

Article

System-Level Dynamic LCA of Si and SiC Inverters for Coastal Battery-Electric Vessels Under Operation Profiles

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Abstract

The accelerated global transition toward eco-friendly mobility has necessitated robust decarbonization measures across the maritime sector, with battery-powered electric propulsion ships emerging as a promising alternative. Accordingly, the applicability of silicon carbide (SiC)-based technology to propulsion inverters, a key component of such vessels, is currently under investigation. Although life cycle assessment (LCA) studies comparing conventional silicon (Si)-based and SiC-based inverters have been conducted previously, these analyses neglect realistic operating profiles and load fluctuations, limiting their applicability. Furthermore, life cycle cost assessment (LCCA) integrating real-world operating conditions has rarely been addressed. To address these gaps, this study conducted a comparative LCA and LCCA of Si IGBT and SiC MOSFET inverters for marine electric propulsion systems across three vessel types: a cruise ship, a passenger and car ship, and a recreational boat, incorporating real-world load profiles to evaluate global warming potential (GWP), fossil depletion (FD), and cumulative energy demand (CED). The static LCA results showed negligible differences between inverter types, contributing less than 1% to total impacts. The dynamic LCA demonstrated that SiC MOSFET inverters reduced environmental impacts by approximately 57%, 52%, and 34% for cruise ships, passenger and car ships, and recreational boats, respectively. Despite a 40% higher initial investment cost, SiC inverters achieved payback periods well within vessel lifetimes across all vessel types. These findings support SiC inverters as a sustainable and economically viable solution for ship electrification.

Keywords: life cycle assessment; electric propulsion ship; silicon carbide inverter; dynamic operation scenario; environmental impact analysis



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1. Introduction

The urgent need to reduce greenhouse gas (GHG) emissions in the transportation sector, including automobiles, aircraft, and ships, has accelerated the global transition toward eco-friendly mobility in recent years [1]. Ships, predominantly powered by internal combustion engines burning fossil fuels, emit substantial amounts of air pollutants. According to the International Maritime Organization (IMO), marine vessels are responsible for approximately 13% of global sulfur oxides (SO_x), 12% of nitrogen oxides (NO_x), and 3% of carbon dioxide (CO₂) emissions [2]. At its 80th Marine Environment Protection Committee (MEPC) session in 2023, the IMO adopted a net-zero strategy to achieve a 100% reduction in GHG emissions from international shipping by 2050, thereby mandating strong decarbonization measures across the maritime sector [3].

Consequently, several countries and shipping companies have accelerated the adoption of eco-friendly propulsion systems. Among these, electric propulsion ships, powered by hydrogen fuel cells or batteries, have garnered increasing attention owing to their high energy efficiency and precise control capability [4]. These systems are particularly suitable for coastal cruise ships and small to medium-sized ships operating on short-sea routes [5].

Table 1 summarizes representative applications of electric propulsion systems in coastal cruise ships and small- to medium-sized ships [6–8].

Table 1. Representative cases of coastal small and medium-sized electric propulsion ships.

Name	Country	Type	Propulsion System	Battery Capacity
K-electric propulsion ship	Republic of Korea	Car ferry	Battery	800 kWh ($\times 2$)
Ampere	Norway	Car ferry	Battery	520 kWh ($\times 2$)
Future of the Fjords	Norway	Passenger Ferry	Battery	1800 kWh
Ellen	Denmark	Car ferry	Battery	4300 kWh

The inverter-based power conversion system is a core component of electric propulsion ships. The inverter is a key component in electric propulsion systems because its efficiency directly affects propulsion performance, thermal behavior, and overall energy consumption. However, inverter switching losses increase heat generation and cooling demand, thereby influencing long-term environmental impacts [9–11]. Conventionally, two-level voltage-source inverters (VSIs) with silicon (Si)-based insulated gate bipolar transistors (IGBT) have been widely employed in small- to medium-sized electric propulsion systems. However, inverters equipped with silicon carbide (SiC)-based metal–oxide–semiconductor field-effect transistors (MOSFETs) have been increasingly commercialized across multiple industries owing to their capability for high-speed switching, reduced switching losses, and stable operation under high-temperature and high-voltage conditions [12–15]. Such characteristics are particularly suitable to the maritime sector, where propulsion systems are subject to substantial load variations and extended operating hours, accelerating the adoption of SiC-based inverters in marine applications [16].

Accordingly, comparative quantitative studies have been actively conducted to assess the performance improvements enabled by SiC-based MOSFETs. Most existing studies have predominantly focused on technical and operational metrics, such as device ratings, voltage ripple, and switching losses [17–19]. However, the primary motivation for introducing electric propulsion ships is compliance with environmental regulations and the reduction in GHG emissions. As such, improvements in technical performance do not necessarily translate into environmental benefits. If the adoption of SiC-based inverters leads to unforeseen environmental burdens, it would contradict with the fundamental objective of eco-friendly ship deployment. Therefore, comprehensive environmental assessments based on the lifecycle perspective—incorporating cumulative energy consumption, cooling power, equipment lifetime, and resource depletion under long-term ship operation—are essential.

Life cycle assessment (LCA) is a methodology that evaluates the environmental impacts associated with all stages of a product's life cycle [20]. Existing LCA studies on ships have predominantly focused on static analyses based on fixed operating conditions or standardized load scenarios. However, such approaches neglect realistic operating profiles—including voyage, standby, and port maneuvers—as well as load fluctuations and annual operating distances, thereby limiting the applicability of the results. This limitation is particularly pronounced in coastal ships, which experience frequent load variations compared with large ocean-going vessels, making static analyses insufficient to ensure accuracy. Inverter-level LCA studies have likewise simplified efficiency and losses as life

cycle averages or standardized duty cycles [21–23], although these parameters are strongly load-dependent in practice. A dynamic LCA incorporating real operating profiles is therefore required, and the methodological background and prior work are discussed in detail in Section 2.3.

This study conducts a quantitative life cycle comparison of Si-based IGBT inverters and SiC-based MOSFET inverters, focusing on small to medium-sized coastal electric propulsion ships equipped with dual 200 kW motors and approximately 1 MWh battery capacity. Realistic operating conditions at sea are incorporated by constructing representative load-profile scenarios, including high-load cruising, low-load standby, and repetitive port maneuvers. Time-resolved estimation of inverter power losses under these varying profiles enables a more realistic LCA analysis. The LCA is performed in accordance with ISO 14040/44 [24,25], which covers the manufacturing phase (device production and component assembly) and operational phase (electricity consumption due to power losses and cooling system impacts). Meanwhile, transportation and end-of-life stages are excluded from the system boundary. The impact assessment focuses on global warming potential (GWP), fossil depletion (FD) and Cumulative Energy Consumption (CED) complemented by Monte Carlo-based uncertainty and sensitivity analyses to provide confidence interval-based comparisons between technologies. The findings demonstrate the environmental advantages of SiC-based inverters under various operating scenarios and establish an objective basis for future eco-design and decision-making in the development of environmentally sustainable electric propulsion ships.

Beyond providing an environmental decision-making basis for component selection in electric propulsion ship design, this study contributes evidence relevant to future policy-making, ship certification, and eco-standardization processes by quantifying whether SiC adoption delivers tangible life cycle environmental improvements. The proposed framework, incorporating dynamic operating conditions into LCA, is also applicable to related sectors such as electric vehicles, rail transport, and aviation.

2. Background

2.1. Navigation Profiles and Operational Characteristics of Coastal Ships

Coastal ships, including fishing boats, passenger ferries, and car ferries, operate within domestic waters, each with distinct operational characteristics. They typically cover short routes of less than 50 nautical miles, which are repeated daily or at regular intervals. Their operations involve frequent departures and arrivals, often with multiple intermediate stops, resulting in repetitive port maneuvers. In addition, acceleration and deceleration occur frequently owing to navigational obstacles, passenger and cargo handling, and intermediate docking, resulting in significant speed variations.

Such operational characteristics are highly compatible with battery-based electric propulsion systems. Short and regular routes facilitate convenient scheduling of battery charging, and frequent port maneuvers and variable-speed operation leverage the key advantages of electric propulsion systems, such as precise speed control, low noise, and high efficiency. Consequently, coastal ships equipped with electric propulsion are particularly effective in environmentally sensitive coastal and urban waters. Figure 1 illustrates representative coastal ships and their corresponding load characteristics.

Navigation profiles reveal that coastal ships are exposed to various operational conditions, such as steady cruising, frequent acceleration and deceleration, and standby periods during berthing. These operating conditions directly influence energy consumption and thermal management requirements. From an LCA perspective, reflecting such operation-dependent variations is essential to realistically estimate the environmental impacts of the entire propulsion system.

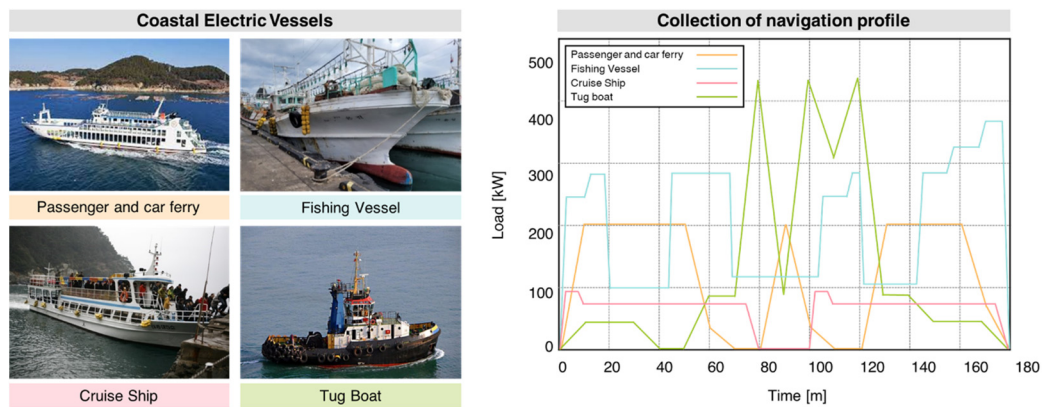


Figure 1. Load variation characteristics of coastal electric vessels based on their navigation profiles.

2.2. Overview of the Power Conversion System in Electric Propulsion Ships

Figure 2 illustrates the configuration of the key components and energy flow in a battery-electric propulsion ship. Among these components, the inverter-based power conversion system plays a critical role because inverter efficiency directly affects propulsion performance, thermal behavior, and overall energy consumption.

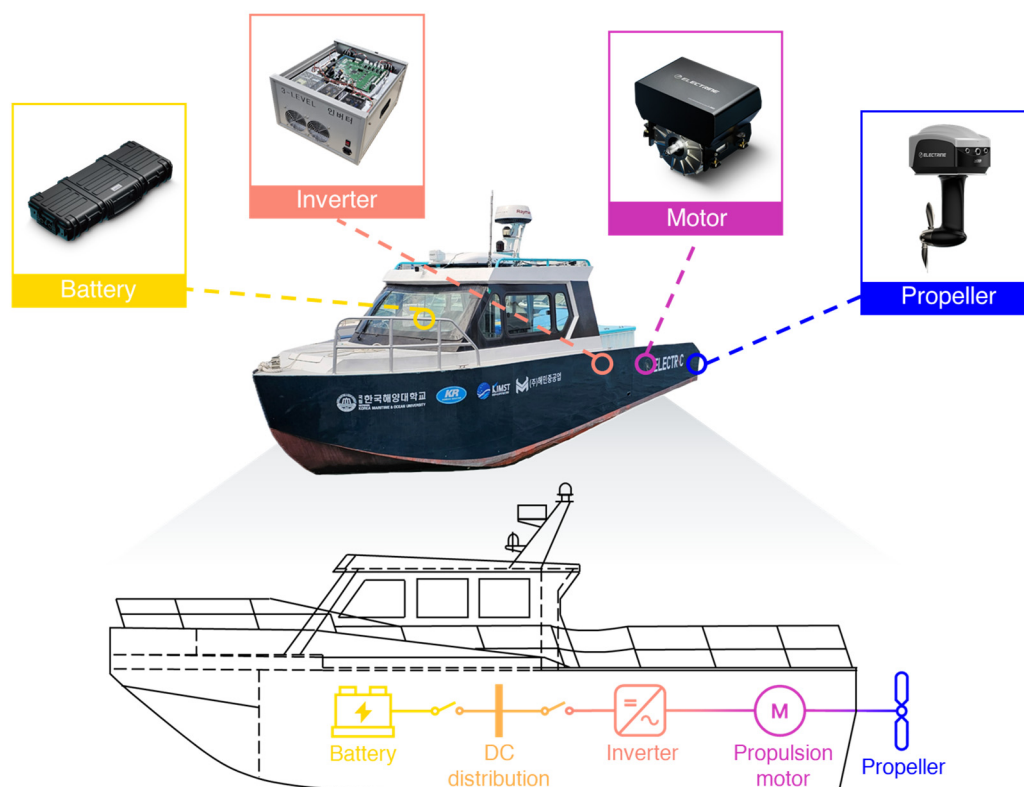


Figure 2. Schematic of the key components and energy flow of an electric propulsion ship.

Two-level voltage-source inverters (VSIs) using Si IGBTs have been widely adopted in coastal electric propulsion systems owing to their simple structure and cost-effectiveness. However, conventional Si-IGBT-based inverters exhibit relatively high switching losses and heat generation under continuous high-power operation [26,27]. Recently, SiC-MOSFET-based inverters have attracted increasing attention owing to their lower switching losses, higher efficiency, and improved thermal performance [12–15,28].

In addition, power conversion systems are also influenced by their cooling configurations, and these differences affect both operational loss characteristics and material

requirements during the manufacturing stage. As a result, differences arise in cooling demand, inverter efficiency, and cumulative energy consumption during long-term operation.

Therefore, the selection of inverter technology directly influences not only propulsion-system performance but also the life cycle environmental impacts of electric propulsion ships. The environmental implications of these differences are investigated through the dynamic LCA framework presented in the following sections.

2.3. Previous LCA Studies on Propulsion Systems and Inverters

LCA is widely used to quantify the environmental impacts of engineering systems throughout their life cycle [20] and has become an important tool for evaluating low-carbon technologies in the maritime sector. In this study, Si- and SiC-based inverter systems are evaluated based on the ISO 14040/44 framework, with particular emphasis on inventory modeling and the incorporation of realistic operating conditions during the use phase.

Previous ship-level LCA studies have largely compared internal combustion engine systems with electric or hybrid propulsion systems [29–32], including cradle-to-grave comparisons of electric ships [33] and analyses of hybrid passenger vessels [34]. At the inverter and power-module level, previous studies reported conflicting results regarding the environmental performance of Si and SiC technologies [22,23]. However, most existing studies rely on static or idealized operating conditions and generalized inventory data [35–39], which do not adequately capture equipment-specific behavior or use-phase dynamics. This limitation becomes more significant in coastal vessels owing to their highly variable operating profiles. Table 2 summarizes representative LCA studies and highlights the research gaps addressed in this work. As shown in Table 2, existing studies mainly rely on static LCA approaches, whereas the proposed framework considers dynamic operating conditions based on actual ship operating profiles.

Table 2. Summary of previous LCA studies and research gaps addressed in this study.

Category	Reference	System/Application	Methodology	Gap Filled by This Study
Ship LCA	[30]	All-electric short-sea vessels	Static LCA	Time-resolved dynamic LCA using actual ship operating profiles
	[31]	Inland ships carbon footprint	Scenario-based LCA	
	[37]	Propulsion options comparison	Static LCA	
Si/SiC Comparison	[14]	Si/SiC device performance	Performance-focused electrical analysis	Environmental impact comparison between Si inverter and SiC inverter
	[12]	Wide bandgap device survey		
	[17]	SiC MOSFET review for EV		

Accordingly, this study introduces a dynamic LCA framework based on experimentally measured inverter efficiency and loss characteristics under real operating load profiles. By incorporating time-resolved operational data into the inventory, the environmental impacts of Si- and SiC-based inverter systems are quantitatively evaluated under realistic coastal-vessel operating conditions.

3. Case Study: Coastal Electric Propulsion Ship

3.1. Target Vessels and Propulsion System Configuration

The target vessel was designed based on the representative coastal electric propulsion ships introduced in Section 1, with electrical-system redundancy taken into account. A twin-shaft battery-electric configuration was adopted, comprising two 500 kWh lithium-ion battery packs (1 MWh in total) and a 200 kW-class induction motor on each shaft, giving

a total propulsion power of 400 kW. The propulsion system consists of three primary subsystems—battery, inverter, and motor—whose specifications are summarized in Table 3.

Table 3. Configuration of the electric propulsion system of the target vessel.

Category	Specification
Battery system	Lithium-ion battery, 500 kWh × 2 (1 MWh total), 700 V-class voltage level, equipped with a battery management system (BMS)
Inverter system	Three-phase two-level voltage-source inverter (VSI) using Si IGBT or SiC MOSFET power modules
Motor system	Twin-shaft configuration with two 200 kW-class induction motors (400 kW in total)

Figure 3 shows the overall configuration of the propulsion system. DC power from the battery is converted into AC by the inverter, which drives the motor and ultimately produces propulsion through the propeller, following a typical electric propulsion pathway. The diagram also indicates the two compared power semiconductor technologies (Si IGBT and SiC MOSFET) and the corresponding cooling configurations (air- and liquid-cooling), together with the load profiles applied for the dynamic LCA. The full propulsion system was implemented in MATLAB/Simulink R2025a (MathWorks Inc., Natick, MA, USA, <https://www.mathworks.com/>) and used to derive time-resolved inverter power losses and cumulative energy dissipation in the subsequent dynamic LCA.

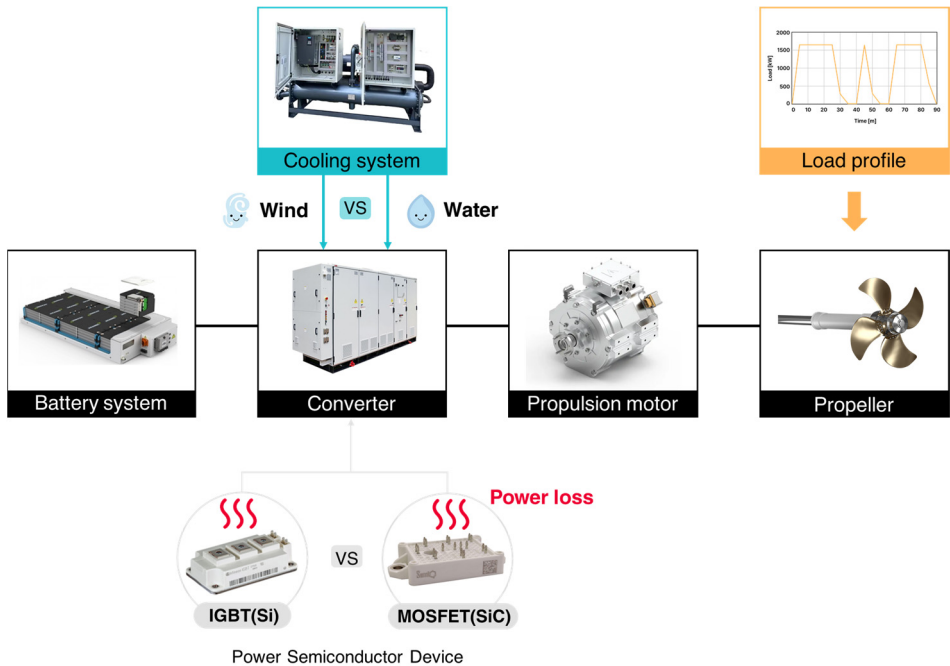


Figure 3. Configuration of the electric propulsion system with a converter (IGBT/MOSFET) and cooling system (wind/water).

The Si IGBT inverter and SiC MOSFET inverter were selected as the comparison targets to assess how differences in semiconductor device technology, cooling configuration, and manufacturing-stage material consumption translate into life-cycle environmental impacts. The two inverters differ not only in power semiconductor type but also in cooling-system architecture, resulting in distinct loss behaviors during operation and different material inventories at the manufacturing stage.

3.2. Operating Load Profiles

Three vessel types were considered—a passenger-and-car ship, a cruise ship, and a recreational boat—to capture the diverse operational characteristics of coastal vessels. The load profiles of the passenger-and-car ship and the cruise ship were obtained from measured propulsion-output data, whereas the recreational boat profile was reconstructed from the speed profile reported by Hong et al. [36] by converting vessel speed to propulsion power under the standard assumption that propulsion power scales with the cube of vessel speed:

$$P(t) = P_{\text{rated}} \cdot \left(\frac{v(t)}{v_{\text{max}}} \right)^3 \quad (1)$$

where $P_{\text{rated}} = 400$ kW is the rated propulsion power of the target vessel, $v(t)$ is the time-varying vessel speed, and $v_{\text{max}} = 17$ knots is the maximum operating speed.

The passenger-and-car ship and the cruise ship exhibit regular operational patterns owing to their repetitive routes, with frequent speed variations characteristic of coastal vessels during repeated departure and arrival maneuvers. By contrast, the recreational boat shows significantly larger fluctuations in speed and acceleration. The corresponding load profiles are presented in Figure 4.

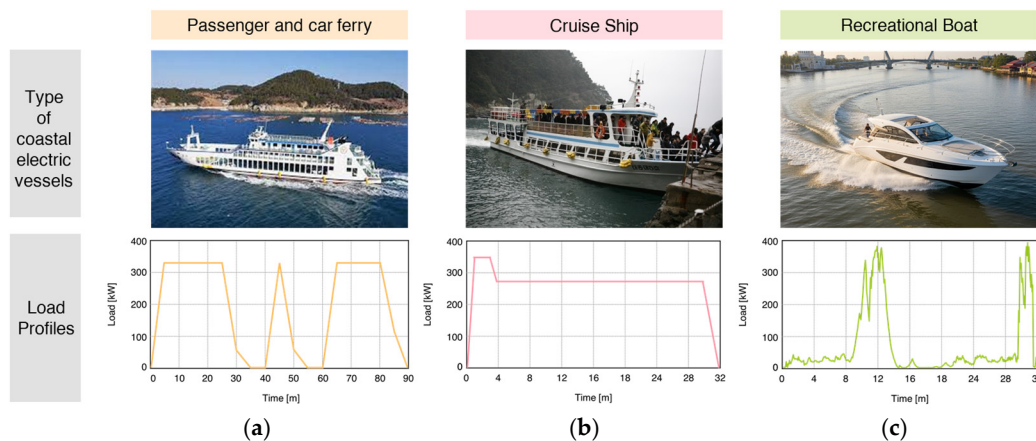


Figure 4. Target operating load profiles: (a) passenger-and-car ship; (b) cruise ship; (c) recreational boat.

Such variations—including acceleration, deceleration, and idle periods—are critical determinants of inverter power losses and cooling-power requirements, and constitute the representative dynamic conditions required for the operation-resolved LCA presented in the following sections.

4. Methodology (LCA)

As discussed earlier, coastal electric propulsion ships operate under distinctive conditions, such as short routes, frequent acceleration and deceleration, and limited cooling capacity. Under these constraints, the environmental impacts of power conversion systems become particularly significant, as they directly influence propulsion efficiency, power losses, and cooling requirements, thereby serving as a critical determinant of the overall life cycle performance of the system.

This study builds on the framework of Baudais B [35] clarifying the quantitative scope of LCA analysis and incorporating process-level emission inventories to verify the environmental advantages of SiC-based inverters. Unlike previous studies, which have primarily focused on fixed loads or static operating conditions, this study addresses the limitations of such approaches by adopting a scenario-based dynamic LCA that incorporates realis-

tic maritime operating conditions, including load fluctuations, weather influences, and cooling constraints.

In terms of data sources, empirical measurements from 200 kW-class Si and SiC inverters were used to derive load-dependent efficiency and loss characteristics. These experimental results were integrated into MATLAB-based simulations to quantify energy consumption and cooling demands under different operational scenarios. For the manufacturing phase, material and process data were supplemented using the Ecoinvent v3.10 database within OpenLCA 2.5. The entire LCI was constructed by combining static database values with dynamic, simulation-based results.

The LCA framework applied to inverter-based power conversion systems is shown in Figure 5. In this schematic, the physical components of the system (e.g., power modules, PCBs) and operational input–output characteristics derived from realistic load conditions are integrated. The framework combines dynamic LCA modeling with static inventory data from Ecoinvent, processed within MATLAB, to provide a comprehensive environmental impact assessment.

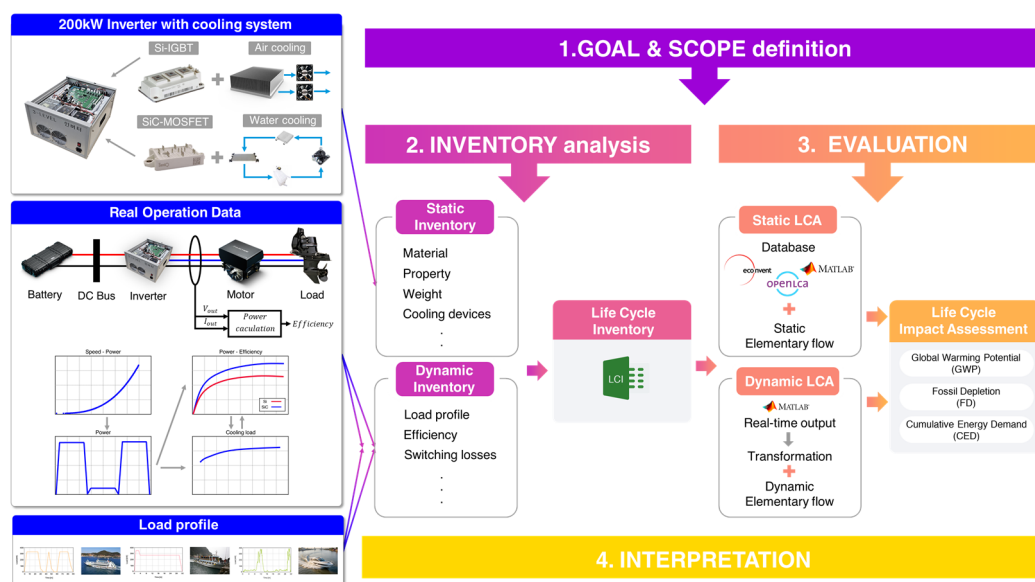


Figure 5. LCA framework for electric propulsion ship inverters based on real operation data.

4.1. LCA Framework

This study quantitatively evaluates the life cycle environmental impacts of power conversion systems for electric propulsion ships in accordance with the international standards ISO 14040 and ISO 14044 [24,25]. The analysis focuses on IGBT-based Si inverters and MOSFET-based SiC inverters, both operated under identical output conditions, with the objective of comparing their efficiency and associated environmental impacts.

A cradle-to-gate approach with a use phase was adopted, covering the component manufacturing and inverter assembly stage and the operational phase under realistic navigation conditions. Upstream semiconductor wafer fabrication, transportation, and end-of-life stages are excluded; the rationale and implications of these exclusions are discussed in Sections 4.2.2 and 5.5. In particular, the use phase was modeled via simulations that calculate power losses, heat generation, and cooling energy consumption under operational scenarios, such as steady cruising, acceleration/deceleration, and berthing. By integrating these scenarios, the study applies a dynamic LCA approach that addresses the limitations of conventional static LCA. This framework enables a more realistic evaluation of the environmental impacts of inverter systems under actual operating conditions.

4.2. Goal and Scope Definition

4.2.1. Research Goal

The primary objective of this LCA is to perform a comparative assessment between two products: Si-IGBT-based and SiC-MOSFET-based inverters. By quantitatively evaluating the environmental impacts across both manufacturing and operational phases, the study aims to provide a basis for sustainable component selection in coastal electric propulsion ships and to support policy-oriented decision-making.

4.2.2. Research Scope

The Functional Unit (FU) is defined as the operation of one 200 kW inverter system for 10,000 h (1000 h per year over a 10-year service life) on a coastal vessel, evaluated under three representative operating load profiles: (a) a passenger-and-car ship (~6 h cycle), (b) a cruise ship (~2.5 h cycle), and (c) a recreational boat (~1 h cycle). All energy use and life-cycle impacts are integrated over time and normalized to this FU unless otherwise stated.

The term “system” refers to a set of interrelated processes associated with material and energy flows that perform defined functions. Accordingly, the definition of the system boundary specifies the extent to which different life cycle stages—including raw material acquisition, manufacturing, distribution and transport, use, and disposal—are included in the analysis.

The motor-drive inverter system for coastal electric propulsion ships can be categorized into life cycle stages as summarized in Table 4.

Table 4. Life cycle stages of the inverter system for a coastal electric propulsion vessel.

Stage	Main Items	Description
Raw material acquisition	Procurement of semiconductor and metal materials	• Mining and refining of raw materials for wafers • Procurement of metal resources
Manufacturing	Component fabrication and assembly	• Processing and packaging of power semiconductor devices • Fabrication of DC-link capacitors, PCBs, and cooling components • Inverter assembly
Transportation	Product delivery and installation	• Transportation of manufactured inverters to shipyards or vessel operating sites • Installation within the battery–inverter–motor drivetrain of electric propulsion ships
Use phase	Operation and maintenance	• Power losses and cooling energy consumption during operation • Accumulation of energy losses over long-term operation
End-of-life	Disassembly, recycling, and disposal	• Collection and disassembly of inverters • Recycling of metals • Incineration or landfilling of non-recyclable components

In this study, the life cycle boundary was defined to include the manufacturing phases, as well as the use phase, whereas the distribution and transport and end-of-life stages were excluded from the analysis. The primary purpose of this LCA is to conduct a comparative

assessment between the two inverter systems. The distribution and transport phase was omitted since identical conditions can be assumed for both products, whereas the end-of-life phase was excluded owing to the lack of reliable recycling data for emerging materials, such as SiC semiconductors, and because operational impacts are known to dominate the overall life cycle impact of inverters. The upstream processes corresponding to the raw-material extraction and wafer fabrication of semiconductor devices were excluded from the system boundary. However, this decision was made because such data are typically proprietary to manufacturers and are not commercially accessible in sufficient detail. Moreover, we aim to evaluate the environmental impacts of the entire electric propulsion system under realistic operating conditions based on a finished inverter product, which varies from the analyses focused on device-level material and process modeling. However, previous studies have reported that their manufacturing-stage environmental impacts may be higher as SiC MOSFETs generally require more complex and higher-temperature processing steps than Si IGBTs. Consequently, we additionally consulted the LCA literature comparing the raw-material extraction, fabrication, and package-manufacturing stages of the Si IGBT and SiC MOSFET power modules, and the interpretation of these results is presented in Section 5.5 (Limitations). Accordingly, the assessment scope was limited to focus on differences in environmental performance under realistic operating conditions.

In particular, the use phase was modeled via MATLAB-based simulations that incorporated actual power profiles of coastal vessels in conjunction with experimentally measured inverter efficiency and loss data. Time-dependent power losses and cooling demands were quantified and accumulated to determine the environmental impact over time, including GWP and FD. For carbon emissions, national emission factors based on Korean standards were applied. This scenario-based analysis represents the core contribution of the study, as it enables a more precise comparison of the environmental performance of alternative inverter technologies under realistic operating conditions—distinguishing it from conventional static LCA approaches. The impact categories applied in this analysis are Global Warming Potential (GWP), Fossil Depletion (FD), and Cumulative Energy Demand (CED). The ISO 14040/14044-based classification, definitions, and units of each category are summarized in Table 5.

Table 5. Impact categories used in the LCA.

Impact Category	ISO 14040/14044 Classification	Definition	Unit
GWP	Climate Change	Indicator expressing the relative radiative forcing of greenhouse gas emissions in terms of CO ₂ -equivalents	kg CO ₂ -eq
FD	Resource Depletion	Indicator representing the potential depletion of fossil resources such as oil, natural gas, and coal	MJ
CED	Energy Resource Use	Indicator representing the total primary energy demand required throughout the entire life cycle, including both renewable and non-renewable sources	MJ

GWP indicates the total amount of carbon dioxide emitted due to inverter power losses during operation. To quantify GWP, the annual average loss energy (E_{loss}) generated during inverter operation is multiplied by the emission factor EF_{GWP} (Emission Factor). The power loss comprises switching losses and conduction losses, which indicate the portion of electrical energy dissipated as heat during inverter operation. The emission factor represents the average amount of CO₂ emitted per unit of electricity generated. In this study, we implemented the location-based, government-approved emission factor for

the Republic of Korea, with a consumer-side value of $EF_{GWP} = 0.4594 \text{ kg CO}_2\text{-eq kWh}^{-1}$ based on the 2024 approved data.

$$GWP = E_{loss} \times EF_{GWP} \quad (2)$$

FD is an indicator that quantifies the amount of fossil resources consumed to generate the electricity required to compensate for the inverter power losses. FD is determined by the product of the annual average loss energy (E_{loss}) and the fossil resource depletion emission factor (EF_{FD}), which represents the amount of fossil resources consumed per unit of electricity produced in Korea. For this calculation, we employed the “electricity, medium voltage, market for, Korea” process in the TRACI v3.0 and Ecoinvent v3.10 databases, based on the cut-off system model, to derive the fossil resource consumption in the Korean electricity production system.

$$FD = E_{loss} \times EF_{FD} \quad (3)$$

CED represents the total amount of primary energy required to generate the electricity corresponding to the inverter power losses. CED is determined by the product of the annual average loss energy (E_{loss}) and the primary energy conversion factor (EF_{CED}), which represents the amount of primary energy required to produce 1 kWh of electricity. The CED factor reflects the national electricity generation mix; in this study, a value of 7.5 MJ per 1 kWh of electricity produced was applied based on the energy mix of the Republic of Korea.

$$CED = E_{loss} \times EF_{CED} \quad (4)$$

4.3. Inventory

This section describes the construction of the LCI and the simulation environment for evaluating inverter systems in coastal electric propulsion ships. In particular, the study integrates experimentally validated loss modeling under operational scenarios with the environmental impact data of major components, enabling an LCA that more accurately reflects actual navigation conditions. The analysis considers both Si-IGBT-based and SiC-MOSFET-based inverters, including the inverters themselves and differences in cooling systems. The LCI was systematically constructed based on the component structures and actual operating patterns of ships.

Two types of inventories were developed in this study: static and dynamic inventory. Static inventory corresponds to the conventional approach in LCA, comprising the BOM, material and manufacturing energy requirements for inverter components, cooling systems, and material properties. This captures the environmental burdens associated with the raw material extraction and manufacturing phases.

By contrast, the dynamic inventory was established to enable a more realistic LCA by incorporating actual operating conditions during the use phase. Instead of relying on fixed averages or standardized values, the dynamic inventory reflects real navigation data, including ship load profiles, inverter efficiency and loss variations with output power, and cumulative energy consumption during long-term operation. This approach allows the LCA to account for temporal and load-dependent variations, thereby providing a more reliable evaluation than conventional static methods.

4.3.1. Raw Material Extraction and Manufacturing: Static Inventory

Static inventory represents a quantitative dataset based on the component structure and material characteristics of the inverter system. For electric propulsion ship inverters, the types of components, material composition, and cooling configuration can significantly influence the overall environmental impact of the system. In this subsection, an LCI

was established for a comparative assessment between Si-IGBT- and SiC-MOSFET-based inverters, incorporating major components and differences in their cooling systems.

As illustrated in Figure 6, the cooling system structures of Si- and SiC-based inverters differ significantly. These differences extend beyond internal semiconductor devices, influencing the environmental impacts during the manufacturing and operational phases. The Si-IGBT inverter typically employs an air-cooled system with heat sinks and fans. Although the structure is simple, the cooling unit is larger in size and requires continuous power consumption for fan operation. In contrast, the SiC-MOSFET inverter typically adopts a water-cooled system, comprising integrated cold plates with heat pipes, a circulating pump, a radiator, and coolant lines. Such configurations allow for more compact designs and improved efficiency compared with conventional air cooling. These differences in cooling systems directly influence the volume and weight of the inverters, resulting in variations in the material requirements and manufacturing processes. Table 6 summarizes the comparison of volume and weight characteristics according to the cooling system configuration.

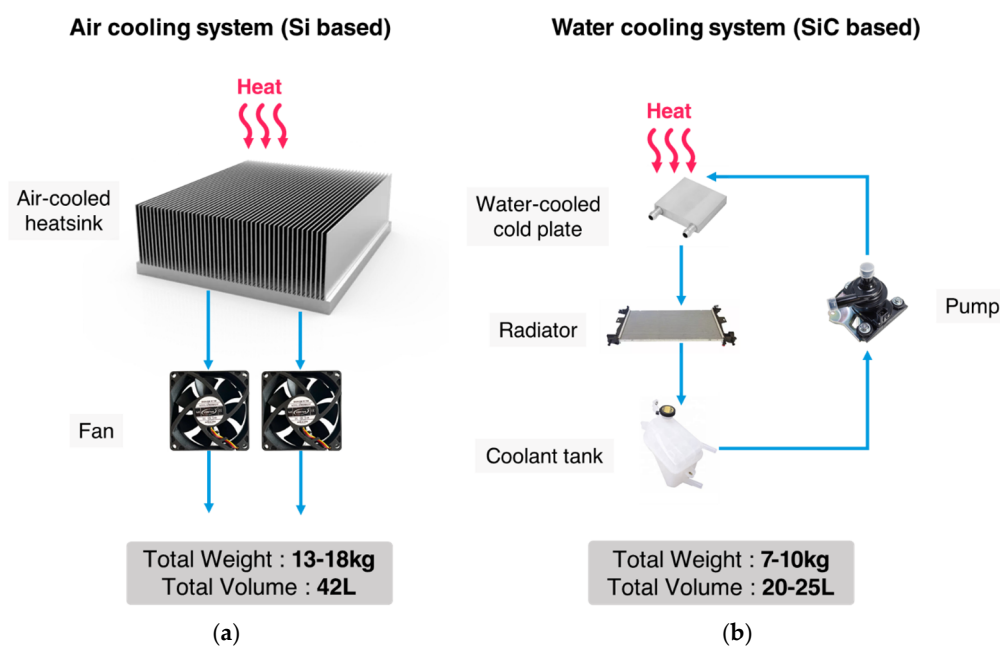


Figure 6. Comparison of cooling system structures: (a) Air-cooled heatsink for the Si IGBT inverter; (b) liquid-cooled loop for the SiC MOSFET inverter.

Table 6. Comparison of the air- and liquid-cooled cooling systems.

Item	Air-Cooled Inverter	Liquid-Cooled Inverter
Heatsink	600 × 400 × 150 mm (36 L)	—
Cooling fan	250 × 250 × 89 mm × 2 (5.6 L)	—
Cold plate	—	300 × 150 × 50 mm (2.25 L)
Pump	—	250 × 150 × 150 mm (5.6 L)
Radiator	—	400 × 300 × 60 mm (7.2 L)
Coolant Tank	—	5–10 L
Total Volume	42 L	20–25 L
Total Weight	13–18 kg	7–10 kg

In this study, the major components considered for the LCI, including the inverter and its cooling system, are summarized in Table 7.

Table 7. Components of the inverter system.

Category	Component	Material/Features	LCA Considerations
Power Semiconductor	Si IGBT, SiC MOSFET	Si, SiC	Energy for manufacturing, Lifetime, Power losses
DC-Link Capacitor	Electrolytic, Capacitor	Electrolyte, Aluminum	ESR variation (Loss variation), Lifetime impact
	Film Capacitor	Film, Aluminum	Longer life, Temperature stability
Cooling System	Heatsink, Fan, Cooler, Pump	Aluminum, Cooling lines	Power consumption, Added system energy
Driver & Control Board	PCB, Microcontroller	FR4, Semiconductor	Process energy, E-waste at end-of-life
Sensors	Voltage Sensor, Temp Sensor	Integrated into control board	Power consumption, Possibly embedded
Enclosure	Aluminum steel, Stainless steel, IP66+	Waterproof, Corrosion-resistant coating	Mass (transport/manufacture impact)
Wiring & Harness	Cables, Connectors, Terminals	Copper, Insulation	Resource recyclability and serviceability
Insulation and Sealants	Si pads, Ceramic coatings	Si, Polymer	Effect depends on hazardous substances used

These cooling system differences directly influence the material requirements during the manufacturing phase and the power consumption of cooling loads during the operational phase. Because cooling efficiency varies depending on the system configuration, differences are observed in inverter losses, efficiency, and cooling demands, which are ultimately reflected in the cumulative energy consumption during ship operation. This aspect is further addressed in Section 4.3.2.

The mass and material compositions of major components in the 200 kW-class inverter are presented in Figure 7. The material properties of each inverter were derived from manufacturer-provided specifications and measurement-based data. The Ecoinvent v3.10 database and OpenLCA software were utilized as data sources for the environmental impact assessment.

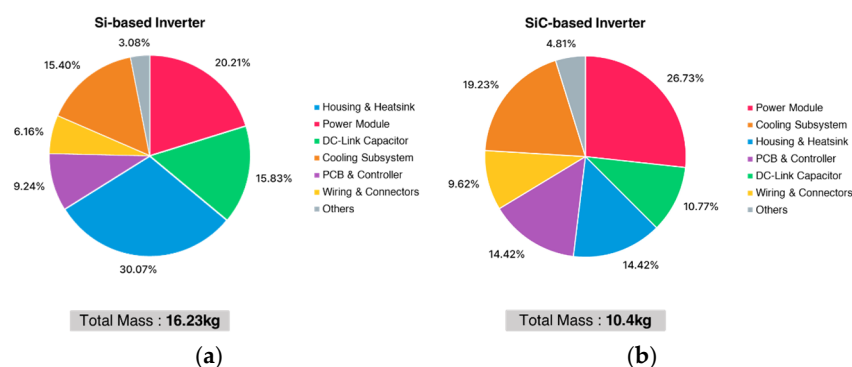


Figure 7. Mass and material compositions of major components in the 200 kW inverter with a cooling system: (a) Si IGBT Inverter; (b) SiC MOSFET Inverter.

4.3.2. Use Phase: Dynamic Inventory

In the use phase, the energy losses of the inverter are explicitly considered. Dynamic inventory data were obtained by combining the experimentally measured loss and efficiency

characteristics of actual inverters with the operational load profiles of coastal electric propulsion ships.

The experimental setup for measuring inverter losses and efficiency is shown in Figure 8. The test bench comprises four parts: (i) power stage, comprising a DC distribution board, a two-level, three-phase VSI, and an induction motor; (ii) control unit, operated in real time employing a control board and laptop; (iii) measurement and analysis unit, which acquires inverter voltage and current data to calculate efficiency and switching losses; and (iv) auxiliary instrumentation. For comparative analysis, identical experiments were performed on both an Si-IGBT-based two-level, three-phase VSI and an SiC-MOSFET-based two-level, three-phase VSI. Each inverter was connected to an induction motor and tested under various rotational speeds (rpm). At each rpm condition, the input voltage and current as well as the output voltage and current were measured. Based on these measurements, inverter losses and efficiencies were derived using a power analyzer. The resulting efficiency values were incorporated into the LCA evaluation for each operational segment, enabling a quantitative comparison of the environmental impacts of Si- and SiC-based inverters. Detailed experimental results—including output power, three-phase voltage and current waveforms, and efficiency/loss characteristics as functions of motor speed—are presented in Section 6.

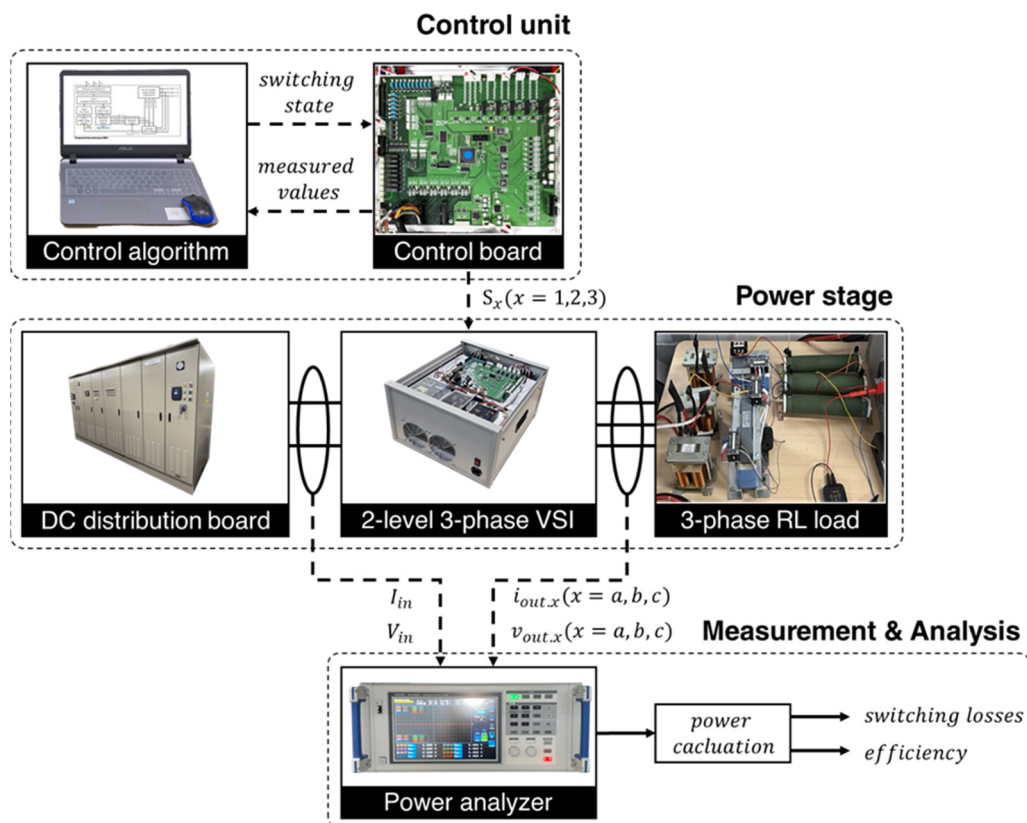


Figure 8. Experimental setup for the efficiency and loss measurement of Si- and SiC-based inverters for dynamic inventory.

In addition to the loss and efficiency characterization under varying load and switching frequency conditions, a supplementary experiment was conducted to evaluate the sensitivity of inverter efficiency to ambient temperature and relative humidity. The experimental setup is shown in Figure 9. This experiment was performed using a temperature- and humidity-controlled chamber, with ambient temperature ranging from 25 °C to 45 °C and relative humidity ranging from 30% to 90%. The purpose of this experiment was to

verify that the efficiency characteristics used in the dynamic LCA remain valid across the range of environmental conditions typically encountered in maritime operations.

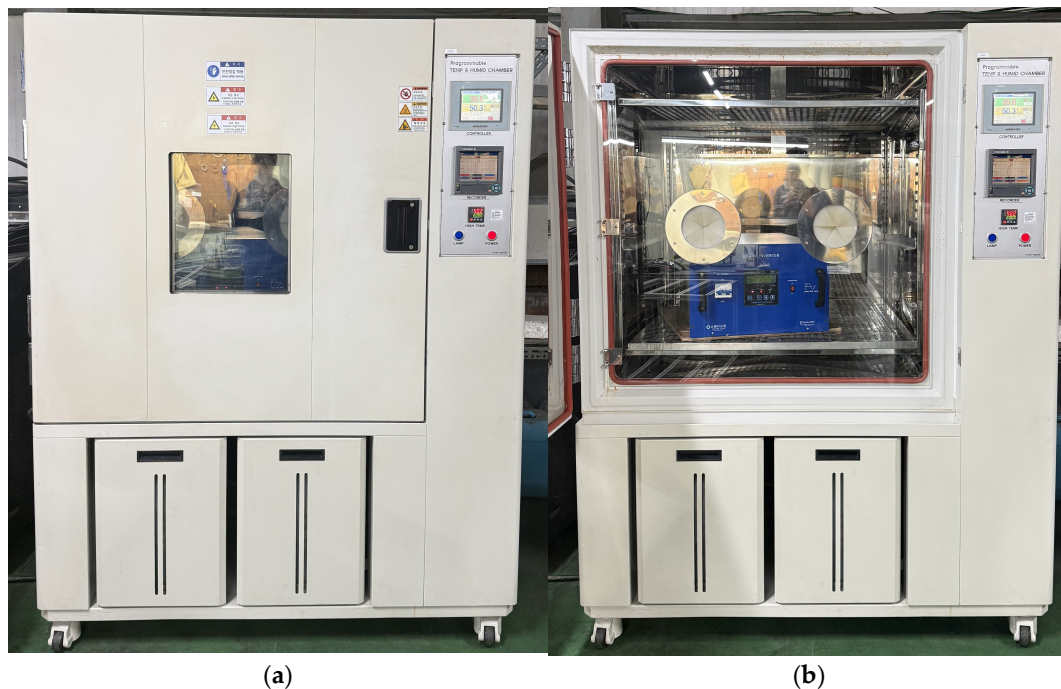


Figure 9. Temperature–humidity coupled environmental chamber: (a) External view; (b) Internal configuration.

For the passenger-and-car ship and the cruise ship, the operating patterns were defined as Cruise, Accel, and Idle. The cruise segment represents steady-speed navigation with relatively stable load conditions. The accel segment corresponds to short-duration navigation with significant load fluctuations, typically observed during departure and arrival. The idle segment represents berthing or low-speed standby, during which only the hotel loads were maintained.

The operating profile of the passenger-and-car ship depicted in Figure 10a spans approximately 6 h and comprises 81% Cruise, 11% Accel, and 6% Idle. The cruise ship profile in Figure 10b covers approximately 2 h, with 65% Cruise, 15% Accel, and 20% Idle.

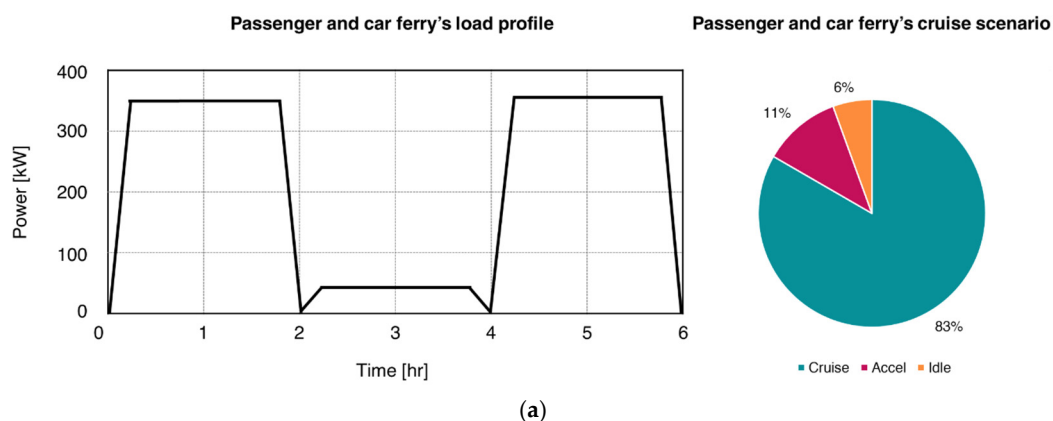


Figure 10. Cont.

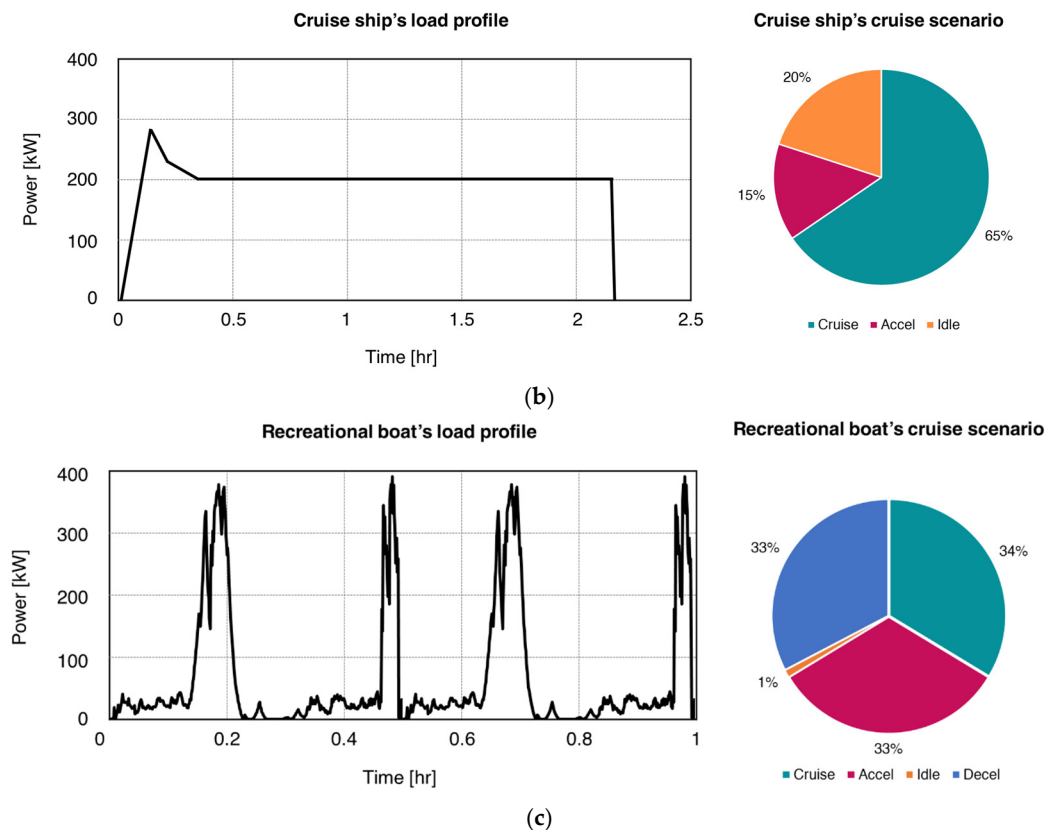


Figure 10. Adopted load profiles and cruise scenario (cruise/accel/idle) of representative coastal electric propulsion vessels: (a) passenger and car ferry; (b) cruise ship; (c) recreational boat.

The recreational boat profile in Figure 10c exhibits highly fluctuating load conditions within a short operating period of approximately 1 h. Its operating patterns are defined as Cruise, Accel, Decel, and Idle, with proportional shares of 34% Cruise, 32% Accel, 33% Decel, and 1% Idle. The accel and decel segments are characterized by rapid and frequent changes in propulsion power, presenting significantly larger temporal load variations compared with the other vessels. The idle segment corresponds to near-stationary or low-speed standby states, during which the propulsion load is almost negligible.

These operating profiles captured the time-dependent variations in actual load conditions and were employed as direct inputs for calculating inverter output power, losses, and cooling requirements in the dynamic LCA analysis.

The quantitative relationship between output power, inverter power losses, and cooling loads under actual operating scenarios is illustrated in Figure 11. First, an output power profile over time was derived from the speed–power correlation. Based on this profile, inverter-specific loss powers were calculated using experimentally obtained lookup tables for each inverter type. The corresponding cooling load was subsequently estimated according to these losses. Because the cooling configurations differ between the two inverter systems, a constant fan power consumption was applied to the air-cooled Si-IGBT inverter, whereas the liquid-cooled SiC-MOSFET inverter incorporated proportional cooling loads from pumps and auxiliary devices. Using this framework, hourly energy consumption was computed for each scenario, and cumulative energy consumption was subsequently derived according to daily and annual operating hours. Importantly, the analysis was designed to account for the environmental impact of cooling differences by quantifying the total energy loss flow, including cooling loads, for both inverter systems. For simplicity, the cooling systems were assumed to operate continuously during inverter operation. The air-cooled Si inverter employed a constant fan power, whereas the liquid-cooled SiC

inverter employed a constant pump power. Temperature-dependent cooling control was not considered because the objective of this study was a comparative assessment of the relative environmental impacts of the two inverter technologies.

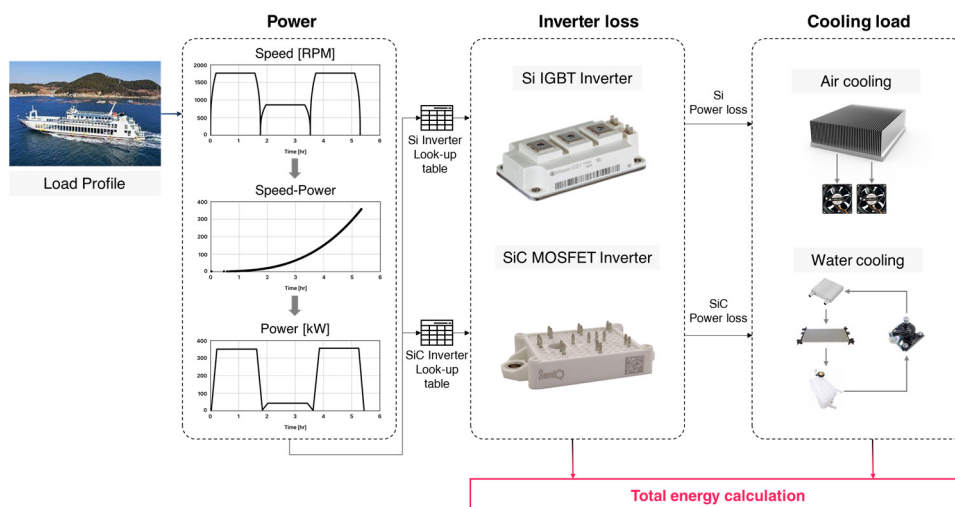


Figure 11. Computation flow of power, loss, and cooling load based on operation scenarios.

The integrated structure of the dynamic LCA, implemented in MATLAB, is presented in Figure 12. In this framework, output power, inverter losses, and cooling loads are computed along the time axis via simulation and directly linked to the LCA model. The scenario-based output-loss profiles established in the MATLAB environment are accumulated in real time, and the corresponding environmental impacts are automatically calculated in terms of GWP, FD and CED.

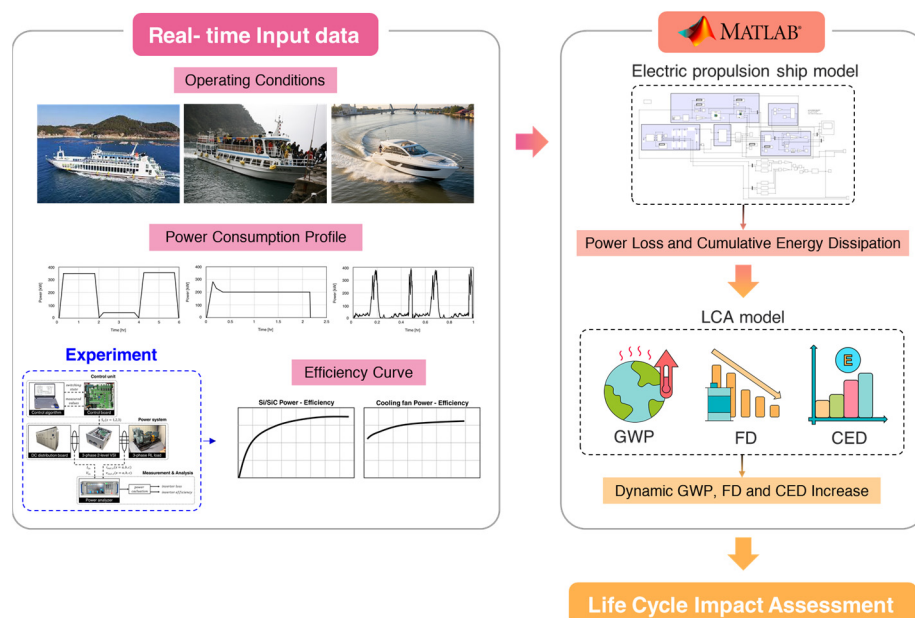


Figure 12. MATLAB-based dynamic LCA framework with actual operation data.

The operating scenarios were applied as time-based inputs to calculate inverter losses and cooling loads, which were then directly converted to GWP, FD and CED at each time step. Through this process, the time-resolved energy use was mapped to GWP, FD and CED. Unlike conventional approaches that rely on fixed conversion factors, this framework integrates real operational data with standardized LCIA methodologies to

quantitatively derive time-based environmental impacts. Accordingly, the linkage from operating conditions–power losses–cooling loads–environmental impacts is maintained within the MATLAB-based dynamic LCA framework.

The static and dynamic inventory items and their data sources applied in this study are summarized in Table 8.

Table 8. Inventory data sources for static and dynamic LCA.

Category	Factor	Description	Data Source
Static LCA	Manufacturing Energy	Impact of component production (e.g., semiconductors, capacitors, cooling units)	Ecoinvent 3.7
	Component Mass (BOM)	Mass breakdown of inverter components	Experimental data/Docs
	Material Properties (e.g., Al, Cu)	Material-specific impacts from manufacturing and disposal	Ecoinvent, Literature
	Cooling Devices (Heatsink, Pump)	Energy consumption based on cooling system architecture	Ecoinvent
	Fixed Operating Time (10 years/3000 h)	Assumed lifetime-based operational profile for static impact estimation	ISO 14040 guideline
Dynamic LCA	Power Consumption Profile	Load profile during actual operation	Measurement data
	Efficiency Curve	Output power vs. efficiency curve (e.g., 0.9–0.965)	Experimental results
	Power Loss and Cumulative Energy Dissipation	Time-varying losses and energy dissipation under operational conditions	MATLAB simulation
	Dynamic GWP, FD and CED Increase	GWP/FD additions based on operational power loss	equation conversion
	Operating Conditions	Operation scenario including trip cycles, departure patterns, and voyage frequency	Use-case scenario

The elements of the static inventory, including material production energy, BOM, cooling system specifications, and material properties, were primarily derived from Ecoinvent v3.10. By contrast, the dynamic inventory incorporates data extracted from MATLAB-based simulations, such as operational profiles, efficiency variations as a function of output power, inverter losses, and cumulative energy consumption. This integration of static and dynamic datasets enables the LCA framework to directly reflect temporal variations in operational loads and differences in cooling systems, distinguishing it from conventional LCA approaches. Consequently, it allows for sensitivity analyses of operating conditions, optimization of system design, and comparative evaluations of operational efficiency. Hence, a more reliable LCA can be conducted by explicitly capturing the actual operating conditions of electric propulsion vessels.

Proprietary measurement data were anonymized and used solely for aggregated analyses; secondary LCI datasets (Ecoinvent v3.10 via OpenLCA) were employed under the respective licenses and are fully referenced. No human or animal subjects were involved. We use the nationally approved location-based electricity factor for Korea (EFGWP = 0.4594 kg CO₂e kWh^{−1}, consumer side, approval year 2024), to translate time-resolved electricity use into GWP. FD is computed by the LCIA method (TRACI v3.0) combined with the Korea electricity market dataset in Ecoinvent v3.10 (process: electricity, medium voltage, market

for, Korea; system model: cut-off). Sensitivity analyses include the 2021 approved factors (0.4781 consumer-side; 0.4434 generation-side) and a market-based residual-mix scenario.

4.4. Life Cycle Cost Analysis (LCCA)

Evaluating the trade-off between economic feasibility and environmental performance is essential for practical applications as SiC inverters typically incur higher costs than Si inverters. Therefore, this study incorporates a life cycle cost analysis (LCCA) to comparatively evaluate the combined cost–environment effects of Si and SiC inverter systems. Figure 13 depicts the overall framework of the LCCA performed in this study.

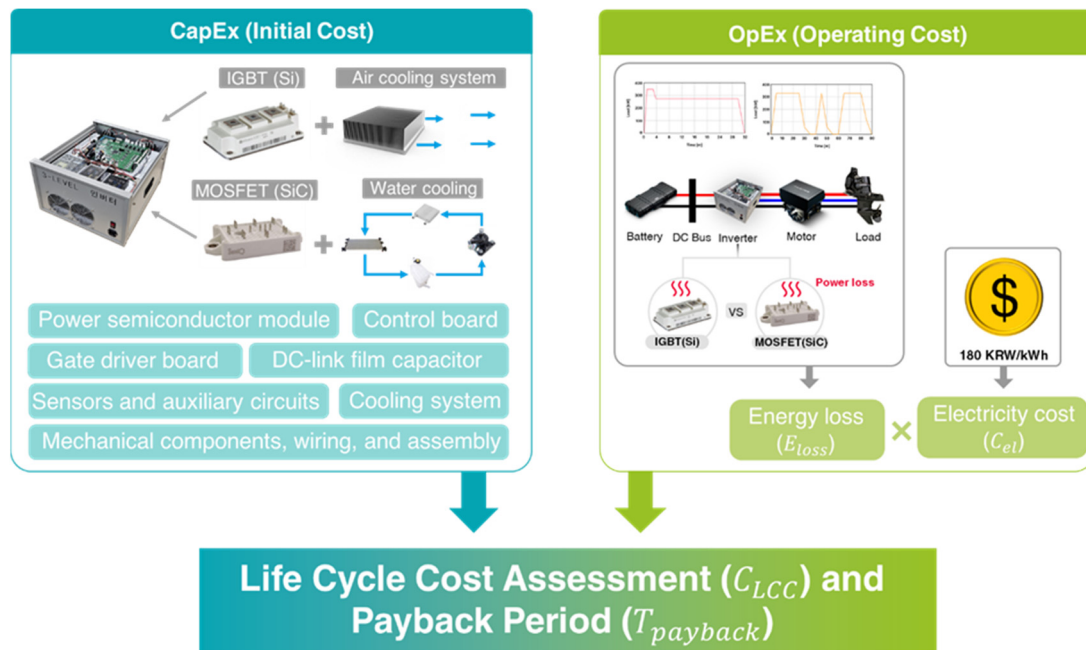


Figure 13. LCCA framework for electric propulsion ship inverters.

4.4.1. Capital Expenditure (CapEx) Modeling

The initial capital expenditures (CapEx) of the Si and SiC inverters were considered to be 10,000,000 KRW and 14,000,000 KRW, respectively. Table 9 summarizes a component-level breakdown of the CapEx for both the inverters. The SiC inverter employs SiC MOSFET power modules, which are more expensive than Si-IGBT devices and exhibit higher voltage slew rates and power-density characteristics during switching. Higher-rated and more durable film capacitors, along with a high-performance cooling system, are required to accommodate these characteristics, presenting an increase in the overall system cost. Based on these considerations, the total CapEx of the SiC inverter was assumed to be approximately 40% higher than that of the Si inverter for the same power rating.

Table 9. Component-wise CapEx breakdown of the 200 kW Si and SiC inverters.

Item	Si Inverter [KRW]	SiC Inverter [KRW]	SiC/Si Ratio
Power semiconductor	4,000,000	7,000,000	1.75
Gate driver board	800,000	1,000,000	1.25
DC-link capacitor	1,200,000	1,500,000	1.25
Sensors and auxiliary circuits	700,000	800,000	1.14

Table 9. Cont.

Item	Si Inverter [KRW]	SiC Inverter [KRW]	SiC/Si Ratio
Cooling system	1,500,000	1,800,000	1.20
Control board (DSP/MCU)	900,000	900,000	1.00
Housing, wiring, and assembly	900,000	1,000,000	1.11
Total CapEx	10,000,000	14,000,000	1.40

4.4.2. Operational Expenditure (OpEx) and Loss-Energy Cost Model

In this study, the LCCA of the inverter was defined as the sum of the CapEx and the operational expenditure (OpEx). The OpEx represents the electricity cost associated with the power losses of the inverter (E_{loss}) during operation. The FU corresponds to that of the LCA and is defined as the operation of a 200 kW inverter for a total of 10,000 h over a lifetime of 10 years under the given ship operating profiles.

The total loss energy generated during inverter operation (E_{loss}) is calculated as follows:

$$E_{loss} = P_{loss,avg} \cdot T_{op} \quad (5)$$

Here, $P_{loss,avg}$ denotes the average loss power (kW) obtained from the operating-profile-based simulation, and T_{op} denotes the total operating time of the inverter (h), which is set to 10,000 h in this study.

The OpEx, defined as the electricity cost corresponds to the power losses during inverter operation, is calculated as follows:

$$C_{OpEx} = E_{loss} \cdot C_{el} \quad (6)$$

Here, C_{el} denotes the electricity price, which is assumed to be 180 “KRW/kWh” based on the domestic industrial electricity tariff.

4.4.3. Total LCCA Formulation

The life cycle costs of the Si and SiC inverters, C_{LCC} , are expressed as follows:

$$C_{LCC,Si} = C_{inv,Si} + C_{OpEx,Si} \quad (7)$$

$$C_{LCC,SiC} = C_{inv,SiC} + C_{OpEx,SiC} \quad (8)$$

Here, $C_{inv,Si}$ is set to 10,000,000 KRW, and $C_{inv,SiC}$ is set to 14,000,000 KRW.

4.4.4. Payback Period Model for SiC Inverter Investment

SiC inverters entail a higher initial investment because they employ SiC power semiconductor devices, higher-rated film capacitors, and high-performance cooling systems. However, their conduction and switching losses are both lower than those of the Si IGBT-based inverters, leading to reduced power losses during operation and lower operational expenditure. To evaluate the period required for these operational cost savings to offset the additional upfront investment, the payback period was calculated as follows.

First, the difference in the lifetime loss energy between the Si and SiC inverters is expressed as follows:

$$\Delta E_{life} = E_{loss,Si} - E_{loss,SiC} \quad (9)$$

The annual energy savings calculated by dividing this lifetime loss-energy difference by the total operational lifetime of the inverter (T_{life}) is expressed as follows:

$$\Delta E_{year} = \frac{\Delta E_{life}}{T_{life}} \quad (10)$$

where the total inverter lifetime (T_{life}) is assumed to be 10 years.

The annual cost savings, calculated by multiplying the annual energy savings by the electricity price, are expressed as follows:

$$\Delta C_{year} = \Delta E_{year} \cdot C_{el} \quad (11)$$

The difference in the initial investment cost between the Si and SiC inverters is expressed as

$$\Delta C_{inv} = C_{inv,SiC} - C_{inv,Si} \quad (12)$$

Finally, the payback period is determined by dividing the initial investment cost difference by the annual cost savings:

$$T_{payback} = \frac{\Delta C_{inv}}{\Delta C_{year}} \quad (13)$$

5. Results and Discussion

5.1. LCA Results

This section presents the environmental impact assessment results of Si- and SiC-based inverters, considering their operational environments. Static and dynamic LCA approaches are both applied in parallel to provide more realistic and reliable comparative outcomes. Particular emphasis is placed on quantitatively analyzing how the high efficiency of SiC inverters and the differences in their cooling systems contribute to long-term environmental benefits.

The experimental results of inverter output power, three-phase voltage, and current as a function of the motor rotational speed are presented in Figure 14. Figure 14a shows the results across the full operating range (100–1800 rpm), whereas Figure 14b provides steady-state waveforms. During the test, the motor speed was increased from 100 to 1800 rpm in 100 rpm increments, with each step maintained for 10 s. At the rated condition of 1800 rpm, the inverter delivered a maximum output power of 100 kW, with corresponding voltage and current measurements. Notably, the measured voltage and current contained approximately 4–5% harmonic distortion attributed to the switching frequency.

The same operating conditions were applied to the Si-IGBT-based and SiC-MOSFET-based inverters. The measured output power, three-phase voltage, and current at each speed step were used to calculate the inverter efficiency. These efficiency characteristics form the basis for quantitatively comparing the two inverter types under various operating conditions and serve as input data for the dynamic LCA evaluation.

The efficiency of Si- and SiC-based inverters was compared under varying load and switching frequency conditions.

Experiments were performed to analyze efficiency characteristics with respect to load variations by changing the load from 10 to 120% of the rated power. As shown in Figure 15a, the SiC inverter exhibited consistently higher efficiency than the Si inverter across all load levels, with the difference particularly prominent in the low-load region of 10–50%. For applicability to ship operating profiles, the efficiency results were normalized as percentages relative to the rated load.

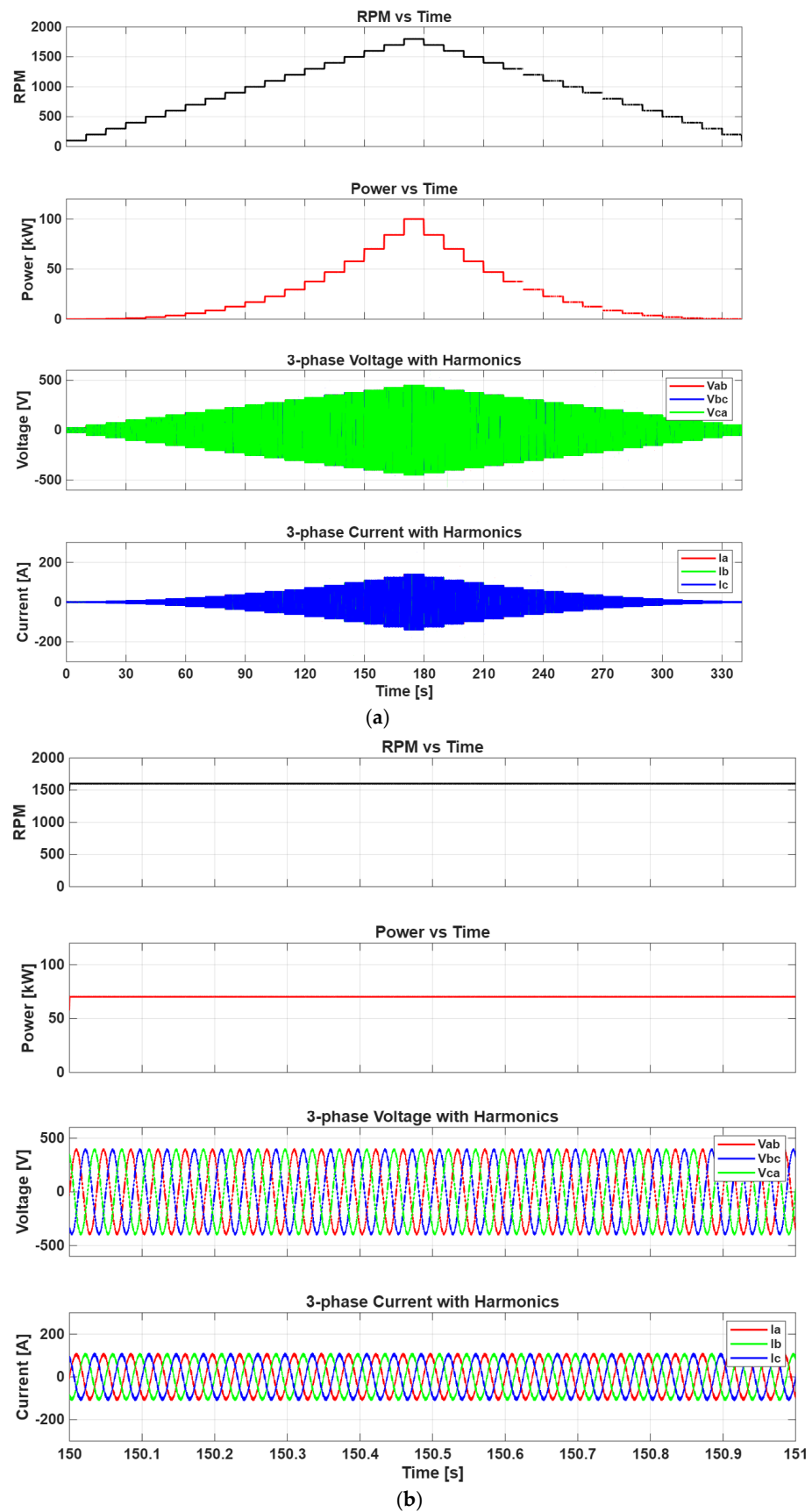


Figure 14. Experimental results of inverter output power, three-phase voltage, and current under varying rotational speeds (rpm): (a) Overall operating range (100–1800 rpm) (b) representative operating points (400, 700, 1400, and 1800 rpm).

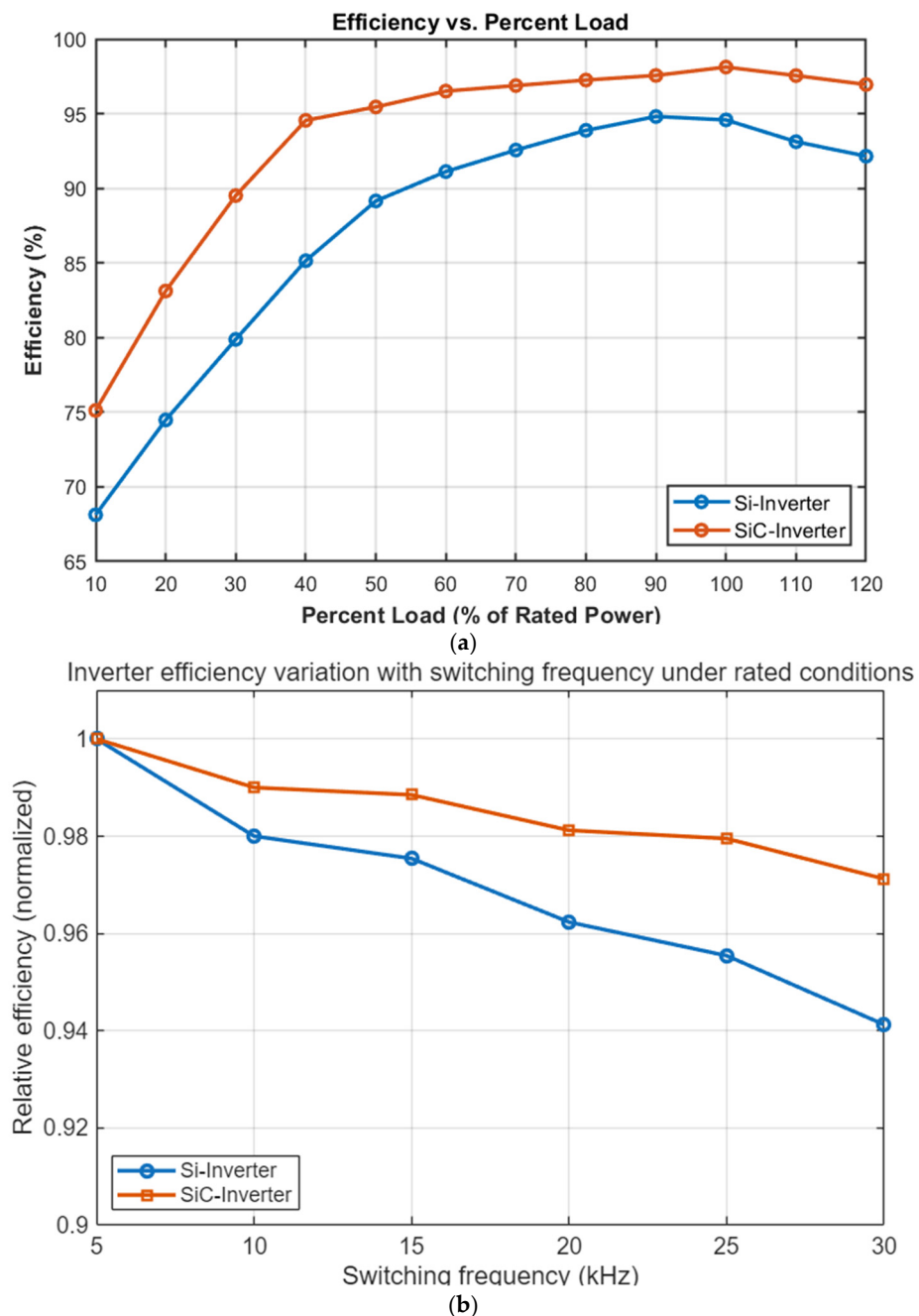


Figure 15. Comparison of Si and SiC inverter efficiencies under varying load and switching frequency: (a) Efficiency characteristics under various load conditions (normalized to rated power) (b) efficiency degradation with switching frequency (normalized to 5 kHz).

The efficiency was evaluated as a function of switching frequency by conducting experiments at a rated load while varying the switching frequency from 5 to 30 kHz. All efficiency values were normalized with respect to the 5 kHz baseline. As observed in Figure 15b, efficiency decreased with increasing switching frequency for both inverters. However, the efficiency degradation of the SiC inverter was comparatively moderate, reflecting the lower switching losses and fast-switching capability of SiC devices. Owing to this characteristic, the SiC inverter maintained relatively stable performance under varying load conditions.

These results suggest that the smaller efficiency drop of the SiC inverter under high-frequency switching makes it more suitable for coastal electric vessels, where diverse

operating conditions—such as cruise, acceleration, and idle—demand robust and long-term energy efficiency.

This trend in efficiency variation is generally attributed to the fact that SiC MOSFETs exhibit lower switching-frequency-dependent switching losses than Si IGBTs under identical switching-frequency and load conditions [40–42]. In addition, owing to the lower switching losses and heat generation characteristics of SiC MOSFETs, relatively smaller efficiency degradation occurs even under high-speed switching conditions [17], making them more advantageous than Si IGBTs in reducing inverter losses and improving efficiency [43]. These results are consistent with the trends reported in previous studies and demonstrate the applicability of the proposed experimental approach for analyzing relative loss characteristics according to power semiconductor materials.

Figure 16 shows the inverter efficiency under varying ambient temperature and relative humidity conditions. Even as the chamber air temperature and relative humidity changed, the efficiency of the SiC MOSFET inverter remained within approximately $\pm 0.25\%$ of the 97% baseline, indicating negligible variation. The Si IGBT inverter also exhibited a variation of about $\pm 1\%$ around the 95% baseline efficiency, suggesting that the effect of temperature and humidity changes on efficiency was generally minimal for both inverter types. These results confirm that the efficiency characteristics employed in the dynamic LCA model are robust across the range of environmental conditions representative of coastal maritime operations. Accordingly, the LCA results presented in the following sections are not significantly affected by ambient temperature or humidity variations, thereby supporting the validity of the assumptions adopted in this study.

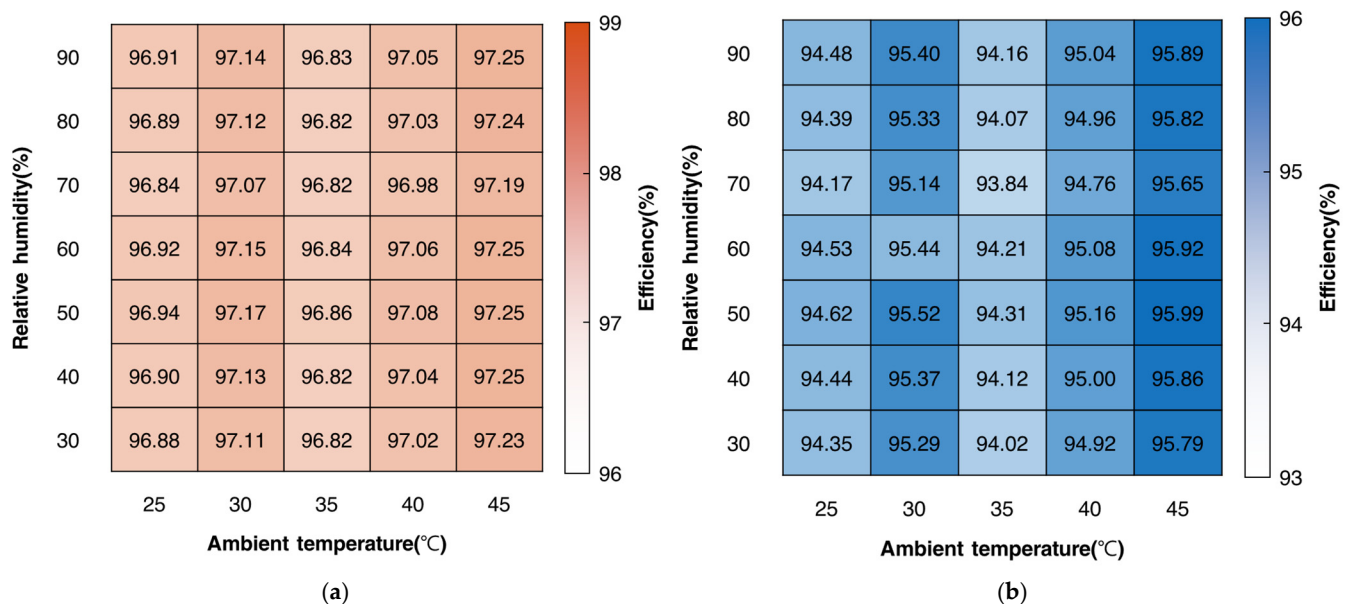


Figure 16. Efficiency variations under varying ambient temperature and relative humidity conditions: (a) SiC MOSFET Inverter; (b) Si IGBT Inverter.

A time-resolved LCA approach was applied to evaluate the environmental impacts of Si- and SiC-based inverters under realistic ship operating conditions. The inverter power losses and the corresponding environmental impact indicators (GWP, FD, and CED) were compared over time for each operating profile. Figure 17a presents the results derived from the 6 h operating profile of the passenger-and-car ship, while Figure 17b shows the results based on the 2.5 h profile of the cruise ship. In both cases, the SiC inverter consistently exhibited lower power losses and reduced environmental impacts compared with the Si inverter, with particularly notable differences under high-load conditions.

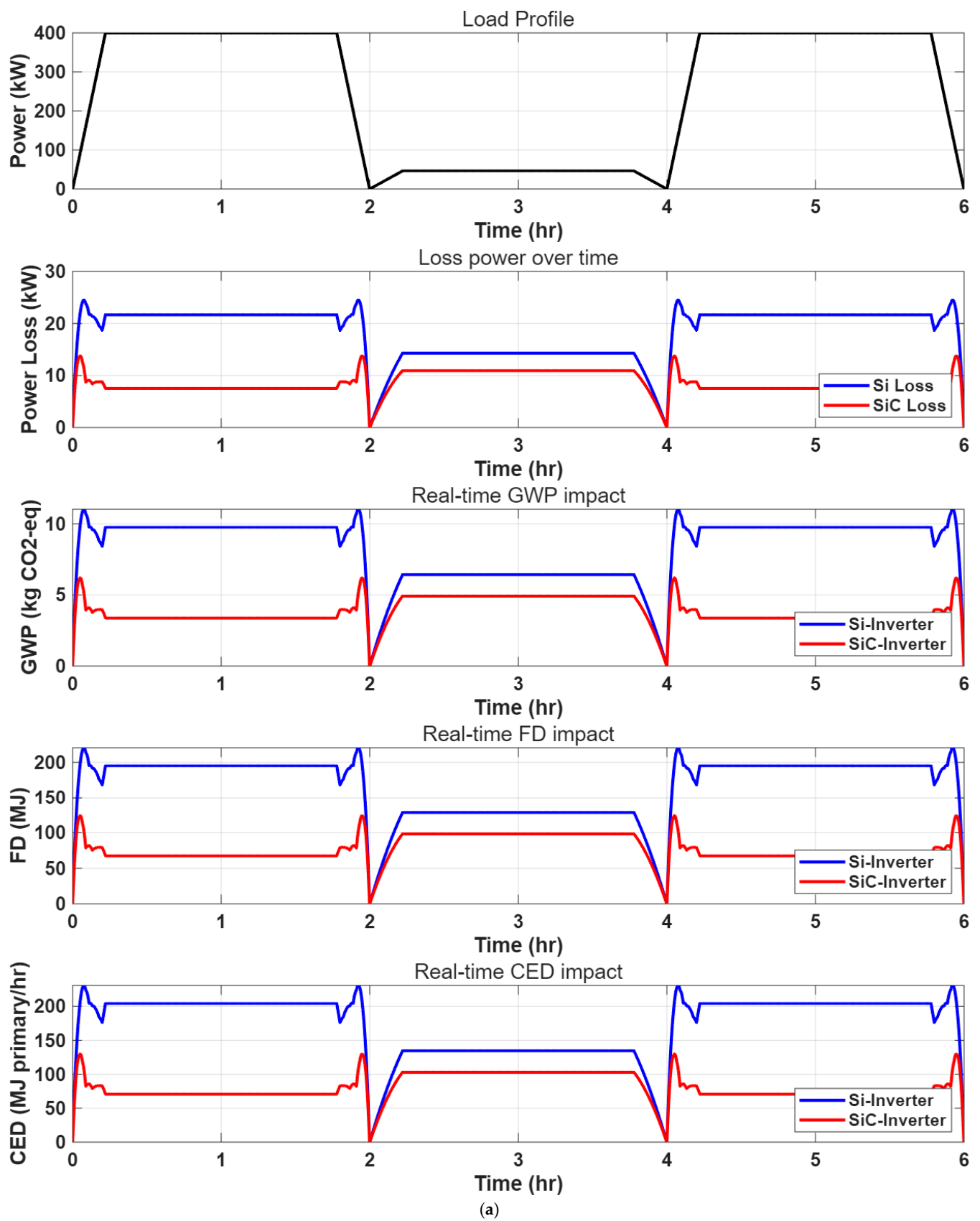


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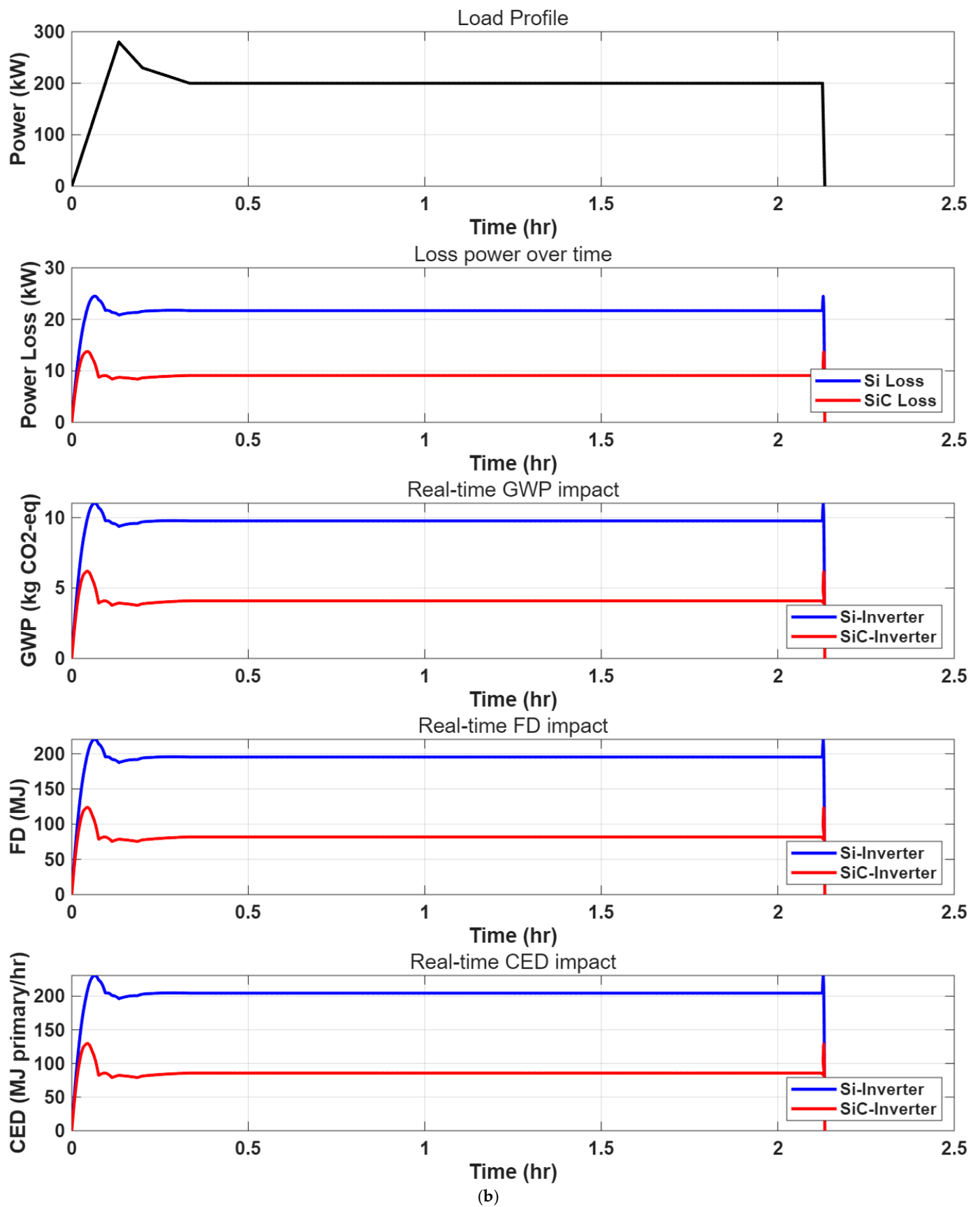


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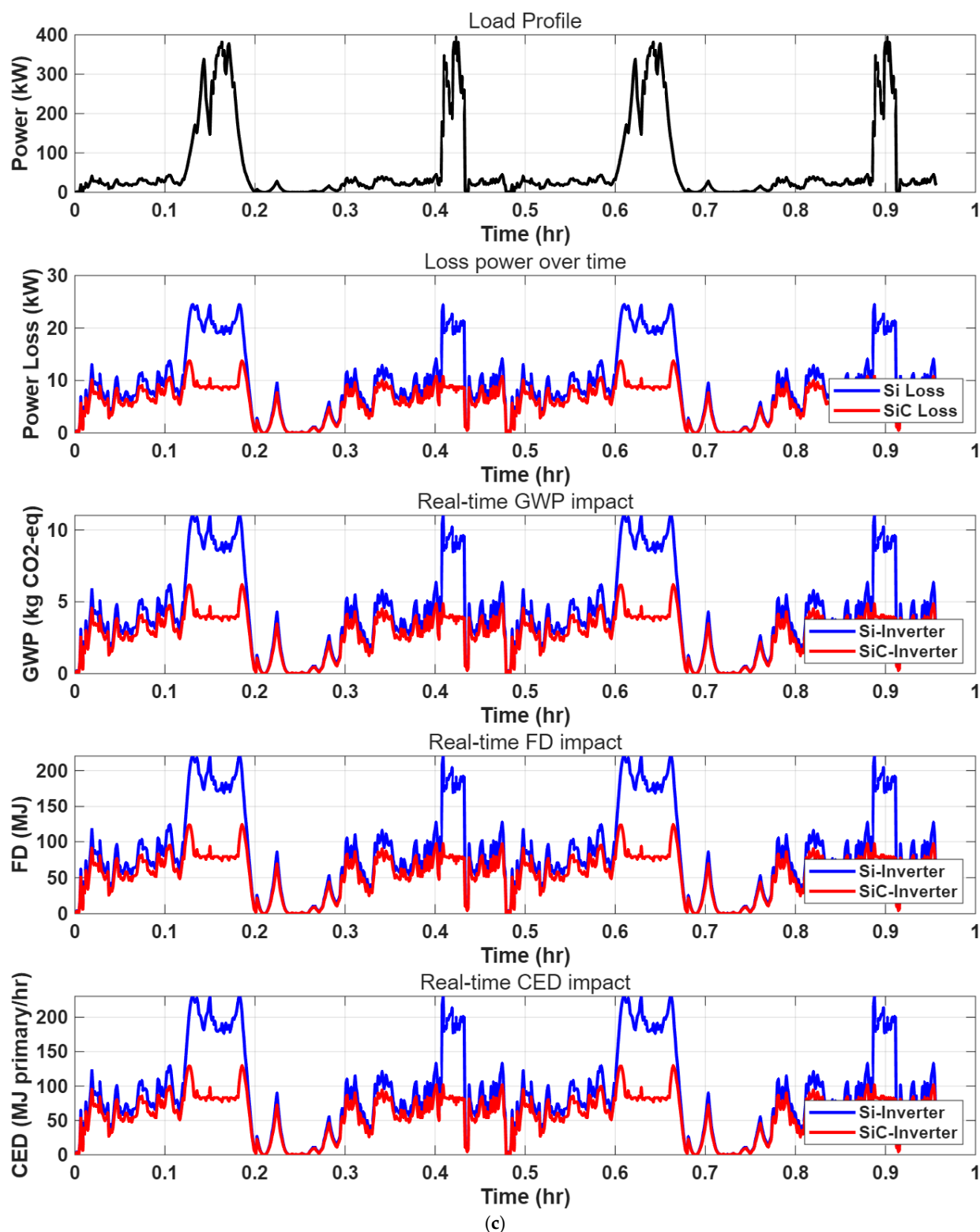


Figure 17. Time-resolved comparison of Si and SiC inverters in terms of power loss and environmental impacts (GWP, FD, and CED) under three vessel load profiles: (a) passenger-and-car ship; (b) cruise ship; (c) recreational boat.

Figure 17c depicts the analysis based on the operating profile of the recreational boat of approximately 1 h. The power losses and environmental impacts varied considerably over time owing to the highly fluctuating load characteristics with repeated acceleration and deceleration. The SiC inverter exhibited lower loss levels and environmental impact

across most segments even under these rapidly changing operating conditions. The differences were particularly pronounced during acceleration phases and peak-load intervals, indicating that the environmental advantages of SiC inverters remain evident even under highly dynamic and variable operating conditions.

Figure 18 depicts the static and dynamic LCA results of the Si and SiC-based inverters under the operating profiles of the three vessel types. All the scenarios assume identical operating conditions of 1000 operating hours per year over a 10-year lifetime. In the graphs, the static and dynamic LCA results are distinguished for comparison.

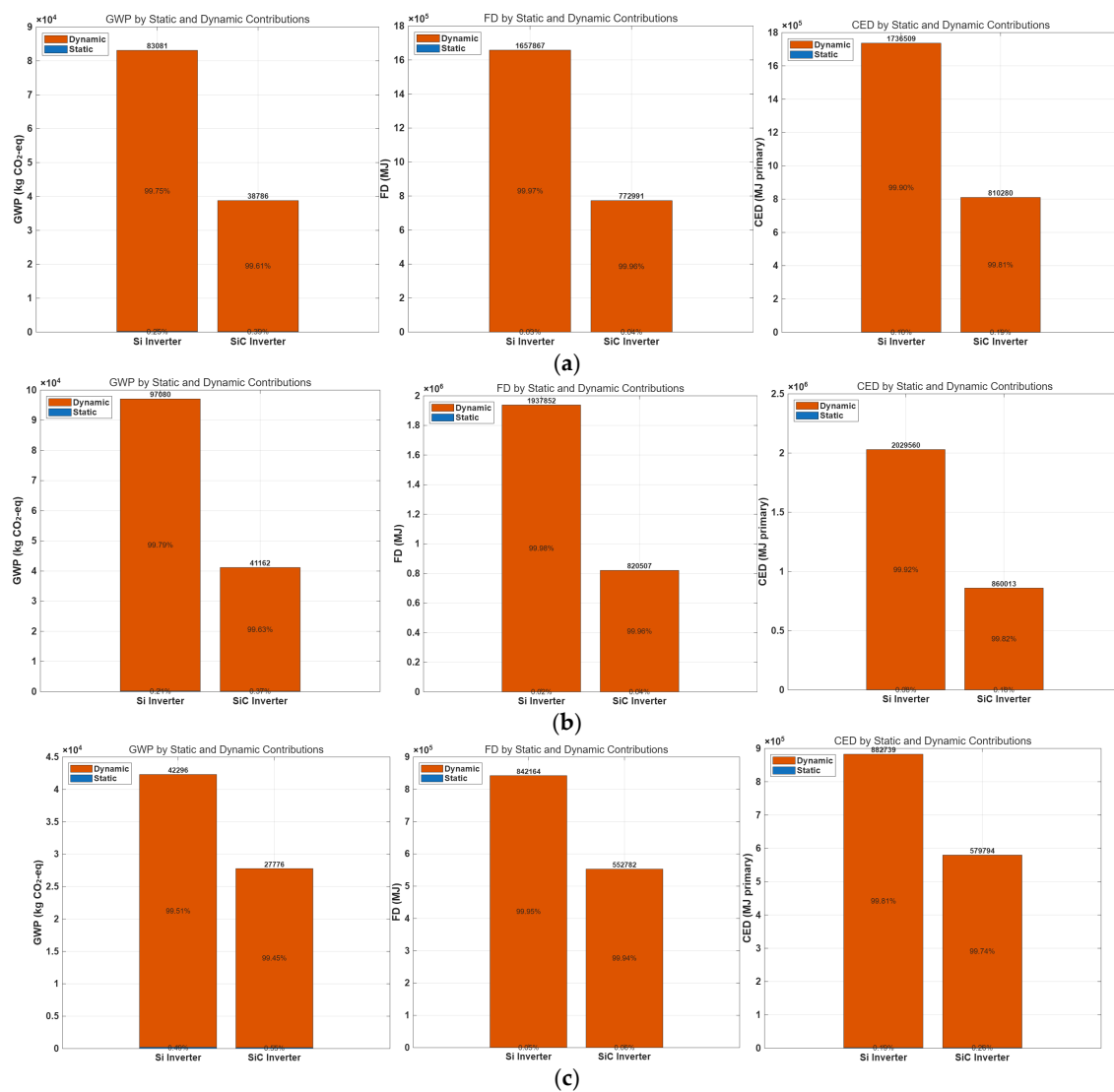


Figure 18. Static and dynamic LCA results of Si- and SiC-inverter operating according to the ship load profile, based on 10 years and 10,000 operating hours: (a) passenger and car ferry; (b) cruise ship; (c) recreational boat.

Across all the scenarios, the SiC inverter exhibited significantly lower GWP, FD, and CED values when compared with the Si inverter. Under the passenger-and-car-ship profile, the reductions were approximately 52–53%, whereas the cruise ship profile exhibited reductions of approximately 57–58%. Conversely, the recreational boat profile, with its highly fluctuating load characteristics, exhibited a reduction of approximately 34%. These results indicate that although the absolute magnitude of environmental impacts varies based on the operating conditions and load characteristics, the environmental advantages of SiC inverters were consistently observed across all the scenarios.

Additionally, for all the cases, the static LCA results of the SiC and Si inverters were almost identical, whereas the dynamic LCA results that account for operational losses exhibited reductions of approximately 52–58% in GWP, FD, and CED for the SiC inverter. The contribution of the static phase was negligible, accounting for less than 1% of the total impact in all the scenarios, whereas the dynamic phase dominated with more than 99%. These findings clearly indicate that the dynamic LCA, which incorporates actual operating conditions, is essential for a realistic assessment of the environmental performance of inverter systems.

The quantitative comparison of GWP and FD for Si- and SiC-based inverters under the two operating scenarios, separated into static and dynamic contributions, is summarized in Table 10. All conditions were set under the same assumption of 1000 annual operating hours over a 10-year lifetime. As shown, the static impacts of GWP, FD and CED reveal no significant differences between the two inverters, although the SiC inverter exhibited approximately 25–30% lower values. This outcome reflects the similarity in material composition and manufacturing processes of the two systems, with minor differences arising from specific components and cooling systems.

By contrast, the dynamic impacts demonstrate a much clearer distinction: the SiC inverter achieved reductions of approximately 53% (passenger-and-car ship), 57% (cruise ship), and 34% (recreational boat) in GWP, FD, and CED relative to the Si inverter. These reductions stem from the cumulative effect of lower operational power losses and become more pronounced as the operating time increases.

Table 10. Comparison of the static and dynamic environmental impacts of Si and SiC inverters under ship load profiles, based on 10 years and 10,000 operating hours.

Ship Type	Impact Category	Si Inverter	SiC Inverter	Reduction Rate [%]	
Passenger and car ship	GWP (kg)	Static	208	151	27.04
		Dynamic	82,873	38,635	53.39
		Total	83,081	38,786	53.33
	FD (MJ)	Static	497	309	37.83
		Dynamic	1,657,370	772,682	53.38
		Total	1,657,867	772,991	53.38
	CED (MJ)	Static	1737	1540	11.34
		Dynamic	1,734,772	808,740	53.36
		Total	1,736,509	810,280	53.34
Cruise ship	GWP (kg)	Static	204	152	25.49
		Dynamic	94,245	41,010	56.48
		Total	97,080	41,162	57.60
	FD (MJ)	Static	388	328	15.46
		Dynamic	1,937,464	820,179	57.67
		Total	1,937,852	820,507	57.65
	CED (MJ)	Static	1624	1548	4.68
		Dynamic	2,027,936	858,465	57.65
		Total	2,029,560	860,013	57.62

Table 10. Cont.

Ship Type	Impact Category	Si Inverter	SiC Inverter	Reduction Rate [%]	
Recreational boat	GWP (kg)	Static	207	153	26.09
		Dynamic	42,089	27,623	34.36
		Total	42,296	27,776	34.36
	FD (MJ)	Static	421	332	21.14
		Dynamic	841,743	552,450	34.36
		Total	842,164	552,782	34.36
	CED (MJ)	Static	1677	1507	10.14
		Dynamic	881,062	578,287	34.37
		Total	882,739	579,794	34.34

5.2. Uncertainty and Sensitivity Analysis

A Monte Carlo-based uncertainty analysis was conducted to enhance the reliability of the environmental impact assessment of Si- and SiC-based inverters, as illustrated in Figure 19. Figure 19 depicts the distributions of GWP, FD, and CED for the Si and SiC inverters obtained through a Monte Carlo-based uncertainty analysis. We performed a total of 10,000 simulations for each inverter, and a normal distribution with a variation range of ± 10 – 12% was applied to each parameter. To propagate input uncertainty to the final LCA results, a Monte Carlo analysis with 10,000 samples was performed. The inverter loss power, operating time, cooling loss ratio, and emission factors were treated as normally distributed variables with ± 10 – 12% variation, and the resulting confidence intervals were evaluated at a 95% confidence level.

The SiC inverter consistently exhibited lower average values for GWP, FD and CED. Importantly, even at the 95% confidence interval, the Si and SiC inverter distributions showed minimal overlap, indicating a statistically significant difference. Because identical emission factors were applied, these improvements are attributed to the intrinsic loss characteristics of the inverter devices rather than the calculation coefficients. Moreover, despite differences in the operating profiles and voyage durations across the two scenarios, the SiC inverter consistently demonstrated superior GWP, FD and CED results, underscoring its environmental advantages under diverse operating conditions.

The sensitivity analysis of the environmental impact assessments for Si- and SiC-based inverters under the two operating scenarios is shown in Figure 20 in the form of tornado charts. The analysis considered four primary input parameters: inverter loss power, emission factor for FD, operating time, and cooling loss ratio. Each parameter was varied by $\pm 10\%$ to quantitatively compare its influence on the results. Across all scenarios and inverter types, power loss emerged as the most influential factor, highlighting that operational losses are the primary determinant of environmental impacts. Emission factors and operating time showed similar levels of sensitivity, whereas the cooling loss ratio exhibited a relatively minor influence.

In addition to achieving lower overall GWP, FD and CED values than the Si inverter, the SiC inverter also demonstrated narrower sensitivity ranges, indicating more stable performance. This suggests that the environmental advantages of SiC inverters are likely to be preserved even under real-world maritime conditions with inherent uncertainties. Furthermore, the experimental validation under varying temperature and humidity conditions confirmed that the efficiency characteristics of both inverters remain stable across typical maritime environmental ranges, reinforcing the robustness of the dynamic LCA results.

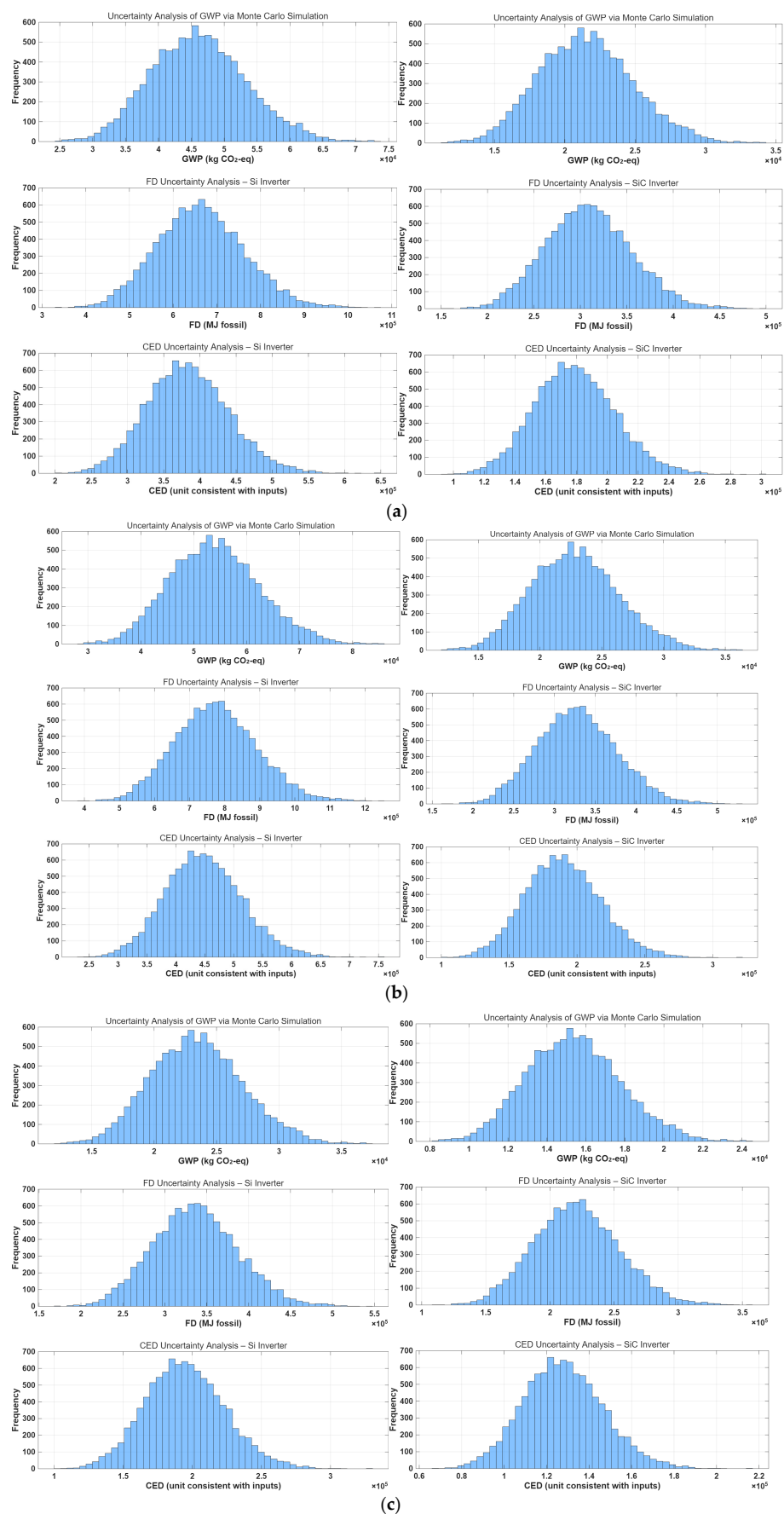


Figure 19. Results of Monte Carlo-based uncertainty analysis over the life cycle of Si and SiC inverters under ship load profiles, based on 10 years and 10,000 operating hours: (a) passenger and car ferry; (b) cruise ship; (c) recreational boat.

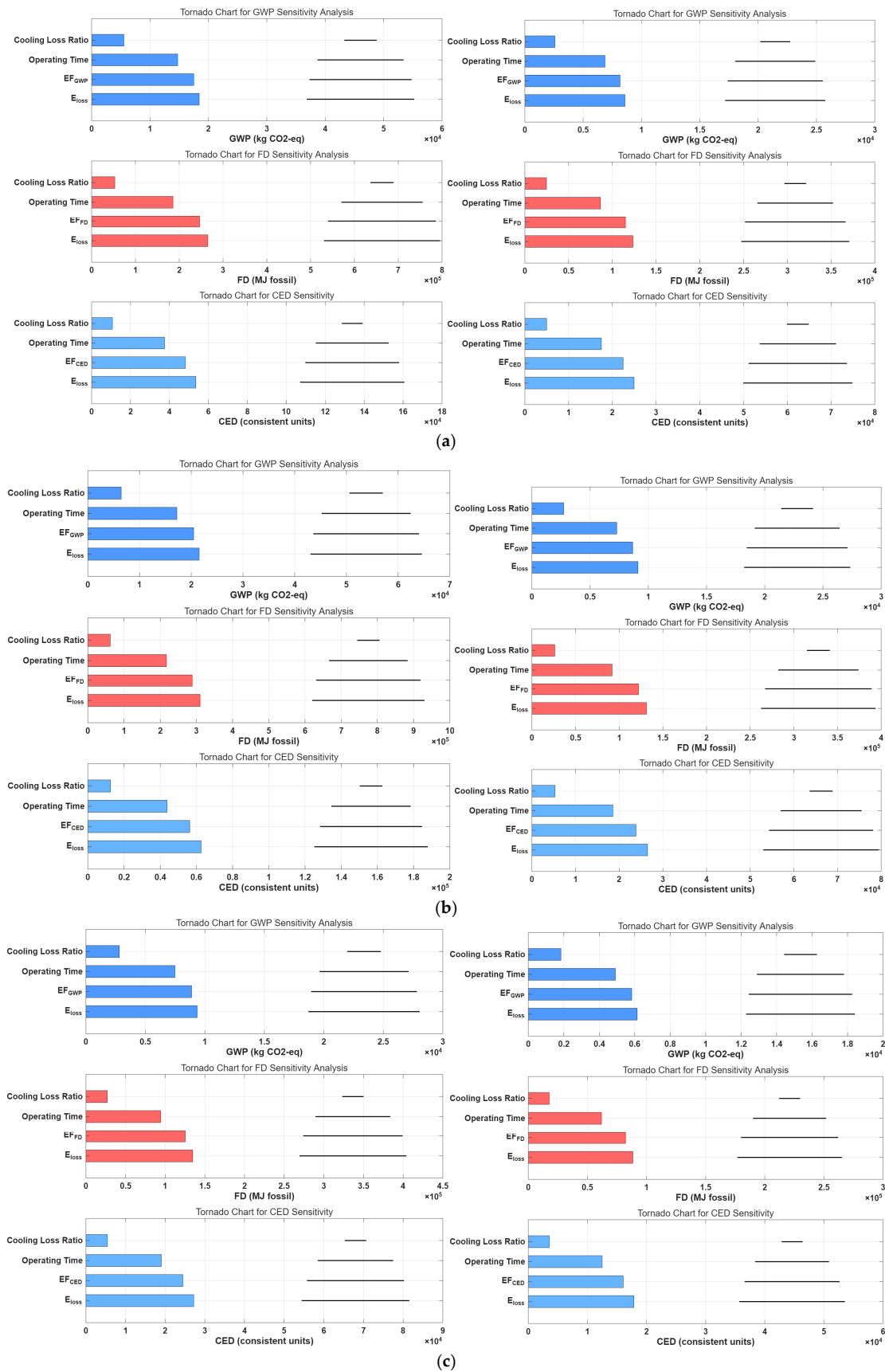


Figure 20. Results of tornado chart-based sensitivity analysis over the life cycle of Si and SiC inverters under ship load profiles, based on 10 years and 10,000 operating hours: (a) passenger and car ferry; (b) cruise ship; (c) recreational boat.

5.3. LCCA Results and Economic Interpretation

This section presents the LCCA of the Si and SiC inverters, evaluating their economic feasibility from a lifetime perspective. We considered the difference in the initial capital expenditures along with the electricity costs corresponding to the operational power losses under actual ship operating profiles. Consequently, we comprehensively evaluated the cost–environmental performance of the two inverter technologies. In particular, we quantitatively analyzed the translation of the lower conduction and switching losses of the SiC inverter into reduced operational expenditure, and how these savings offset the higher initial investment through the calculated payback period. Based on this approach, the economic viability of the SiC inverter, along with its environmental advantages, is demonstrated for coastal electric propulsion ships.

The average loss power values ($P_{\text{loss,avg}}$) obtained from the simulations for the navigation profiles are as follows: for the Passenger and Car ship profile, 18.4161 kW for the Si inverter and 8.5854 kW for the SiC inverter; for the Cruise ship profile, 21.5270 kW for the Si inverter and 9.1134 kW for the SiC inverter; for the Recreational boat profile, 9.3527 kW for Si inverter and 6.1386 kW for the SiC inverter.

Based on these values, the LCCA results were derived as shown in Table 11. For convenience, all the cost items were expressed in units of 106 KRW.

Table 11. LCC results of Si and SiC inverters.

Case	Inverter	$P_{\text{loss,avg}}$ [kW]	E_{loss} [kWh]	C_{CapEx} [10 ⁶ KRW]	C_{OpEx} [10 ⁶ KRW]	C_{LCC} [10 ⁶ KRW]
Passenger and car ship	Si	18.4161	184,161	10.00	33.15	43.15
	SiC	8.5854	85,854	14.00	15.45	29.45
Cruise ship	Si	21.5270	215,270	10.00	38.75	48.75
	SiC	9.1134	91,134	14.00	16.40	30.40
Recreational boat	Si	9.3527	93,527	10.00	16.83	26.83
	SiC	6.1386	61,386	14.00	11.05	25.05

In both the operating scenarios, the SiC inverter exhibited significantly lower operational expenditure owing to reduced power losses, presenting a significantly lower total LCC when compared with the Si inverter.

For the Passenger and Car ship profile, the total LCC of the Si inverter was approximately 43.15 million KRW, whereas that of the SiC inverter was approximately 29.45 million KRW, indicating a cost reduction of approximately 13.70 million KRW.

For the Cruise ship profile, the Si inverter presented approximately 48.75 million KRW, whereas the SiC inverter yielded approximately 30.40 million KRW, corresponding to a cost reduction of approximately 18.34 million KRW.

For the Recreational boat profile, the Si inverter yielded approximately 26.83 million KRW, whereas the SiC inverter yielded approximately 25.05 million KRW, corresponding to a cost reduction of approximately 1.78 million KRW.

Based on these results, the payback periods of the SiC inverter corresponding to the Si inverter were calculated, as shown in Table 12.

Although the initial CapEx of the SiC inverter is approximately 40% higher than that of the Si inverter, the significant reduction in operational power losses leads to notable electricity cost savings. Consequently, the payback period was calculated to be approximately 2.26 years for the Passenger and Car ship scenario and 1.79 years for the Cruise ship scenario, which was significantly shorter than the assumed 10-year service life of the

system. For the recreational boat, the loss-reduction benefit was relatively minimal owing to its low absolute operating losses. Consequently, the payback period was increased to approximately 6.9 years.

Table 12. Payback time of SiC inverter corresponding to the Si inverter.

Case	ΔE_{life} [kWh]	ΔC_{year} [KRW/yr]	ΔC_{inv} [KRW]	T_{payback} [years]
Passenger and car ship	98,307	1,769,526	4,000,000	2.26
Cruise ship	124,136	2,234,448	4,000,000	1.79
Recreational boat	32,141	578,538	4,000,000	6.91

These results indicate that, in the context of coastal electric propulsion vessels, SiC inverters provide clear environmental advantages along with robust economic feasibility corresponding to the life cycle cost.

5.4. Discussion

The LCA results of this study demonstrated that SiC-based inverters consistently provide environmental advantages in static analyses and under dynamic operating conditions, as further confirmed via uncertainty and sensitivity analyses. These findings indicate that adopting SiC inverters in small- to medium-sized coastal electric vessels offers technical performance improvements and tangible environmental benefits. Particularly for coastal vessels that require long-term operation, the loss reduction characteristics of SiC inverters are expected to translate into pronounced reductions in environmental burdens over their lifetime.

The SiC inverter characterized in this study reflects the performance of current-generation commercial modules; as SiC device technology continues to advance [37,38], the operational-phase environmental benefits reported here are likely to grow further.

The time-resolved LCA applied in this study also confirmed that environmental impacts under actual operating conditions can be captured, which are otherwise overlooked in conventional static LCA. This emphasizes that for electric propulsion vessels, where both efficiency and environmental performance are critical, LCA must incorporate dynamic operating factors. Moreover, the evaluation of power conversion systems should not rely solely on average efficiency values or standardized operating scenarios. Instead, it must account for real inverter performance, including efficiency variations, power losses, load fluctuations, and cooling demands observed during actual operation.

The use-phase divergence between Si and SiC inverters observed in this study also has implications for environmental certification of eco-friendly ships. Under Korea's certification scheme operated by the Ministry of Oceans and Fisheries, inverters are evaluated only under the single category of "high-efficiency power conversion equipment," with a 0.5-point bonus for efficiencies above 97% and no distinction between semiconductor technologies. The present results suggest that nominal efficiency alone does not capture the operational environmental performance differences between Si and SiC inverters, indicating that future certification criteria for power conversion equipment may benefit from incorporating technology-specific use-phase impacts.

5.5. Limitations

The operational assumption of 1000 h per year and a 10-year service lifetime may not generalize to all coastal routes. Sensitivity to load-profile duration and voyage frequency is analyzed in Section 5. Cooling power models vary with inverter cooling system and are parameterized through experiments. Alternative thermal design could shift the absolute

impacts. The propulsion motor and its control method were fixed; future work will consider other motor types (e.g., Induction motor) and integrated propulsion-system dynamics. This LCA focused on GWP, FD and CED, while other impact categories and the end-of-life phase will be addressed in subsequent studies. Although the raw-material extraction and wafer-processing stages of semiconductor devices were not included in the system boundary, the production of SiC materials can contribute to environmental burdens owing to high-temperature and multi-step fabrication processes. Based on the LCA studies that compared the cradle-to-gate impacts of SiC MOSFET and Si IGBT power modules [22], the manufacturing-stage GWP of a SiC MOSFET module under the global electricity mix was approximately 4.0–6.0 kgCO₂-eq, whereas that of a Si IGBT module was 1.7–1.9 kgCO₂-eq. The total contribution amounts to only several tens of kgCO₂-eq even when scaled to six power modules, which is typically required for a three-phase, two-level voltage-source inverter. This magnitude is negligible when compared with the static LCA results (hundreds of kgCO₂-eq) and dynamic LCA results (thousands to tens of thousands of kgCO₂-eq) obtained in this study. Therefore, although SiC MOSFETs exhibit a relatively higher manufacturing-stage impact, their significant efficiency advantages during operation can offset these burdens over the entire life cycle.

6. Conclusions

This study assessed the life-cycle environmental and economic performance of Si IGBT and SiC MOSFET inverters in coastal battery-electric vessels, combining a static LCA of the manufacturing phase with a dynamic LCA built on experimentally measured losses and real vessel operating profiles. The main conclusions are summarized as follows.

- (1) The static phase contributed less than 1% and the dynamic phase more than 99% of total life-cycle impacts across all three vessel types, confirming that operational losses dominate inverter LCA outcomes.
- (2) Under dynamic conditions, the SiC inverter reduced GWP, FD, and CED by approximately 57%, 52%, and 34% for the cruise ship, passenger-and-car ship, and recreational boat, respectively, relative to the Si inverter.
- (3) Monte Carlo uncertainty and tornado-chart sensitivity analyses confirmed the robustness of these results and identified inverter power loss as the dominant determinant of environmental impact.
- (4) The LCCA showed that the higher upfront cost of the SiC inverter is offset by reduced operational electricity costs within payback periods well below the assumed 10-year service life for all vessel profiles, supporting the economic viability of SiC adoption.
- (5) These findings establish the SiC inverter as a technically efficient, environmentally favorable, and economically viable option for coastal electric propulsion vessels and demonstrate that load-resolved dynamic LCA is essential for realistic component-level evaluation. The framework is also extensible to other electrified transport sectors such as automotive, rail, and aviation.

Future work will extend the assessment beyond GWP, FD, and CED to additional impact categories, broaden the system boundary to include transportation and end-of-life stages, and explore scenario analyses across diverse power-system configurations, cooling architectures, and regional electricity mixes. For completeness and reproducibility, the major assumptions and implicit premises adopted in this study are summarized in Appendix A.

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C.R.; Project administration, C.R.; Funding acquisition, C.R. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Summary of Key Assumptions and Implicit Premises Used in This Study.

Category	Description in the Manuscript	Underlying Assumptions
Operating Conditions (Functional Unit)	The functional unit was defined as one set of power conversion equipment delivering 1 MWh of energy in a 200 kW coastal electric propulsion vessel, assuming 1000 h of operation per year and a total service lifetime of 10 years (10,000 h).	It was assumed that all scenarios share identical annual operating hours and system lifetime.
Operating Scenarios	Three coastal operating profiles were applied: Passenger and Car Ship, Cruise Ship and Recreational Boat.	These three scenarios were assumed to represent the repetitive and short-distance operating characteristics of typical coastal vessels.
System Boundary	Only the manufacturing and use phases were included; transportation and end-of-life phases were excluded.	The environmental impact differences from transportation were assumed to be negligible for comparing the Si and SiC inverters. The end-of-life phase was excluded due to the high uncertainty of relevant LCI data.
Electricity Factors	For GWP, we used Korea's officially approved location-based electricity emission factor (consumer-side, 2024). For FD, TRACI v3.0 and the Ecoinvent v3.10 process "electricity, medium voltage, market for, Korea (cut-off model)" were applied.	All scenarios were assumed to use the same Korean electricity mix for charging power.
Cooling System Modeling	The Si IGBT inverter used an air-cooling system, whereas the SiC MOSFET inverter used a liquid-cooling system.	Although ambient temperature and humidity were not incorporated into the main dynamic LCA model, a dedicated experimental validation was conducted to assess the sensitivity of inverter efficiency to varying temperature and humidity conditions. The results, presented in Section 5.1, confirm that efficiency variations remain within acceptable bounds, supporting the validity of the main LCA assumptions.
Lifetime	Both inverters were assigned a lifetime of 10 years.	Degradation, performance decline, and component replacements were not considered.
Component Data (LCI)	Environmental impacts of the manufacturing phase were calculated using BOM data and the Ecoinvent database.	Material and process data in the database were assumed to sufficiently match the actual characteristics of the components.

Table A1. Cont.

Category	Description in the Manuscript	Underlying Assumptions
Experimental Loss Model	Losses were experimentally measured using a 200 kW inverter test platform.	Power losses were assumed to increase linearly with rated capacity.
Operating Environment	External factors such as ambient temperature and seawater temperature, as well as seasonal variations, were not considered.	Environmental variations were assumed to have minimal influence on cooling performance and power losses.
Impact Conversion Method	Time-resolved losses were directly converted into GWP, FD and CED using MATLAB.	The relationship between energy loss and environmental impact indicators was assumed to be linear.

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