | 2.35 |
| Number of units | 8 | 10 | 7 |

limitation in mind, as the maximum available power for methanol DF engines is capped at 5,400 kW, resulting in the Engine-2 unit having a lower power output compared to alternative configurations.

Using specific FC (SFC) curves given in the Appendix A as a Supplementary Information provided by engine manufacturers, along with the operational load and durations, the FC for each scenario has been calculated. The SFC values of DF engines are calculated from the energy values by including the pilot fuel usage. The additional power required for EV charging has been included in the operational load. Regarding the required charging power changes in generator load are computed, and the corresponding SFC values were interpolated from the curves. The product of SFC, power, and operational hours yield the FC in metric tons.

## Modeling

This section presents the resistance and power estimations for the case study RoPax vessel, along with the determination of energy efficiency metrics and battery charging estimates for EVs. The section also addresses model overall uncertainty and error rate.

### *Resistance calculations*

The initial stage in determining the necessary installed engine power for maritime vessels is the overall resistance determination. The power denoted as $P_E$, which is necessary to tow a ship at a velocity of $V$, can be determined by utilizing Eq. (1) [62].

$$P_E = \text{Resistance} \times V \tag{1}$$

Estimating power losses across all components from the main engine to the propeller, as well as during propeller rotation, is crucial for determining the installed engine power. This determination is essential for achieving the necessary thrust from the propeller to propel the ship forward. In this context, the term propulsion efficiency ($\eta_P$) is significant, with researchers generally agreeing that a typical propulsion system experiences a loss of 60 % of the total power generated by the main engine before it is effectively converted into usable power [63]. This phenomenon, referred to as the hull effective power to main engine brake power ratio, denoted as $P_B$ is depicted in Eq. (2) [64].

$$\eta_P = \frac{P_E}{P_B} \tag{2}$$

### *Energy efficiency metrics*

The EEXI framework evaluates design or technical efficiency in operational ships over 400 gross tonnages (GT), where GT reflects the vessel's total enclosed volume. Existing ships failing to meet specific type specifications can enhance fuel efficiency through engine power limits and energy-saving modifications [65]. Eq. (3) represents the simplified formula used to compute the attained EEXI [66].

$$\text{Attained EEXI}\left(\frac{g}{t \times NM}\right) = \frac{C_f \times FC\left(\frac{g}{h}\right)}{\text{Capacity} \times V_{ref}(kn)} \tag{3}$$

In this context, FC is the FC per hour, calculated by multiplying the SFC in g/kWh by the engine power in kW. The engine power is typically assumed to be 75 % of the rated power [67]. It is a typical application and is considered the maximum continuous rating for marine diesel engines in EEXI calculations [68]. The capacity of the Ro-Ro vessels is measured in GT, whereas $V_{ref}$ reflects the reference speed of the vessel in knots (kn) at the given engine power according to the International Association of Classification Societies [69].

The term $\mathbf{C_f}$ denotes the carbon factor, which varies based on the type of fuel used in the engine [70]. Table 8 presents the $C_f$ values for the fuels studied which are currently commercially available alternative options in the marine industry [71].

The lower calorific value (LCV), also known as the thermal value or heat of combustion, measures the energy released when a fuel is burned. It serves as a fundamental basis for calculating the thermal efficiency and FC of an engine that utilizes that fuel [72]. Eq. (4) demonstrates the computation of the required EEXI for the reference RoPax [73].

$$\text{Required EEXI} = \left(1 - \frac{X}{100}\right) \times \left(\frac{DWT}{GT}\right)^{-0.7} \times DWT^{-0.471} \tag{4}$$

The reduction factor (X) is derived from tables issued by the IMO specifically for the reference ship, and it amounts to 15 % [67]. In marine transportation, DWT stands for deadweight, which refers to the total weight a vessel can carry. This includes cargo, fuel, crew, passengers, and supplies, effectively quantifying a vessel's cargo capacity in metric tons [74].

The CII assesses annual operational fuel efficiency using a rating system [75]. The attained CII has been calculated using Eq. (5).

$$\text{Attained CII}\left(\frac{g}{t \times NM}\right) = \frac{C_f \times FC(g)}{\text{Capacity} \times \text{Distance}(NM)} \tag{5}$$

The FC has been aggregated across the entire operation period instead of being calculated on an hourly basis as stated in Eq. (5). Distance denotes nautical miles (NM) covered during the voyage [76]. Eq. (6) illustrates the computation of the required CII [77].

$$\text{Required CII} = \left(1 - \frac{Z}{100}\right) \times 5739 \times GT^{-0.631} \tag{6}$$

The reduction of the factor for CII, represented by $Z$, is 5 % in 2023 relative to 2019 and will increase by 2 % each year until 2026 [78]. The CII rating predictions in this study are constrained to the year 2026, aligning with the current validity of the IMO's established reduction rates. As the IMO has announced plans to reevaluate these rates in 2026, the reduction ratios may be subject to change [79].

The computation of CII rating boundaries is achieved by multiplying the required CII and dd coefficients for the reference vessel for 2019, as indicated in Table 9. The variation of dd coefficients is ensured by applying the Z through the years [80]. Fig. 1 depicts the CII boundaries and their corresponding ratings.

The dd vectors presented in Table 7 define the boundary values for CII ratings, acting as reference thresholds. These vectors outline the limits for each rating band (e.g., A to E) based on factors such as vessel

**Table 8**
Evaluated marine fuel carbon contents and factors [70].

| Fuel Type | $C_f$ (t-$CO_2$/ t-Fuel) | LCV (kJ/kg) |
|---|---|---|
| HFO | 3.114 | 40,200 |
| LFO | 3.151 | 41,200 |
| Methanol | 1.375 | 19,900 |
| LNG | 2.75 | 48,000 |

**Table 9**
Criteria for determining the boundaries of CII ratings [80].

| d1 | d2 | d3 | d4 |
|---|---|---|---|
| 0.86 | 0.94 | 1.06 | 1.16 |

type and size.

A ship's efficiency category is determined by its CII, classified as A, B, C, D, or E. If a ship receives a D rating for three consecutive years or an E rating for one year, it must submit an action plan to improve its index to C or higher [79]. Government agencies and stakeholders should reward ships with A or B grades [81]. Ships with a GT of 5,000 or more, and those applying to the EEXI, are required to undergo annual assessments of their CII [82].

*Battery charging and engine load distribution*

The required power ($P_{req}$) in kW to meet the charging demand of EVs has been calculated by using the available capacity of the battery ($C_{av}$) and SoC of the batteries. The computation of *SoC* has been ensured by employing Eq. (7), and $P_{req}$ has been calculated by each case by applying Eq. (8) [83].

$$SoC(t) = SoC(0) - \frac{\int_0^t \eta \times I(t)}{C_{av}} dt \tag{7}$$

SoC(t) represents the SoC at time t, SoC (0) is the initial SoC, I(t) denotes the current being discharged or charged at time t, and $\eta$ is the coulombic efficiency, which is assumed to be 1 in this study [40]. The charging process follows a constant current constant voltage protocol, whereas the discharging process maintains a constant current. The state of charge of the batteries in the model is considered between 20 % and 80 % to prevent an increase in internal resistance and the subsequent rise in power demand on the vessel [39].

$$P_{req} = \frac{SoC(t) \times C_{inital} \times n}{t_c} \tag{8}$$

where $C_{initial}$ is the initial capacity of the battery in kWh at 100 % SoC, n is the charging station number, and $t_c$ is the charging hours.

The EV capacity calculations are based on the average battery capacity of twenty EVs listed in Appendices, which is 49.98 kWh. The charge available on the vessel reaches up to 39.99 kWh, representing 80 % SoC. Additionally, it is assumed that the ship will not accept EVs with 10 % or less SoC for charging onboard.

Charging EV batteries presents several challenges within the current technological framework. It is crucial to optimize the charging rate, determine the necessary charging duration [84], and strategize the entire journey [16]. Therefore, to ensure the effective design of a RoPax ship, it is essential to include adequate and suitable accommodation and storage spaces, along with provisions for EV charging infrastructure.

*Uncertainty analysis*

Uncertainty measures the reliability of results and is vital for evaluating data suitability for informed decision-making [85]. Among various statistical methods, uncertainty analysis successfully determines scenarios influenced by uncertainties and enhances accuracy [86]. Different levels of uncertainty are aggregated using Eq. (9) [87].

$$U_R = \sqrt{\left[\left(\frac{\delta R}{\delta x_1}U_1\right)^2 + \left(\frac{\delta R}{\delta x_2}U_2\right)^2 + \cdots + \left(\frac{\delta R}{\delta x_n}U_n\right)^2\right]} \tag{9}$$

In Eq. (9), U values denote the fractional uncertainties of individual independent variables ($x_1$, $x_2$,…$x_n$), $U_R$ presents the uncertainty of the combined computation, while R corresponds to the result or utilised value for each independent parameter [88].

This analysis determines two primary sources of uncertainty. First, the engine FC depends on SFC curves supplied by the manufacturer for various configurations. Although experimental data is scarce, engine manufacturers and studies indicate an error rate of roughly 5 %, with one study reporting an error rate of 5.63 % [89]. Second, the Holtrop-Mennen methodology presents an average uncertainty rate of approximately 5.74 % By applying Eq. (9), the mathematical model reveals a combined uncertainty of 8.04 %, which remains within an acceptable margin.

## Results

In the parametric analysis, all 200 EVs are assumed to have an initial SoC ranging from 10 % to 70 %. The required power in kW, battery capacity, number of stations, and charging times based on the stations' capacity have been determined. Fig. 5 illustrates the battery capacity, required charge times, and power concerning the varying initial SoC of 200 EVs.

In Fig. 2(a) the initial battery capacity of the EVs has varied from 5 to 34.99 Ah and the batteries having SoC over 70 % have not been accepted for charging. The required charging time is 3.18 and 1.49 h for slow and fast chargers from 10 % SoC. Considering the EV capacity and navigation time, 50 fast, and 100 slow charging stations would meet the demand. In Fig. 2(b) the required additional power to charge EVs has been illustrated. The worst-case scenario with 200 cars having 10 % initial SoC (Case-1 in scenario analysis) adds an extra 1,100 kW to the power generation unit. This value represents 0.002 % of the total propulsion and hotel load capacity; however, it accounts for a significant 37.10 % of the exclusive hotel load. Based on the additional powers, loads of the generator sets have been calculated, and the FC regarding SoC, and engine type has been calculated. Fig. 3 illustrates the FC of engine types that use various fuels depending on the initial SoC.

The inferior LCV of methanol compared to other fuels causes higher consumption amounts. The opposite trend can be observed for the LNG. The average FC has been calculated at around 50 t per navigation. LFO is the only common fuel of the investigated three engines. The configuration that involves Engine-2 has consumed the largest amount of LFO among the three engines due to a higher number of working engines during the navigation operation. Fig. 4 illustrates the base scenario's FC amounts and the FC difference between the highest and lowest demands.

In Fig. 4, the right vertical axis represents the FC, and the left vertical axis depicts the difference in FC compared to the base scenario. The

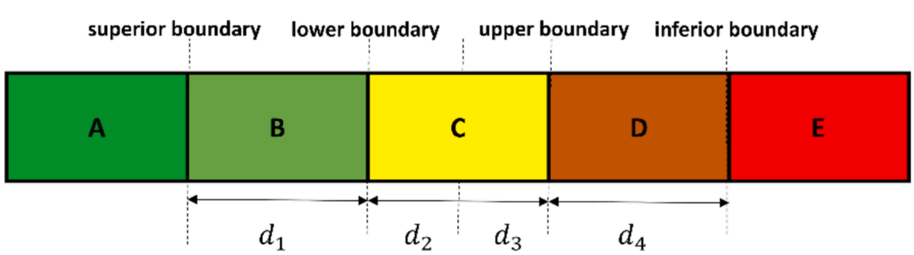


**Fig. 1.** Determining CII boundaries using dd vectors and required CII [80].

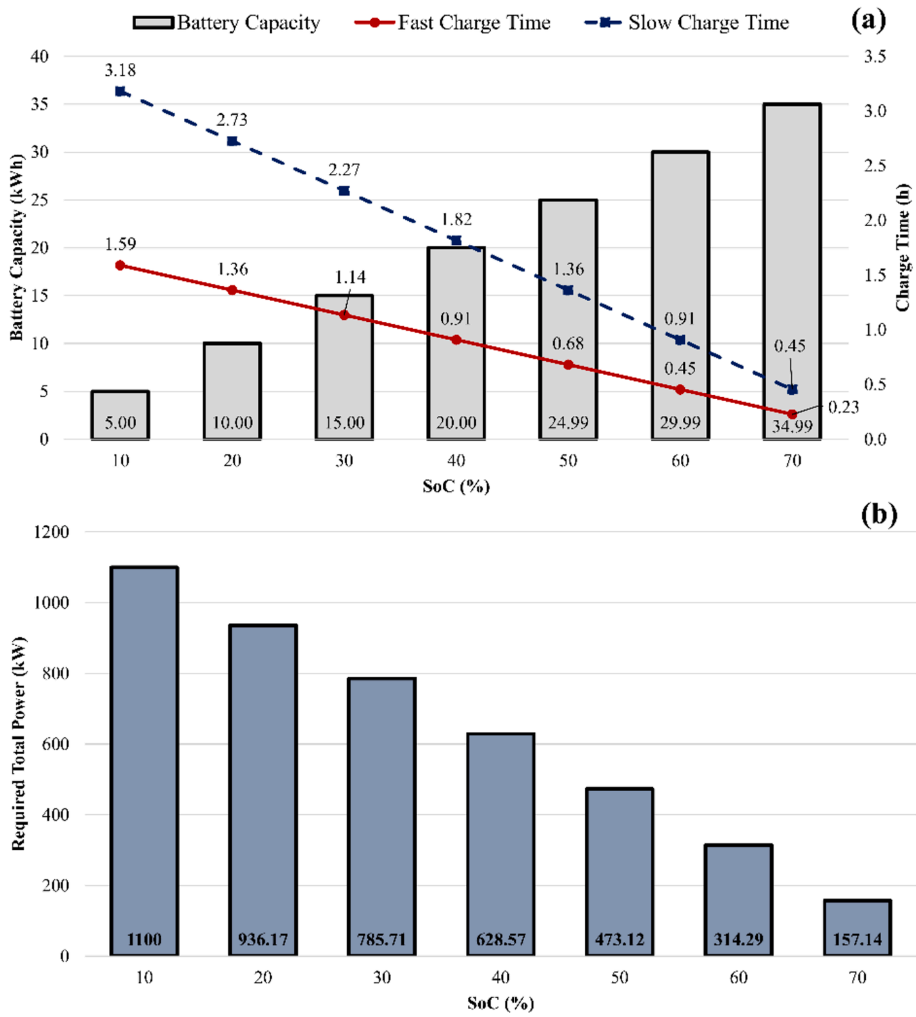


Fig. 2. The results of parametric analysis for 200 EVs according to initial SoC: (a) SoC – battery capacity/ charge time, (b) SoC – required total power for charging.

differences have been taken considering the data shown in Fig. 3 by using the minimum (70 %) and maximum data points (10 %). In the worst-case scenario, the configuration involving Engine-1 has resulted in the consumption of an excess of 1,653.45 metric tons of HFO or 1,565.85 t of LFO annually, contingent upon the operating fuel choice. Engine-2 has subsequently utilized an additional 1,394.3 t of LFO or 2,814.15 t of methanol, while Engine-3 has consumed an extra 1,084.05 t of LNG or 1,226.4 t of LFO within the same timeframe for the purpose of charging EVs.

Conversely, in the case of all EVs charge levels at 70 %, these consumption values have been significantly reduced to 175.2 t for Engine-1, regardless of whether HFO or LFO is employed. For Engine-2, the annual consumption has decreased to 197.10 t of LFO or 405.15 t of methanol, and for Engine-3, it has been reduced to 175.20 t of LFO or 153.30 t of LNG, depending on the selected fuel type.

The calculations of additional fuel usage indicate a potential $CO_2$ emission of up to 5,156.35 t annually for charging EVs in Case-1 with HFO-powered diesel engines. This figure corresponds to a 3.16 % increase in $CO_2$ emissions compared to the scenario without EV charging, designated as Case-0. When operations proceed with alternative fuels that have lower Cf coefficients, the projected annual $CO_2$ increment is calculated at 2,981.138 t for LNG and 3,869.456 t for methanol, reflecting increases of 2.31 % and 2.37 %, respectively, compared to their Case-0.

A corresponding power calculation has been conducted for scenarios involving varying numbers of EVs, as presented in Table 6, to facilitate a scenario-based analysis. Fig. 5 visually illustrates the total power and energy requirements for navigation under specified conditions, as well as the charging power necessary for EVs in each scenario.

Depending on the charge level of EVs, the FC per voyage fluctuates. The maximum variations have been mentioned previously since Case-1 is the scenario where all 200 EVs arrive with 10 % SoC. The required charging power in Case-1 is determined to be 37.10 % of the hotel load. For Case-2, Case-3, and Case-4, these percentages are 26.47 %, 15.91 %, and 21.18 %, respectively. In the worst-case scenario, up to 7,000 kWh of charging energy is required, while in a more mediocre demand case such as Case-4, this value is approximately 4,000 kWh per voyage. Fig. 6 illustrates the average load, the number of working engines, and the FC for each engine per voyage.

Fig. 6a shows the average engine load for three engines across examined cases. The bar heights represent the load, while the overlaid markers indicate the number of working engines for each case. The Engine-1 configuration employs eight engines that operate at an average load of 83.7 % in the base case. In scenarios of higher demand, such as Case-1 and Case-2, an additional engine becomes necessary. In Cases 3 and 4, a corresponding increase in the average load of each engine is observed, specifically by 0.9 % and 1.2 %, respectively.

Conversely, the Engine-2 configuration utilizes ten engines, maintaining an average load of 83.7 % without EV charging. Notable load augmentations of 2.18 %, 1.56 %, 0.94 %, and 1.25 % have been recorded across Cases 1 through 4. The Engine-3 configuration operates with eight engines at a reduced load of 75.5 % without the integration of

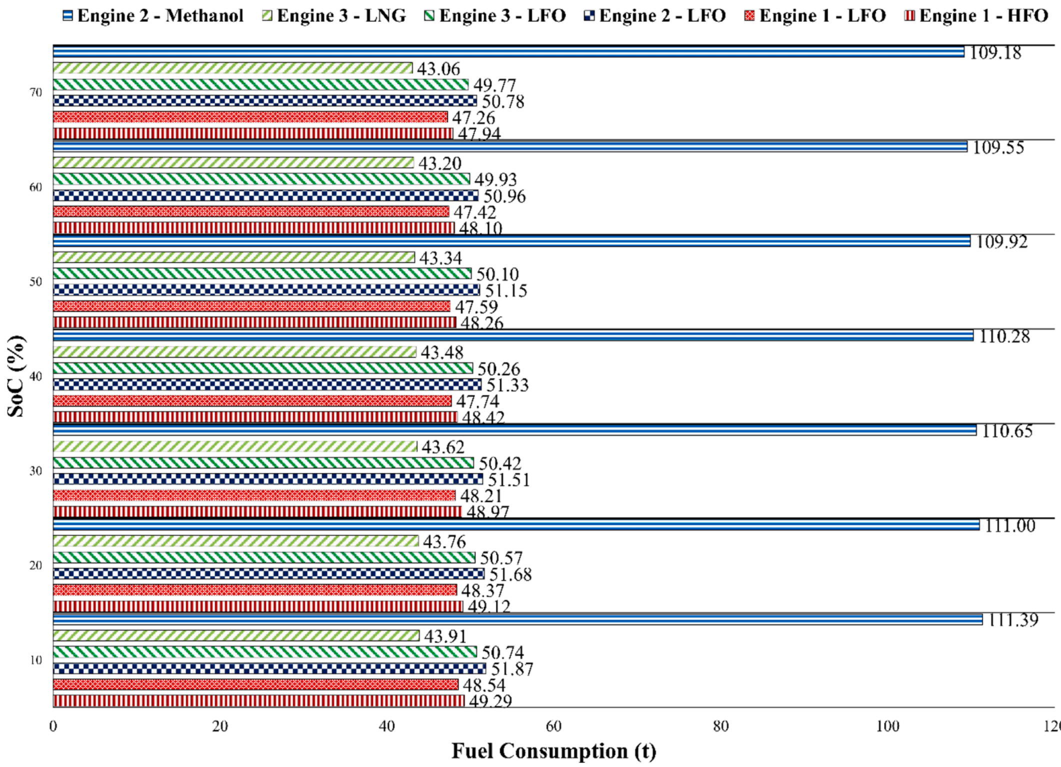


**Fig. 3.** The parametric analysis of FC per navigation regarding engine types and the initial SoC.

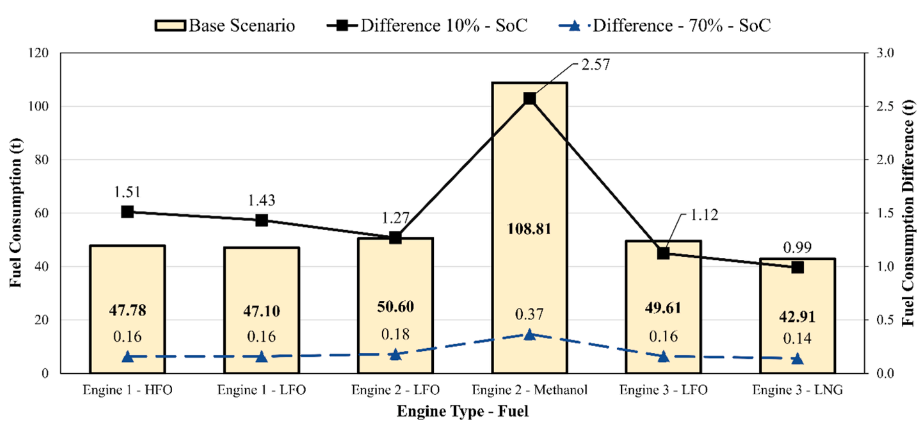


**Fig. 4.** The FC per navigation in the base scenario and the variations in FC.

EV charging. Incremental load increases of 1.97 %, 1.41 %, 0.84 %, and 1.12 % have been documented across Cases 1 to 4.

Fig. 6b presents FC by engine type and fuel type across cases. The primary y-axis measures FC in t for fuels other than methanol, while the secondary y-axis tracks methanol consumption. Highlighted points and trends represent variations in consumption for each case. The FC for methanol in Engine-2 generally increases across various cases, primarily due to the inferior LCV of methanol. Conversely, LNG exhibits a decreasing trend in FC, attributable to its superior LCV. Notably, Case 4 exhibiting a normal distribution for EV numbers, indicates increases in FC ranging between 1.30 % and 1.48 %, contingent upon the specific fuel and engine type employed.

It is important to determine the $CO_2$ levels of each case since the FC alone does not depict the scenario due to different energy levels of the fuels. Fig. 7 indicates the $CO_2$ emissions of each case regarding the engine and fuel type.

The highest $CO_2$ emissions have been calculated for the configuration using Engine-2 with LFO as the fuel across all cases. Engine-3 with LFO follows closely with high $CO_2$ production. In contrast, LNG usage has significantly reduced $CO_2$ emissions per navigation. The average reduction for this combination compared to Engine-2′s LFO configuration is 42.13 tons per navigation, equating to 6.79 tons per hour. Annually, this configuration results in a CO2 reduction of 59,518.69 tons.

The use of methanol in Engine-2 leads to a mean reduction of 10.09 tons of $CO_2$, resulting in a decrease of 1.63 tons per hour and 14,257.88 tons per year. The $CO_2$ prevention rate for Engine-2 utilizing methanol stands at 6.33 %, while Engine-3 with LNG achieves a 26.42 % reduction compared to Engine-3 using LFO.

Utilizing a conventional engine has yielded more benefits in terms of operational $CO_2$ emissions. When examining Fig. 9, the combinations with Engine-1 using LFO and HFO rank as the second and third lowest $CO_2$ producers, respectively. This trend is attributed to the lower output power of Engine-2, which necessitates the operation of more engines.

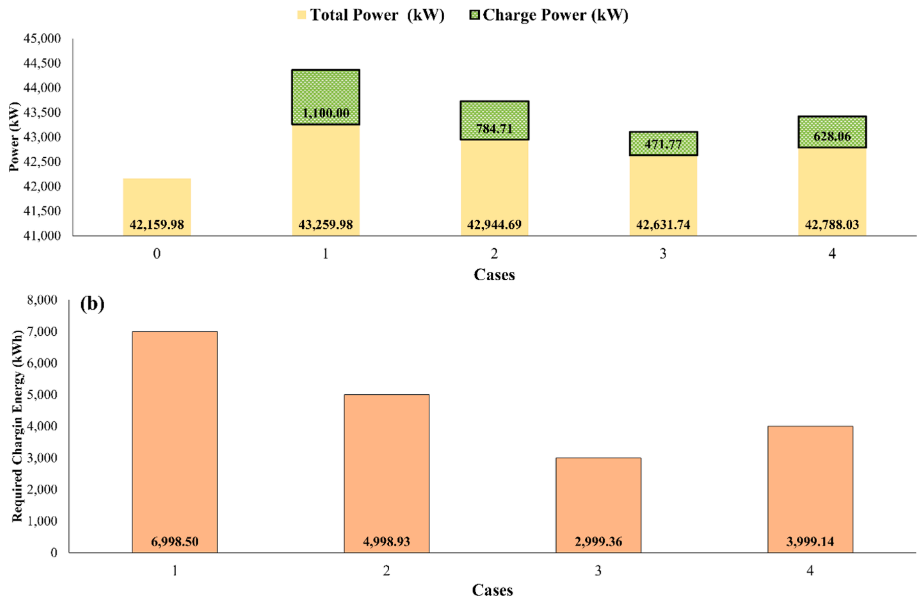


**Fig. 5.** The required power (a) and energy (b) per voyage for EV charging.

The limited power of Engine-2 is due to its commercial availability. The readiness of LNG dual-fuel engines for diesel-electric propulsion offers an advantage over methanol dual-fuel engines in this analysis, underscoring the significance of selecting the appropriate engine size for diesel-electric applications.

The elevated $CO_2$ emissions affect both environmental sustainability and regulatory compliance. To evaluate the compliance of the reference vessel with recent regulations, the EEXI values for each engine and fuel type have been calculated and are presented in Fig. 8.

The EEXI values for Engines 2 and 3 using LFO have consistently exceeded the EEDI reference values. After applying the reduction factor and ensuring compliance with the required EEXI line, only Engine-3 operating on LNG meets the requirement. Fig. 9 illustrates the CII ratings for Case 1, which is the scenario with the highest $CO_2$ emissions, alongside the base scenario for comparison.

The most suitable configuration for achieving A-level CII ratings until 2026 is Engine-3 using LNG fuel, which maintains this rating when EV charging is implemented, as per Case 1. The CII ratings for Engines 2 and 3 operating on LFO are at the B level, with a decline to the C level projected by 2024. The use of methanol in Engine-2 has significantly improved its CII rating compared to LFO. Engine-1 has attained a rating close to B levels for both fuels but is expected to drop to C level by 2026 with EV charging. The EV charging implementation has resulted in a CII value variation of 5.3 % for Engine-2 using LFO, the highest among the configurations. The average increase in CII values across configurations is 3.02 %, with Engine-3 using LNG showing the smallest change at 2.26 %.

## Discussion

The study investigated the potential impacts of EV charging on RoPax vessels concerning energy efficiency regulations and operational $CO_2$ emissions. It stands as a leading research effort in this area, offering pioneering insights and outcomes for the field. The adoption of LNG-DF engines has significantly facilitated compliance with regulations in the case study. by decreasing $CO_2$ emissions. LNG as the primary fuel has demonstrated a substantial impact on both environmental outcomes and regulatory compliance, aligning with findings from analyses reported in the literature [73,90]. The main reason behind this, the significantly superior LCV of LNG compared to methanol providing lower fuel combustion and storage capacity [91].

Conversely, incorporating methane slip into the calculations can alter the results, as the study focused solely on regulatory compliance and operational $CO_2$ emissions. This has been identified as the most significant drawback of LNG as a marine fuel, in addition to its failure to meet long-term targets [92]. Methane has a global warming potential that is 28 to 30 times higher than $CO_2$, making it a significant challenge for decarbonization efforts [93]. As energy efficiency regulations and emissions trading schemes increasingly encompass methane, the outcomes could influence the development of methanol DF engines [94,95]. Despite its drawbacks, LNG remains a valid candidate for the near future. Methane abatement techniques and carbon capture and storage technologies can enhance its sustainability and effectiveness in the maritime industry [96].

Renewable energy sources onboard can enhance energy efficiency and facilitate compliance with the EEXI and CII requirements. Solar panels can be integrated into the ship electrification system, serving as an optimal solution for vessels on liner routes, such as RoPax ships. This integration can significantly enhance energy efficiency, resulting in improved EEXI and CII values [97]. Similarly, wind systems for wind-assisted propulsion and electrification systems can positively impact regulatory compliance, further supporting the achievement of energy efficiency and emissions targets [98]. Another important candidate for RoPax and RoRo vessels is fuel cells, which have been demonstrated to effectively assist in meeting updated energy efficiency requirements [89,99].

The addition of charging systems to the existing vessels may influence the total weight of the vessel, which can subsequently affect its cargo capacity. An increase in weight may necessitate adjustments in design and operational strategies to maintain optimal performance. Additionally, the dynamics of the power system onboard may also be affected by the EV charging infrastructure. The demand for electricity from charging EVs can create fluctuations in power supply and require advanced management systems to ensure a stable and efficient energy distribution [100].

## Conclusion

The study examined the potential impacts of EV charging on a case study RoPax vessel, with particular emphasis on its implications for energy efficiency regulations and operational $CO_2$ emissions. Utilizing a reference route and operational usage distributions, the EEXI and CII

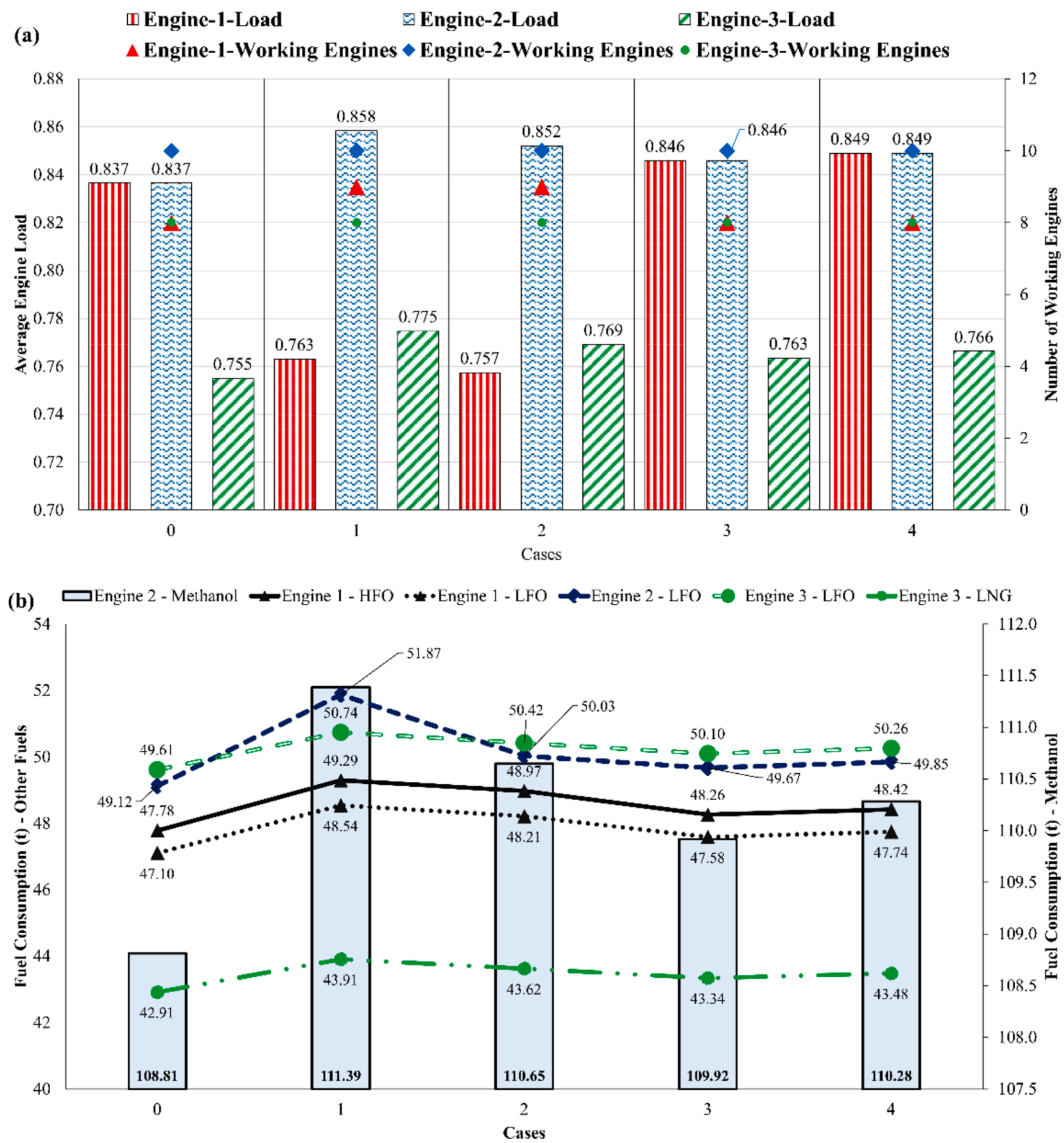


**Fig. 6.** The average load, number of working engines (a), and FC per voyage (b).

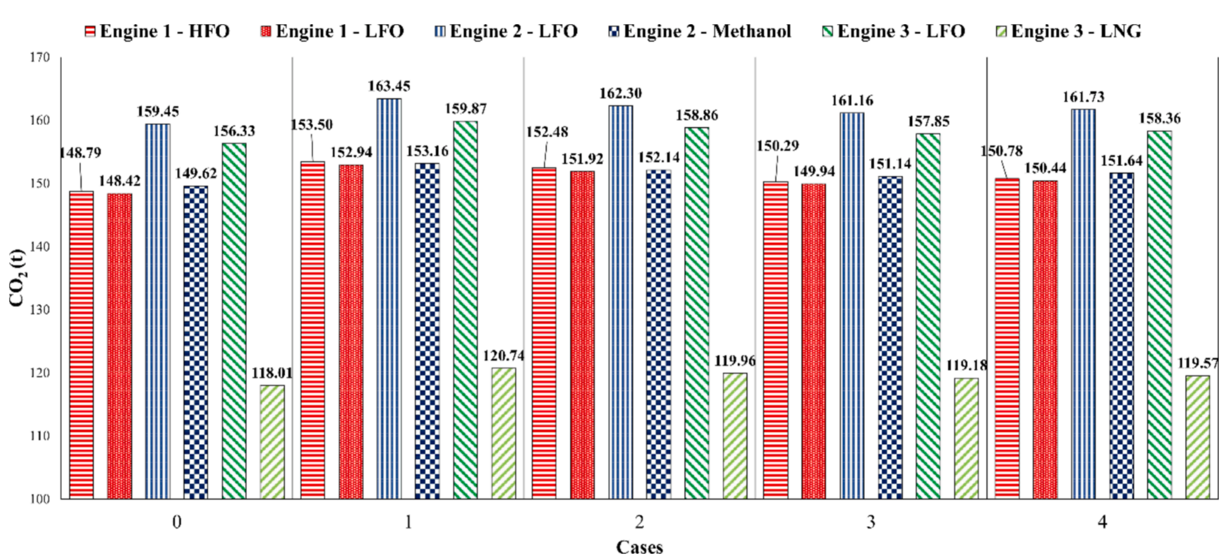


**Fig. 7.** $CO_2$ per navigation regarding the engine and fuel type.

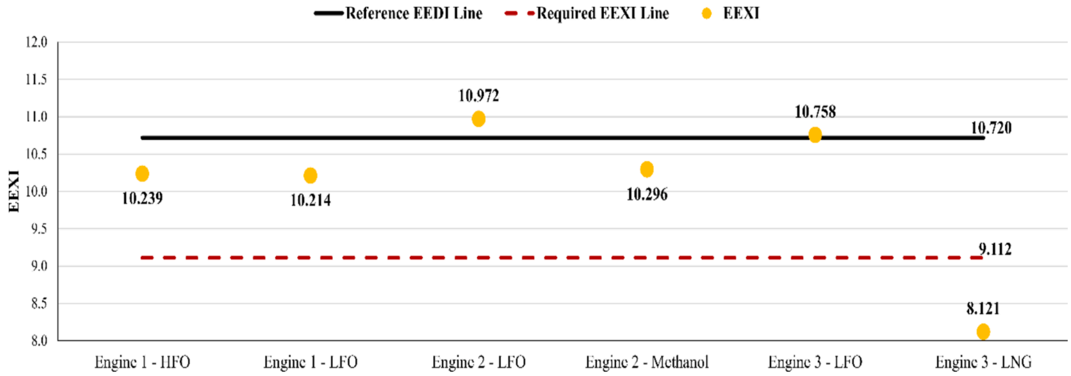


**Fig. 8.** EEXI values of configurations.

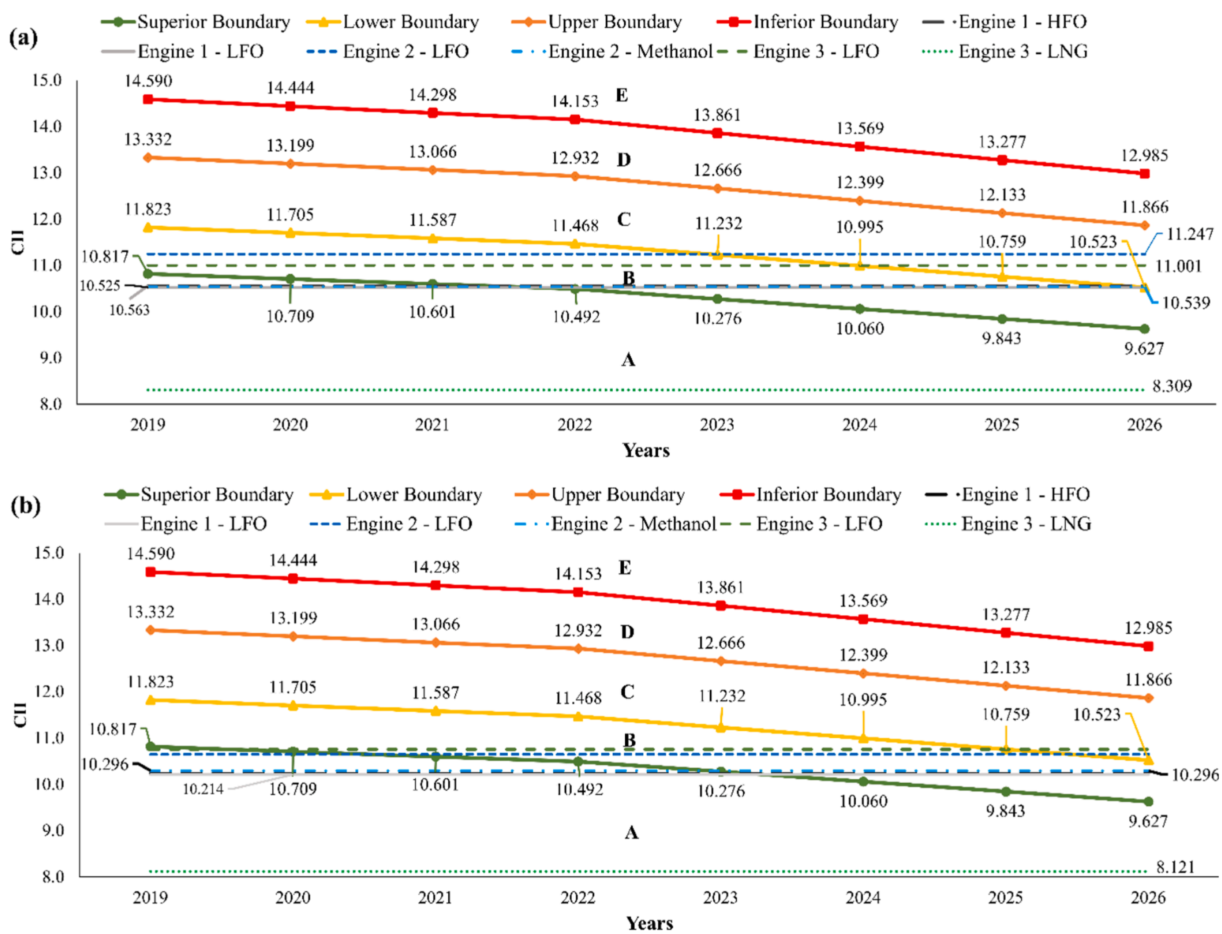


**Fig. 9.** CII values and ratings of (a) Case-1 and (b) base scenario.

values were calculated for various DEP and fuel configurations. The fuels investigated included HFO, LFO, LNG, and methanol [101].

The findings emphasized that LNG configurations yielded the lowest operational $CO_2$ and attained EEXI/CII values, positioning them as the most promising solutions. However, discussions also raised concerns about potential increases in greenhouse gases (GHGs) attributed to methane slip. The LFO usage in Engines 2 and 3, which are DF engines, resulted in non-compliance with EEXI requirements. If LFO is planned as the primary fuel in the case study, the diesel engines yielded a lower EEXI complying with EEDI limits. However, the LNG-DF configuration was the only one that complied with the required EEXI line, with reduction factors resulting in a CII rating at A levels until 2026.

EVs offer numerous benefits but also face challenges, such as the need for charging infrastructure. The integration of sustainable energy sources in port regions may impact the long-term environmental viability of EV transportation. Additionally, regulations governing the transport of EVs on ships emphasize the safety of batteries and charging systems. Technological advancements and increasing demand for EVs are expected to boost their use for long-distance travel, driving progress in ship design, battery technology, and charging infrastructure. EV transportation on ships reflects a broader trend toward electrification and sustainability in the transportation sector.

This theoretical study has limitations in addressing certain practical aspects comprehensively. Notably, a detailed stability analysis of different charging strategies is beyond its scope and is recommended for future investigations. $CO_2$ emission calculations in the study do not account for external factors such as route variations and weather conditions, which necessitate real-world data and operational testing. This introduces uncertainty in the CII rating calculations; however, the study primarily focuses on potential increases associated with EV charging. Forthcoming research could enhance accuracy and applicability by incorporating real-data calculations and conducting a more comprehensive environmental analysis on EV charging. This analysis should consider other GHGs like methane and nitrous oxide including well-to-tank emissions for RoRo and RoPax vessels.

Future studies should perform a detailed analysis of critical aspects to enhance the scope and applicability of findings. This includes optimizing charging station layouts, assessing impacts on electrical systems, evaluating safety measures and redundancy, and developing effective power management strategies. Performance analysis under varied route conditions is essential for real-world adaptability. Additionally, exploring ship-to-shore power grid optimization and emerging energy storage technologies would strengthen relevance. Expanding the analysis to different vessel types would enhance insights and generalizability.

Moreover, comprehensive economic analyses are recommended to understand the financial implications of EV charging strategies. These should evaluate infrastructure investment costs, variations in operational expenses, tariff determination, and return on investment. Such evaluations would provide insights into the economic feasibility and long-term sustainability of implementing EV charging on RoPax and RoRo vessels, aiding informed decision-making and strategic planning.

## CRediT authorship contribution statement

**Onur Yuksel:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation. **Burak Goksu:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2025.104238.

## Data availability

Data will be made available on request.

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