Environmental and Economic Evaluation of Shore-Power Integration for Cruise-Ship Hoteling Operations

Mahmoud A. Saadeldin[a], Andriy Vasylyev[a], Massimo Rivarolo[a] and Alessandro Sorce[a]
Thermochemical Power Group, University of Genoa, via Montallegro 1, 16145 Genoa, Italy
Corresponding Author: mahmoud.ahmed@edu.unige.it

Abstract:
Growing pressure to reduce fuel consumption and greenhouse-gas emissions has intensified efforts to improve energy performance in maritime transport. Cruise ships, due to their high hoteling demand, generate significant port-side emissions, making on-shore power supply a promising measure to enhance efficiency by allowing auxiliary engines to be switched off and replaced by cleaner grid electricity. Consequently, it is necessary to evaluate how on-shore power supply can be integrated with onboard systems diesel generators, boilers, and heat-recovery units to achieve environmental gains while maintaining economic feasibility. This study develops a mixed-integer linear programming framework to assess the environmental and economic impacts of on-shore power supply integration across multiple berthing and navigation scenarios. In addition, an energy storage system integrated with OPS is considered in an alternative operational scenario to evaluate its potential benefits in reducing fuel consumption during sailing operations. The model optimizes the operational scheduling and power allocation among onboard technologies, including alternative-fuel options, and is applied to a real cruise-ship power profile to quantify changes in fuel use, emissions, and operating costs.

Keywords:
On-shore power supply, Mixed-integer linear algorithm, Hoteling emissions, Energy optimisation

1. Introduction

The global shipping sector plays a dominant role in world commerce, carrying 11 billion tons of freight annually and facilitating nearly 90% of all international trade (Yuksel et al., 2025). With approximately 96% of the world's vessels operating on fossil fuels, the sector's associated air pollutants and greenhouse gases are a growing environmental issue, currently responsible for around 2.9% of global GHG emissions (M. A. Saadeldin et al., 2024; Yuksel et al., 2025). A significant share of these emissions is produced while ships are berthed, particularly during loading and unloading operations, when auxiliary engines must remain active to supply onboard electrical and thermal loads (Bakar et al., 2022). This problem is even more pronounced in the cruise ship segment, where vessels typically spend extended periods in port while sustaining high hoteling energy demands, leading to disproportionately elevated emissions in coastal and urban environments (Albo-López et al., 2024; Herrero et al., 2022). Figure 1 illustrates the distribution of total berthing hours and the associated energy consumption for different ships across major European ports in 2023, based on vessels above 400 GT (TE-FINAL-EU, 2024).

Growing environmental concerns have pushed the maritime sector to reduce emissions (Hatef et al., 2024; Zhou et al., 2024). The International Maritime Organization (IMO) has introduced stricter regulations, including limits on sulphur content in marine fuels, the Energy Efficiency Design Index (EEDI) for new ships, and the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) for existing vessels (MA Nasser et al., 2022; M. A. N. Saadeldin et al., 2023). Meeting these standards often requires the use of more expensive low-sulphur fuels or operational adjustments to maintain efficiency. As a result, ports and ship operators are exploring measures that directly reduce emissions at berth. Numerous initiatives have been launched to support the environmental transition toward greener port operations (Zis, 2019). One of the key measures is onshore power supply (OPS), which enables vessels to shut down their auxiliary diesel generators and draw electrical power from the port grid instead (Albo-López et al., 2024; M. A. Saadeldin et al., 2023). Using OPS during berthing significantly reduces emissions and noise levels, leading to improved air quality and a quieter port environment (Abu Bakar et al., 2023). OPS is widely recognized as an effective solution for cutting emissions from ships at berth and supporting green port initiatives within broader maritime decarbonization strategies (Qiu et al., 2022). However, the substantial upfront investment required—including infrastructure installation, grid upgrades, and vessel retrofits—remains a major barrier for ports and ship operators, often causing hesitation due to long payback periods and operational uncertainties (Glavinović et al., 2023).

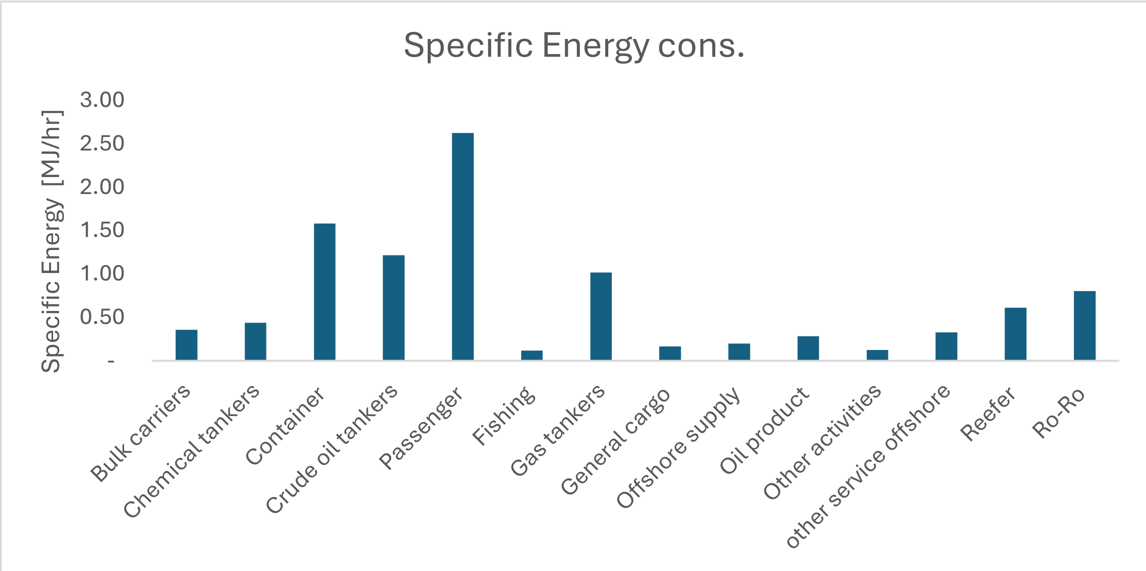


Figure 1 *Specific energy consumption of different ship types during port stay (MJ/h), based on vessels up to 400 GT.*

To mitigate these obstacles, governments and regulatory bodies are increasingly promoting OPS through financial incentives, subsidies, and supportive policy frameworks. Measures such as FuelEU Maritime penalties and the EU Emission Trading System (EU ETS) provide strong economic drivers for low-emission technologies (Ingwersen et al., 2025; Kwon et al., 2025). At the same time, emerging technologies in power electronics, energy management, and standardized OPS systems are reducing implementation complexity and helping shorten the return-on-investment timeline. Together, these regulatory and technological developments are making OPS more feasible and accelerating its uptake worldwide.

Consequently, there is growing interest in complementary strategies that can deliver deeper emission reductions, among which OPS has emerged as a highly effective option for ships at berth. (Yuksel et al., 2025) investigated shore-based PV/PEMFC and PV/battery systems for cold ironing under varying solar irradiation. Their study evaluated hydrogen production via ammonia electrolysis using green, blue and grey ammonia and compared these configurations with grid-based cold ironing and onboard diesel/LNG generation. (Sciberras et al., 2016) analysed different electrical configurations for cold ironing, including grid-supplied power and onsite LNG-based generation, to reduce emissions from berthed vessels. Their results show that cold ironing can cut CO_2 emissions by up to 40%, while LNG shore generation can reduce sulphur and particulate emissions to very low levels.

Building on these advances, recent research has increasingly employed mixed-integer linear programming (MILP) models to optimise ship energy systems in conjunction with shore power supply during berthing, enabling detailed assessments of both economic performance and environmental benefits (M. Saadeldin et al., 2026; Vasylyev et al., 2024). (Peng et al., 2019) developed an integer programming model to optimise OPS capacity and adoption patterns, aiming to balance shore power costs with ship-related carbon emissions; using a simulation-based optimisation framework and a Chinese port case study, they demonstrated that electricity prices strongly influence the optimal OPS sizing. Similarly, (Fang & Wang, 2021) and other authors applied MILP and related optimisation techniques to multi-source shipboard microgrids, showing that optimal power scheduling can significantly reduce fuel consumption and operating costs in electric vessels. (Bischi et al., 2014) linearised a nonlinear optimisation model for short-term operation of CCHP systems with multiple prime movers and thermal storage, illustrating how MILP can efficiently handle complex multi-energy configurations relevant to shipboard and port-side energy optimisation. In another application, an all-electric roll-on/roll-off emission-free ship concept treated fuel cells, battery storage and cold ironing as complementary energy sources, where a MILP model was used to derive cost-effective energy management strategies (Banaei et al., 2021). the present study aims to address these limitations by developing a comprehensive optimisation framework that integrates shipboard energy demands—namely electricity, cooling and heating—into a unified optimisation framework that evaluates cold ironing as part of the vessel's overall energy strategy during berthing. Unlike previous works that typically examine OPS from a port-side perspective or consider only electrical aspects, this study explores a wide set of operational scenarios that cover all feasible energy-supply configurations available to shipowners. In particular, it explicitly compares full CI, partial operation of auxiliary engines to exploit waste-heat recovery, while accounting for both direct and life-cycle emissions associated with energy production, as well as actual energy costs. This approach enables a detailed investigation of the environmental–economic trade-offs shaping operational decisions, particularly under tightening regulatory frameworks such as FuelEU Maritime, the EU ETS and the IMO's net-zero strategy. By capturing these multi-dimensional interactions within a single MILP-based optimisation model, the study provides a level of decision-support capability and operational insight not previously offered in the literature.

2. Methodology

To evaluate the environmental and economic implications of integrating OPS into the ship's power demand, a MILP model is developed to represent power flows, operational constraints, and combined cost–emission objectives (Vasylyev et al., 2024). The methodology begins with defining the ship's electrical architecture, the hoteling load profile, and the assumed OPS configuration. Based on this system description, the MILP formulation captures the operational limits of auxiliary generators, shore-connection interfaces, and energy-balance requirements during berthing. The optimisation model is then applied across different operating scenarios to quantify the benefits of OPS and identify the conditions under which shore power delivers the greatest economic and environmental advantages. The resulting MILP problem is implemented in MATLAB and solved using the Gurobi 11.0 optimiser.

2.1. Objective function

The objective function seeks to minimise the total annualised operating cost (C_{AOC}) of the system, taking into account environmental and economic parameters, as expressed in Eq. (1).

$$C_{AOC} = C_{op}^{M} + C_{op}^{F} + C_{Reg}^{E} + C^{CI} \tag{1}$$

In this formulation, the operational cost terms include C_{op}^{M}, representing maintenance and routine operational expenses, and C_{op}^{F} which accounts for the fuel consumption cost for marine engines and boilers. The term C_{Reg}^{E} captures the emission-related regulatory costs; in this study it includes the applicable charges under the EU ETS as well as penalties associated with FuelEU Maritime compliance. Finally, C^{CI} corresponds to the electricity cost charged by the port for cold ironing services, covering the purchase of shore-side electricity and any OPS usage fees. The annual maintenance cost is calculated as Eq. (2).

$$C_{op}^{M} = \sum_{u}\left(c_{op}^{fix} \cdot CAPEX_u + c_{start} \cdot N_{su,u}\right) \tag{2}$$

Where c_{op}^{fix} is the fixed O&M factor expressed as a percentage of the unit's capital cost (typically 2–5%), $CAPEX_u$ is the capital cost of unit u ($), c_{start} is the start-up cost associated with switching on the unit ($), and $N_{su,u}$ represents the number of start-ups during the operating year. The annual emission-related regulatory cost is expressed as Eq. (3).

$$C_{Reg}^{E} = \sum_{u}\left(CT_y \cdot E^{cO_{2eq}} + FP_y \cdot COM_{fuel}^{FP}\right) \tag{3}$$

Where CT_y is the carbon tax or allowance price under the EU ETS ($/ton$CO_{2eq}$), and $E^{cO_{2eq}}$ is the annual CO_2-equivalent emissions generated by the ship (tonCO_{2eq}/year). The second term represents the FuelEU Maritime penalty, where FP_y is the penalty cost (($/ton$CO_{2eq}$) and COM_{fuel}^{FP} is the compliance gap, defined as Eq. (4). Where $GHGI_a$ is the actual greenhouse-gas intensity of the fuel (gCO_{2eq}/MJ) and $GHGI_t$ is the required target intensity, which for 2025 is set at 89.9 (gCO_{2eq}/MJ). The actual GHG intensity is determined from Eq. (5).

Where ${E_u}^{cO_{2eq}}$ is the total CO_2-equivalent emissions from unit u (gCO_{2eq}), and ${E_u}^{fuel}$ is the total energy content of the fuel consumed by unit u (MJ).

$$COM_f^{FP} = GHGI_a - GHGI_t \tag{4}$$

$$GHGI_a = \sum_u \frac{{E_u}^{cO_{2eq}}}{{E_u}^{fuel}} \tag{5}$$

The annual cold-ironing cost is expressed as Eq. (6). Where C_p is the electricity price or tariff charged by the port for providing shore-side power $[\$/\mathrm{kWh}]$, and P_{CI} represents the total electrical energy drawn from the cold-ironing connection during hoteling $[\mathrm{kWh/year}]$.

$$C^{CI} = \sum \left(C_p \cdot P_{CI}\right) \tag{6}$$

2.2. Equipment Modelling and Constraints

The internal combustion engine (ICE) is represented through load-dependent electrical and exhaust efficiency curves, as shown in Figure 2 (Ancona et al., 2018). The electric efficiency (η_{elec}) is normalised to the nominal efficiency η_{nom}=0.47 and nominal power P_{nom}=14.4 MW (Ancona et al., 2018), increasing with engine load toward its peak near rated operation. In contrast, the normalised exhaust heat fraction (ηth, with a reference value of 0.60) decreases as load rises, indicating a lower share of the released heat is discharged with the exhaust gases at higher utilisation.

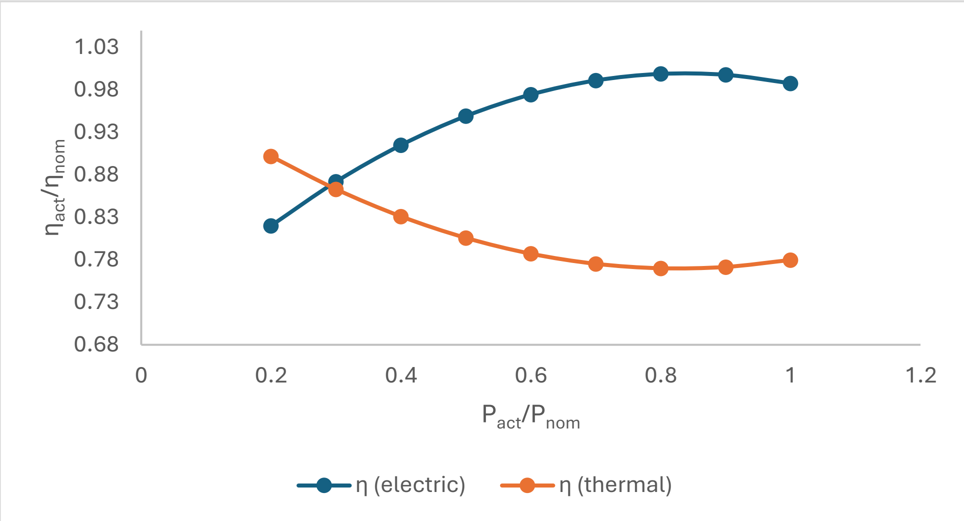


Figure 2 *Normalised electrical and thermal efficiency curves.*

To embed the nonlinear performance curves of the units in the MILP, a piecewise-linear approximation is adopted. For each unit u and each power segment j, the slope and intercept of the linear relation between power and the corresponding flow variable are computed as Eq. (7) and (8).

$$a_{(u,j)} = \frac{\dot{m}_{\max\,(u,j)} - \dot{m}_{\min\,(u,j)}}{P_{\max\,(u,j)} - P_{\min\,(u,j)}} \tag{7}$$

$$b_{(u,j)} = \dot{m}_{\max\,(u,j)} - a_{u,j} \cdot P_{\max\,(u,j)} \tag{8}$$

where $m_{\max\,(u,j)}$ and $m_{\min\,(u,j)}$ are the values of the flow variable at the upper and lower bounds of segment j, respectively, and $P_{\max\,(u,j)}$ and $P_{\min\,(u,j)}$ are the corresponding upper and lower power limits of that segment. The coefficients $a_{u,j}$ and $b_{u,j}$ are then used in the linear constraint to approximate the original nonlinear curve. To enforce the piecewise-linear approximation within the MILP, each segment j of unit u is bounded by a linear operating region activated through the binary on/off variable. The power in each segment is constrained as Eq. (9), ensuring that power is assigned only when the segment is active. The corresponding mass-flow variable is linearised as Eq. (10). Where $\mathrm{onoff}_{(u,j,t)}$ is the binary variable indicating whether segment j of unit u is active.

$$P_{\min\,(u,j)} \cdot onoff_{(u,j,t)} \leq P_{(u,j,t)} \leq P_{\max\,(u,j)} \cdot onoff_{(u,j,t)} \tag{9}$$

$$\dot{m_{\text{fuel}}}_{(u,j)} = a_{(u,j)} \cdot P_{(u,j)} + b_{(u,j)} \cdot onoff_{(u,j,t)} \tag{10}$$

For the shore-power interface, operation is allowed only when the ship is physically at berth. This condition is enforced by linking the activation of the port connection to the port-availability schedule as Eq. (11). Where $Port\_available_{(u,t)}$ is a binary parameter equal to 1 only when the ship is at berth. This constraint ensures that cold ironing power can be supplied exclusively during port-stay periods.

$$\sum_j onoff_{port,(u,j,t)} = Port\_available_{(u,t)} \tag{11}$$

3. Case study

The case study examined in this study is the Norwegian Gem, a 294-m cruise vessel operated by Norwegian Cruise Line (NCL) (Zhang et al., 2023). The ship is deployed across several regions worldwide, including the Caribbean, the Bahamas, the Mediterranean, and Eastern Canada/New England. Its service patterns typically feature 5-day Bahamas cruises, 12-day Caribbean round-trip itineraries departing from U.S. home ports, as well as 7-day sailings from Ravenna and other European ports. Table 1 presents the vessel main characteristics (Hou, 2011).

Table 1 Main technical and operational specifications of the Norwegian Gem

Item	Value
Year built / Last refurbishment	2007/2022
Overall length (m)	294
Maximum beam (m)	32-38
Gross tonnage (GT)	93,530
Passenger capacity	2,394
Total number of staterooms / cabins	1,197

According to the available itineraries, although the vessel operates on various routes throughout the year, the majority of its deployments in recent seasons have been within the European region, particularly on routes connecting Ravenna with Piraeus–Athens or Civitavecchia–Rome during the May–November operating period. In this study, we focus on the 7-day round-trip itinerary between Ravenna and Civitavecchia–Rome, as it represents the most recurrent annual operating pattern, as illustrated in Figure 3a (CruiseMapper, 2025). Building on this, Figure 3b presents the distribution of operational time for the selected 6.63-days itinerary: over the 159-hour cycle, the vessel spends approximately 74 hours in port (44%), 85 hours at sea (51%), and around 5% of the time in manoeuvring operations associated with arrival and departure phases.

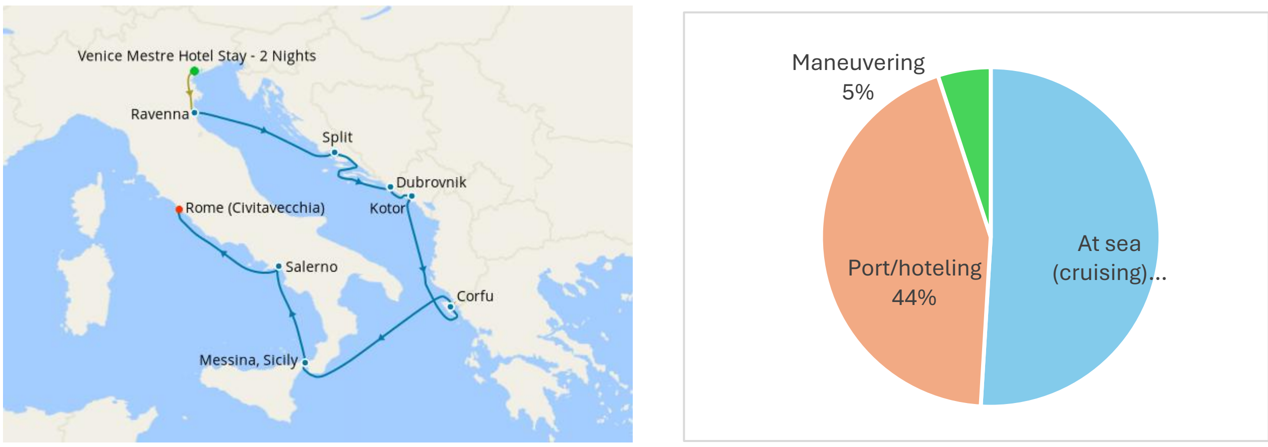


Figure 3 *(a) Selected 7-day itinerary between Ravenna and Civitavecchia–Rome. (b) Operational-time distribution*

3.1. Ship Energy Demand

During the itinerary, the vessel calls at six ports, remaining berthed for different durations before resuming navigation until completing the full cycle. Figure 4 illustrates the corresponding ship energy-demand profile, which comprises four main components. The Electrical demand—associated with propulsion—reaches peak values of approximately 22 MW during sailing periods. The electrical demand, which covers lighting, hotel services, auxiliary machinery, and general onboard equipment, remains relatively stable in the harbour with a maximum of about 5 MW. The thermal demand accounts for space heating and domestic hot-water production about 16 MW, while the cooling demand, dominated by air-conditioning systems, exhibits peak requirements of around 8 MW. To meet both the mechanical and electrical demands, the vessel is equipped with five marine diesel engines—four dedicated to normal operation and one reserved for emergency use—along with five generators supplying power to two electric propulsion motors, each driving a single propeller. An onboard transformer further conditions the electrical power for hotel and auxiliary loads, as illustrated in Figure 5. The ship's thermal requirements are satisfied through waste-heat recovery from all operating engines, supplemented by two auxiliary boilers when necessary.

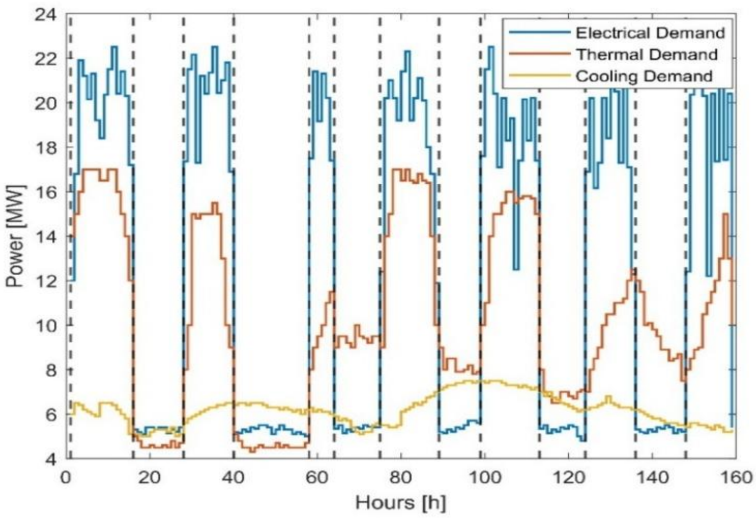


Figure 4 *Energy demand profiles*

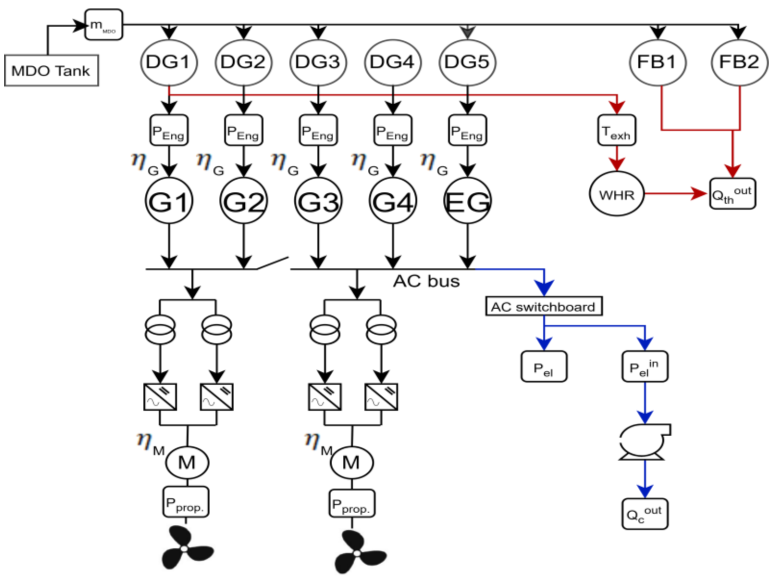


Figure 5 *Schematic of the vessel's energy system*

In addition, the vessel is equipped with a compression-chiller system for cooling production, operating with an energy efficiency ratio (EER) of approximately 3.5. The technical specifications of all major energy-system components are summarized in Table 2.

Table 2 Technical specifications of the main components of the ship's energy system

System component	Parameter	Value	System component	Parameter	Value
Main Propulsion Eng.	N. of installed	5	Generator	El. Output (kW)	13,500
	Rated power (kW)	14,400		Efficiency	0.96
	Speed (rpm)	500	Electric motor	Rated power (kW)	12,000
	SFO cons. (g/kWh)	185		Efficiency	0.97
	Efficiency	0.47	Aux Boiler	Th. Capacity (kW)	4,500
Heat Recovery Unit	Th. output (kW)	12,000		Fuel type	MDO
	Exhaust T_{in} (°C)	420	Comp. Chiller	C. Capacity (kW)	4000
	Recoverable Fr. (%)	35		EER	3.5

3.2. Ports description

Effective use of shore power requires electrical compatibility between the port grid and the ship's onboard system. Under the IEC/ISO/IEEE 80005-1 high-voltage shore-connection standard, cruise vessels typically receive OPS at 6.6 kV or 11 kV with a supply frequency of either 50 or 60 Hz, depending on the regional grid (Prousalidis et al., 2023). Since European ports operate at 50 Hz while many cruise ships use 60 Hz, a frequency converter is commonly needed, as illustrated in Figure 6. The port substation adjusts the grid supply to the required medium-voltage level, while a transformer on board conditions the power for the ship's distribution network. Proper alignment of voltage and frequency is therefore crucial to ensure safe and reliable OPS operation (Prenc et al., 2018).

The analysis requires detailed information on the ports included in the selected itinerary, as port operating conditions directly influence the energy requirements and the feasibility of shore-power integration. For each port, data on berthing time, average electrical load, and total energy demand were compiled from publicly available sources and operational records, as summarised in Table 3. Additional parameters such as time-dependent electricity prices and grid CO_2 emission intensity were also considered, as they influence the comparative performance of the alternative operating scenarios, as shown in Figure 6 (entsoe, 2025; Interactive App, 2025). Figure 6a illustrates the hourly variation of electricity prices at the selected ports, based on the day-ahead wholesale electricity market prices for the corresponding national grids (€/MWh). These values represent the average market clearing prices and exclude taxes and end-user retail tariffs. Figure 6b presents the corresponding hourly CO_2 emission intensities of the electricity mix (gCO_2eq/kWh) associated with the respective grids.

Table 3 Technical and operational characteristics of the ports included in the selected itinerary

Port name	Berthing time (h)	Average electrical load (kW)	Total energy (MWh)
Split, Croatia	12	5400	64.8
Dubrovnik, Croatia	18	5500	99
Kotor, Montenegro	11	5500	60.5
Corfu, Greece	10	5700	57
Messina, Sicily	11	5500	60.5
Salerno, Italy	12	5500	66

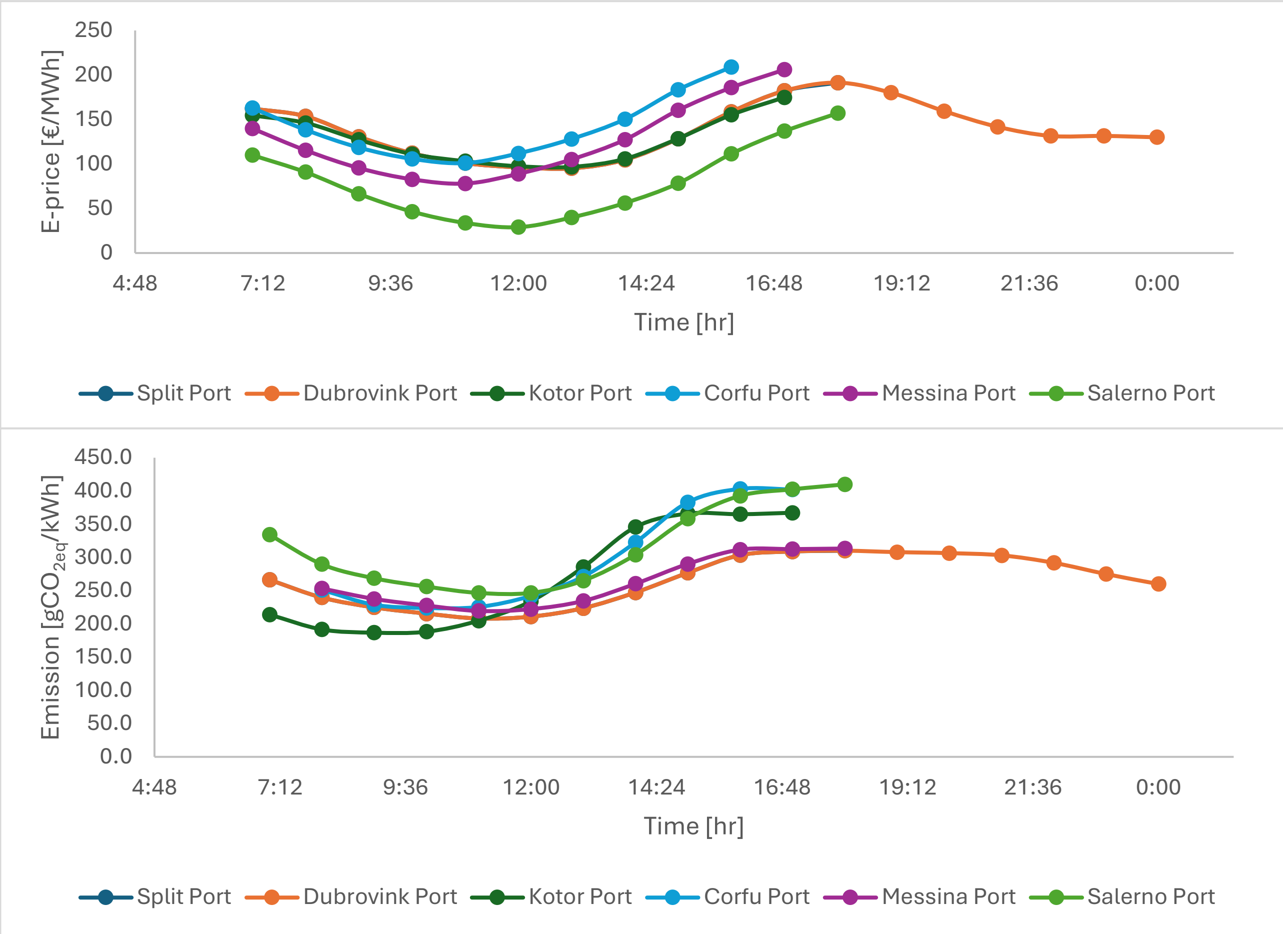


Figure 6 *Time-dependent characteristics of shore electricity at the selected ports: (a) hourly electricity prices (€/MWh); (b) corresponding grid CO_2 emission intensity (gCO_2eq/kWh)*

4. Main assumptions and scenario definition

To evaluate the most cost-effective and environmentally favourable configuration and operating strategy for the ship's onboard energy system, the MILP framework is applied to five distinct operating scenarios, each representing a different set of technological and fuel-supply assumptions.

Conventional (baseline) Scenario (BLS): In the reference configuration, the ship operates with conventional marine fuel (MDO) and no onshore power supply. All electrical and thermal hoteling demands in port are covered by the auxiliary engines and conventional boilers. This scenario represents the current practice and is used as a benchmark for comparison.

Alternative fuel Scenario (AFS): In this scenario, the use of alternative marine fuels is considered as a decarbonisation strategy. Among the available options studied in the literature, such as methanol, LNG, biofuels, and ammonia, LNG is selected as the representative case due to its high technological maturity, lower emission factors compared to conventional marine fuels (e.g., marine gas oil or heavy fuel oil), and its frequent use as a benchmark fuel in previous comparative studies(Deniz & Zincir, 2016; Nasser et al., 2023). Accordingly, the auxiliary engines are assumed to operate on LNG throughout the entire voyage to evaluate the economic and environmental implications of a full fuel-switching strategy relative to OPS adoption

Partial OPS Scenario (OPS_PS). In this scenario, the ship connects to the OPS system during berthing, and the full hotel electrical load is supplied by shore power whenever infrastructure is available. The onboard boilers continue to supply the heating demand, while the HRSG operates only when the auxiliary engines are running. Thus, OPS replaces engine-based electricity generation in port, but thermal production remains fully dependent on the ship's onboard systems.

Full OPS Scenario (OPS_FS). In this scenario, it is assumed that OPS infrastructure is fully available across all visited ports, enabling the vessel to supply its entire hotel electrical load from the shore grid during berthing. In addition to electrical demand, the port infrastructure is assumed to support thermal energy provision through the use of electric boilers onboard, allowing all heating requirements in port to be met using electricity rather than conventional fuel. Under this configuration, the auxiliary engines remain shut down during berthing, and both electrical and thermal loads are entirely covered through shore-side electricity.

Full OPS + BESS Scenario (OPS_BESS): Full OPS with onboard battery storage, where shore power supplies hoteling electrical and thermal demand during berthing, while an onboard battery energy storage system (BESS) is integrated to provide electrical services such as peak shaving, short-duration backup, and transient load support.

5. Results

The following section presents the outcomes of the optimisation model for all defined scenarios, providing a comparative assessment of environmental performance, energy balances, fuel consumption, and operational behaviour of the ship's integrated energy system. Each scenario reflects a distinct combination of OPS availability, fuel type, and onboard energy technologies, allowing the influence of these factors to be evaluated against the conventional baseline. For clarity, the results are organised around key performance indicators—emissions, energy flows, generator dispatch, and operational costs—so that the impact of OPS integration and alternative-fuel operation can be clearly quantified. This structure enables a coherent comparison across scenarios and highlights how real-world constraints, such as limited OPS infrastructure in certain ports, shape the achievable benefits. The graphical results, including time-series plots, bar charts, and energy-sharing diagrams, are used to support the quantitative analysis and provide deeper insight into the system behaviour under each scenario.

5.1. Fuel use and energy balance

Figure 7 presents the annual fuel energy consumption for the different operational scenarios, distinguishing between the energy used for main fuel consumption and the additional fuel used in the fuel boiler. The results show that the baseline scenarios, BCS and AFS, exhibit the highest overall fuel energy demand, with total consumption exceeding 210 GWh/year. In these cases, most of the energy demand is met through engine fuel consumption, while a smaller share is attributed to fuel used in the auxiliary boiler for heating purposes. The introduction of shore power configurations leads to a noticeable reduction in total fuel energy consumption. In particular, the OPS_PS reduces annual fuel use compared with the baseline cases, mainly due to the partial substitution of onboard electricity generation with shore-based power. However, some fuel consumption

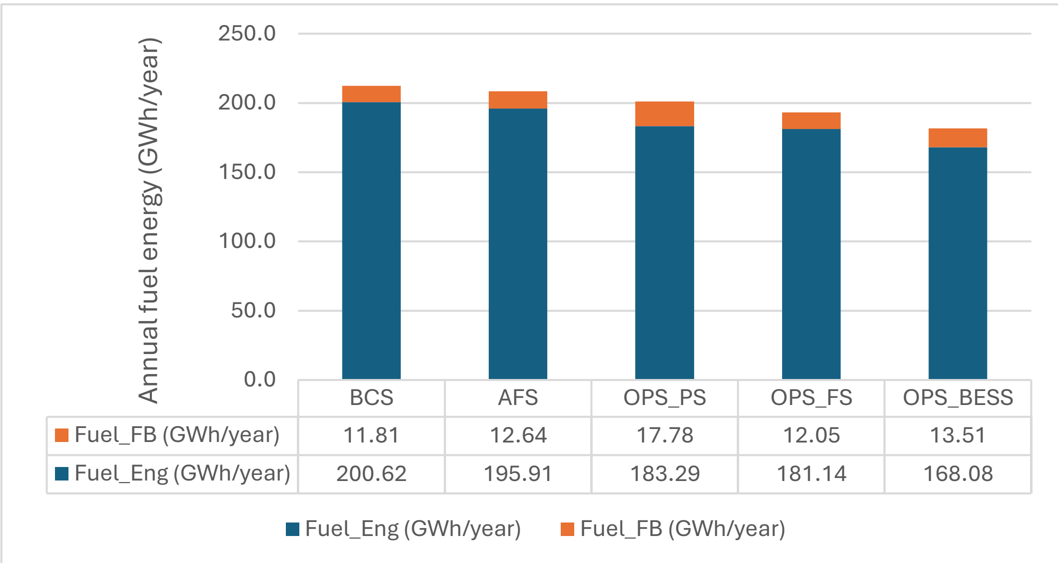


Figure 7 *Annual fuel energy consumption under different operational scenarios, distinguishing between fuel used by engines (Fuel_Eng) and fuel used in boilers (Fuel_FB).*

remains necessary to satisfy heating demands, which is reflected in the continued use of the fuel boiler. Further reductions are observed in the OPS_FS, where fuel consumption decreases slightly compared with OPS_PS. The most significant reduction occurs in the OPS_BESS, which exhibits the lowest overall fuel energy demand among all configurations, falling to approximately 180 GWh/year. This reduction can be attributed to the more efficient integration of shore electricity with onboard energy systems, which reduces the reliance on auxiliary engines and fuel boilers.

For the energy balance, Figure 8a presents the technological and thermal energy supply per trip across the different operational scenarios. Figure 4a shows the distribution of technological energy sources, including engine-generated electricity, port electricity, and BESS operations, while Figure 8b presents the thermal energy supply through WHR and boilers. In the baseline scenarios BCS and AFS, the technological energy demand is almost entirely supplied by onboard engines, reaching approximately 2 GWh per trip. With the introduction of shore power in the OPS_PS, part of the electrical demand is shifted from auxiliary engines to port electricity, resulting in a 6.6% reduction in engine-generated energy. Further diversification occurs in the OPS_FS and OPS_BESS, where port electricity plays a larger role and engine operation is further reduced. In addition, the BESS is utilised, being charged from shore power and later supplying onboard energy, leading to a 14% reduction in engine-generated energy.

The thermal energy supply patterns in Figure 4b highlight the interaction between engine operation and heating systems. In the baseline scenarios, most thermal demand is met through WHR from auxiliary engines, supplemented by fuel boilers. As shore power reduces engine operation, the availability of waste heat declines, increasing reliance on alternative heating technologies. In the OPS_FS and OPS_BESS, electric boilers are introduced to utilise shore electricity for part of the heating demand, resulting in a combination of fuel boilers and electric heating to meet the remaining thermal requirements.

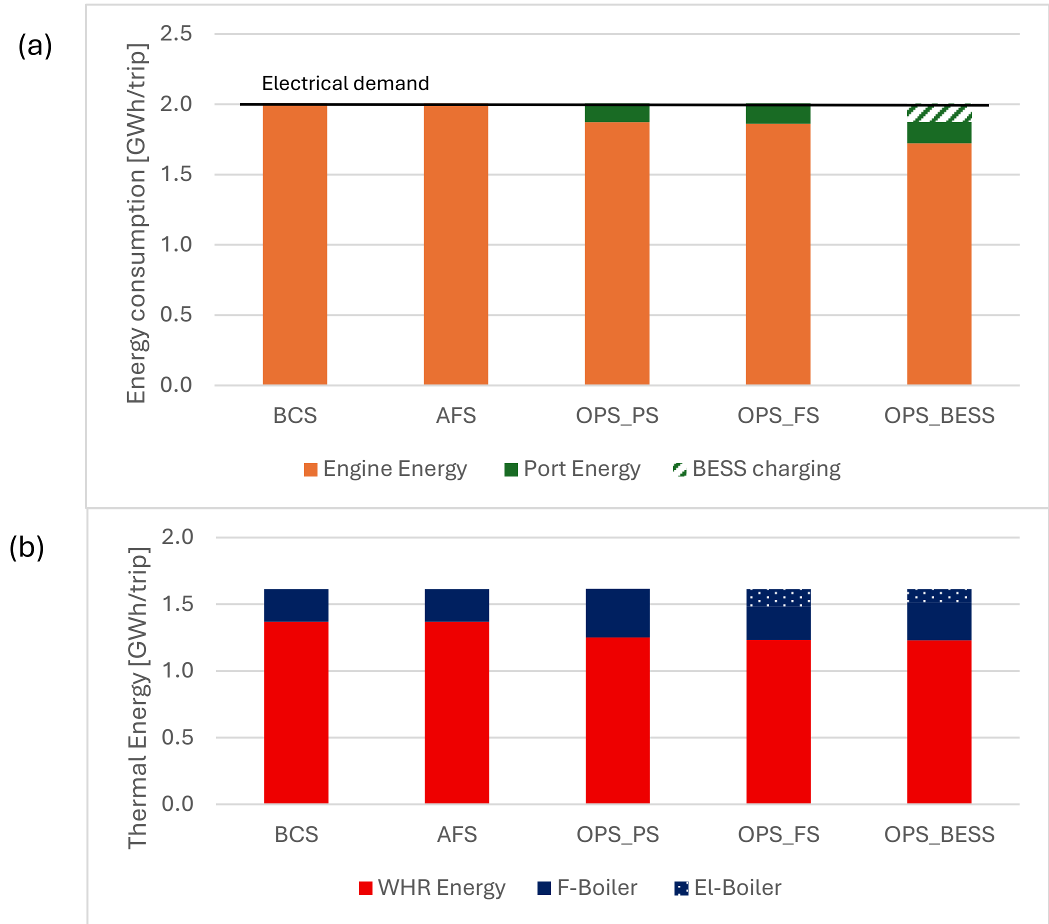


Figure 8 *Energy supply breakdown per trip across the different operational scenarios: (a) energy supply by different technologies; (b) thermal energy sources*

5.2. Time-Dependent Energy Analysis

Figure 9 shows the hourly electrical energy balance for the different operational scenarios during the weekly schedule. The dashed vertical lines indicate the vessel's port stays. In the baseline scenario (Figure 9a), the entire electrical demand is supplied by the auxiliary engines. The load varies between approximately 5 MW during low-activity periods and peaks of about 22–23 MW during intensive hoteling operations. Engine output follows the demand profile closely, indicating full reliance on onboard power generation. While, in the OPS_PS (Figure 9b), shore electricity partially replaces onboard generation during port stays. While the total demand remains similar, shore power contributes approximately 4–6 MW during low-load periods, reducing engine output accordingly. However, engines still supply the majority of the demand during peak loads.

In the OPS_FS (Figure 9c), shore electricity plays a larger role in meeting the electrical demand. During several port calls, shore power provides up to 10–15 MW, while engine output decreases significantly compared with the baseline case. Additional electrical demand also appears due to the electric boiler, which increases electricity consumption during certain periods. Further diversification of the energy supply is observed in the OPS_BESS (Figure 9d). In this configuration, shore electricity becomes the primary energy source during berthing, while auxiliary engines operate at lower levels. The BESS is actively used, with charging periods reaching approximately 10–15 MW and discharging used to support peak loads. This integrated energy management strategy further reduces engine operation and improves load balancing.

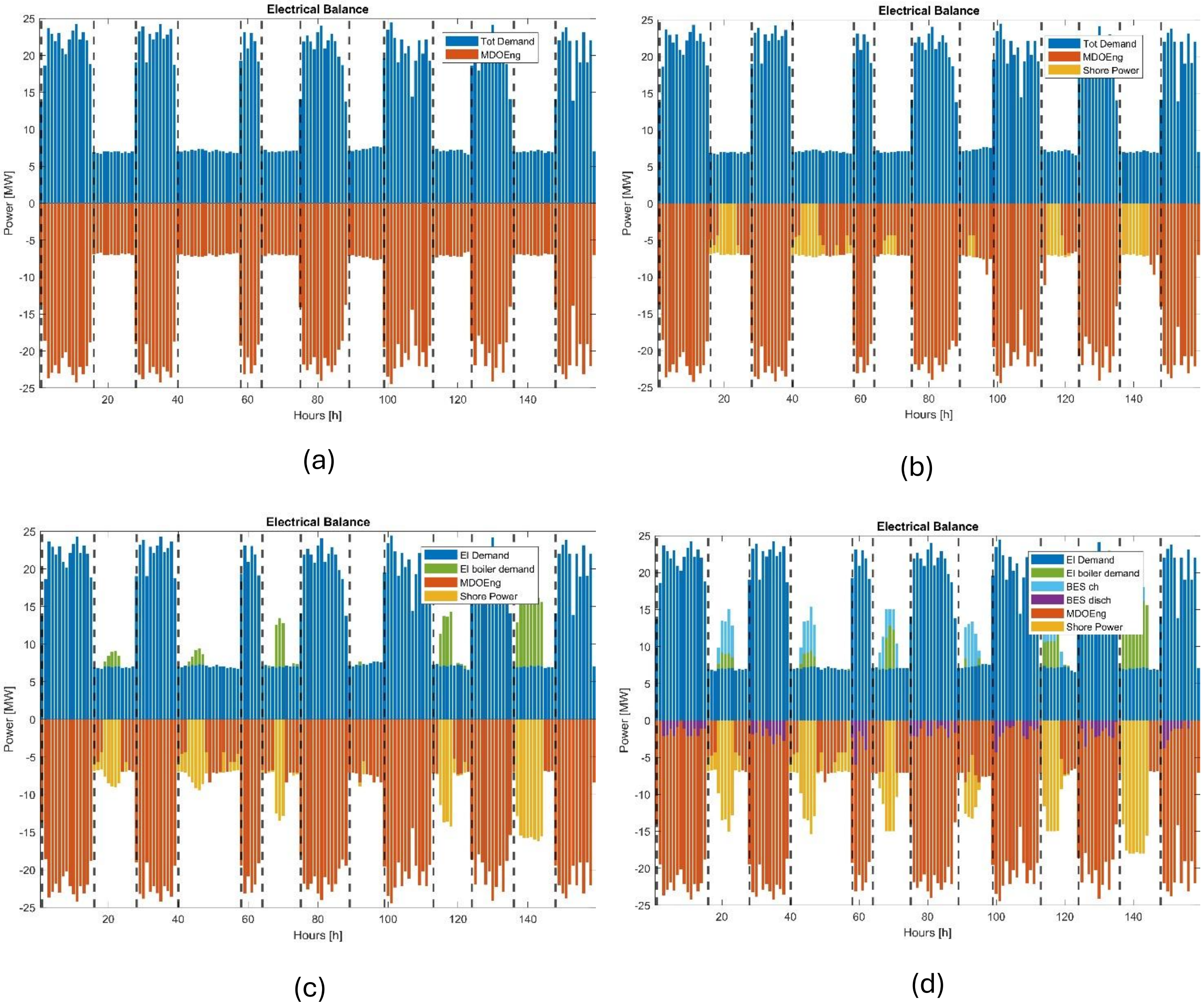
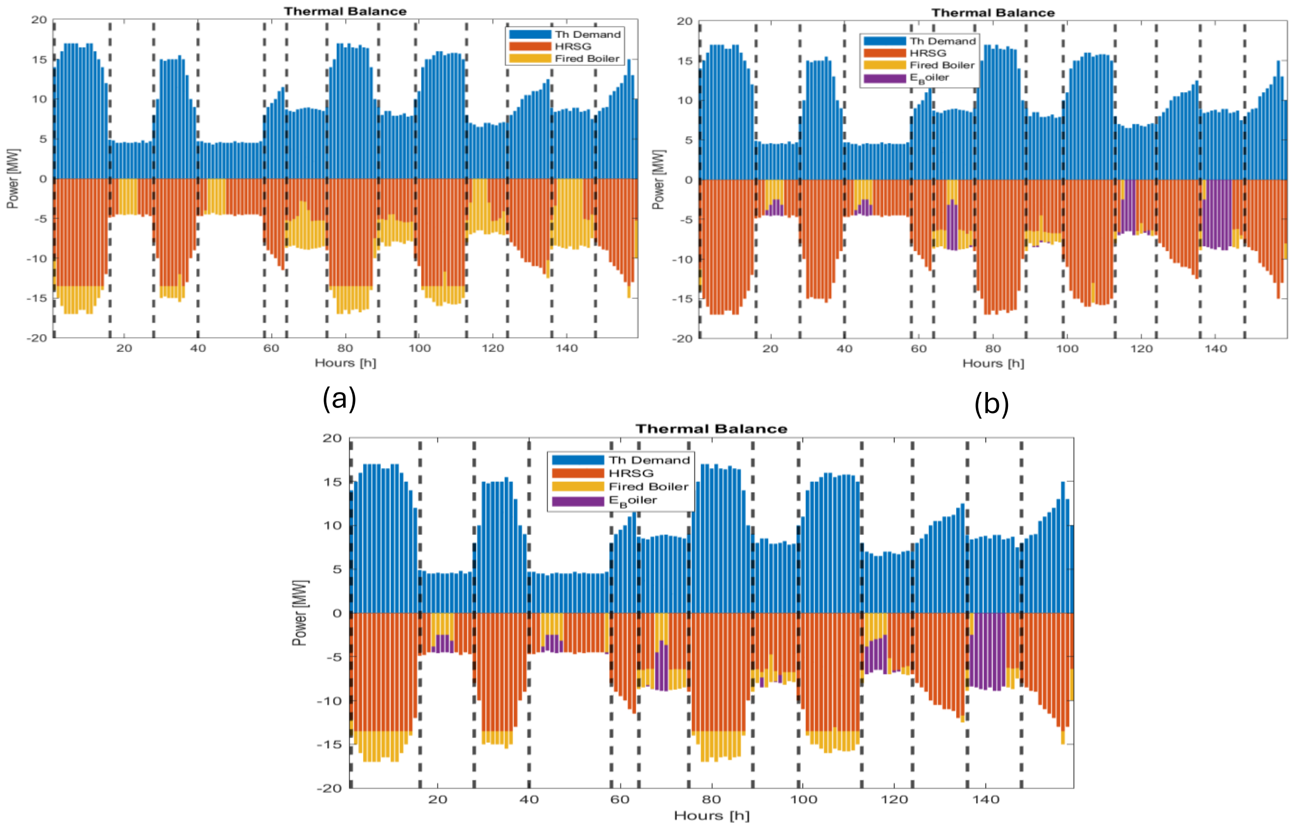


Figure 9 *Time-dependent electrical balance for different scenarios: (a) Baseline (BCS); (b) OPS_PS; (c) OPS_FS; (d) OPS_BESS. Dashed lines indicate port stays.*

Figure 10 shows the hourly thermal energy balance for the different operational scenarios. The dashed vertical lines indicate the vessel's port stays. In the baseline scenario (Figure 10a), the thermal demand varies between approximately 4 MW during low-activity periods and peaks of about 16–17 MW. Most of this demand is supplied by waste heat recovery through the WHR, which provides up to 15–16 MW of thermal energy. When the recovered heat is insufficient, the fired boiler supplies the remaining heat, typically contributing 1–3 MW during peak demand periods. In the OPS_PS scenario (Figure 10b), the thermal demand profile remains similar (~4–17 MW). However, as engine operation decreases due to the use of shore electricity, the available waste heat from the WHR is slightly reduced. Consequently, the fired boiler operates more frequently, supplying approximately 3–5 MW during several port stays to compensate for the reduced waste heat. In the OPS_FS and OPS_BESS scenarios (Figure 10c), the thermal balance changes further. While the overall thermal demand remains within 4–17 MW, the reduced engine load limits the heat available from the HRSG. As a result, the electric boiler is activated, supplying about 2–6 MW of thermal energy during several periods, while the fired boiler continues to provide supplementary heat when required.



(a) (b)

(c)

Figure 10*Time-dependent thermal energy balance during port operations:* ***(a)*** *BCS baseline scenario;* ***(b)*** *OPS_PS scenario;* ***(c)*** *OPS_FS and OPS_BESS scenarios.*

5.3. Annual Cost Analysis

Figure 11 compares the annual cost distribution for the different operational scenarios, including fuel cost, CO_2 cost, electricity cost at port, O&M, retrofit CAPEX, and FuelEU penalties. The baseline BCS shows a total annual cost of approximately 21,000 k$, where fuel cost represents the largest share, accounting for nearly 14,000 k$. In addition, CO_2 compliance costs contribute around 4,500–5,000 k$, while FuelEU penalties add roughly 2,000 k$ due to the high carbon intensity of onboard fuel consumption. The AFS exhibits a slightly higher total annual cost of about 21,500 k$, mainly driven by increased fuel prices and operational costs, despite a similar emission cost profile compared with the baseline case. With the introduction of shore power in the OPS_PS, the total annual cost decreases to approximately 19,000 k$. This reduction is primarily due to lower fuel consumption and reduced CO_2 compliance costs. However, a new cost component appears in the form of port electricity costs, which partially offsets the savings. Further cost optimization is observed in the

OPS_FS, where the total cost remains close to 19,000 k$, with slightly higher electricity costs but lower fuel expenditures.

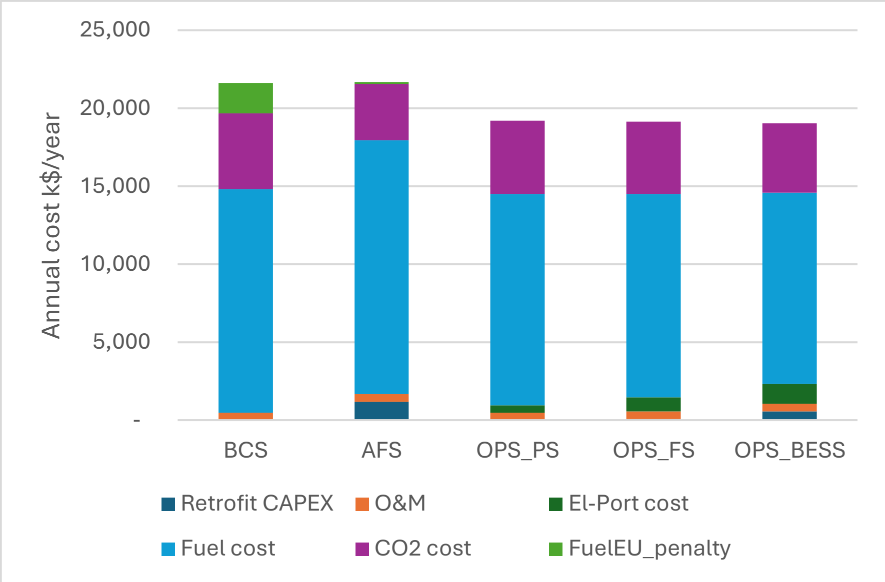
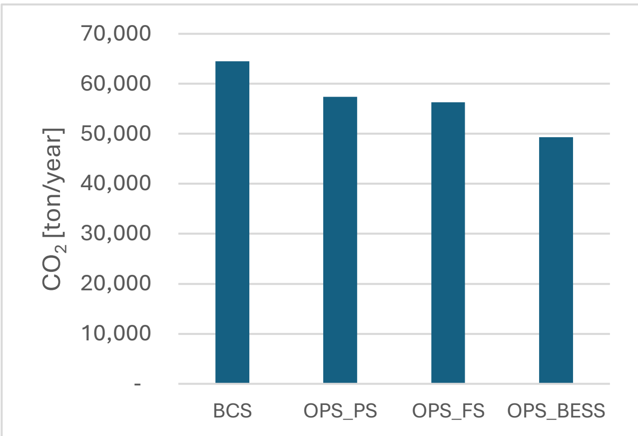


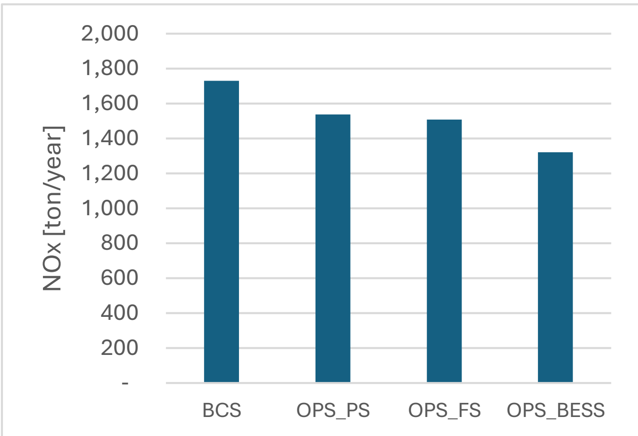
***Figure 11** Annual cost breakdown for the evaluated operational scenarios*

5.4. Environmental Impact of Operational Scenarios

Figure 12 presents the annual atmospheric emissions for the evaluated operational scenarios. Figure 12a shows the CO_2 emissions, while Figure 12b illustrates the corresponding NO_x emissions. The results show that the baseline BCS scenario produces the highest emissions, with approximately 64,000 ton/year of CO_2 and about 1,720 ton/year of NO_x, due to the full reliance on auxiliary engines during port operations. The introduction of shore power in the OPS_PS scenario leads to a noticeable reduction in emissions. CO_2 emissions decrease to around 57,000 ton/year, representing a reduction of roughly 11%, while NO_x emissions drop to approximately 1,540 ton/year. This reduction is mainly attributed to the partial replacement of onboard engine generation with electricity supplied from the port grid. Further improvements are observed in the OPS_FS, where emissions decrease slightly compared with OPS_PS. CO_2 emissions fall to about 56,000 ton/year, and NO_x emissions decline to approximately 1,510 ton/year, reflecting the increased use of shore electricity and reduced engine operation during berthing. The lowest emissions are achieved in the OPS_BESS, where the integration of shore power with battery energy storage significantly reduces engine operation. In this case, CO_2 emissions decrease to around 49,000 ton/year, representing an overall reduction of approximately 23% compared with the baseline scenario. Similarly, NO_x emissions drop to about 1,330 ton/year, corresponding to a reduction of nearly 23%.



(a)



(b)

***Figure 12** Annual atmospheric emissions for the evaluated scenarios: (a) CO_2 emissions (ton/year); (b) NO_x emissions (ton/year)*

6. conclusion

The present study develops a techno-economic optimisation framework to evaluate shore power OPS integration as part of the overall onboard energy management strategy during vessel berthing. The model simultaneously considers the ship's electrical, cooling, and heating demands using a MILP formulation, enabling the assessment of multiple operational configurations. Several scenarios are investigated, including conventional onboard generation, partial shore power utilisation, and advanced configurations integrating electric boilers and BESS. In the proposed configurations, shore electricity partially or fully replaces auxiliary engine operation during port stays, while waste heat recovery, fuel boilers, and electric boilers are used to satisfy thermal demand. The framework also incorporates life-cycle emission factors, port electricity price variability, and regulatory costs associated with CO_2 emissions and FuelEU Maritime penalties. The analysis therefore enables a comprehensive evaluation of the environmental and economic trade-offs associated with alternative energy supply strategies during berthing. The main findings of the study are summarized as follows:

- The results show that in the baseline configuration the ship relies entirely on auxiliary engines to meet electrical demand during berthing, with loads varying between approximately 5 MW and 23 MW. The introduction of shore power progressively shifts the energy supply by replacing part of the onboard generation with port electricity. In the OPS_PS scenario, shore power partially supplies the electrical load, while in OPS_FS and OPS_BESS the contribution of shore electricity increases further, supported by battery storage to balance peak demand.
- These operational changes lead to a clear reduction in fuel consumption. The baseline cases exhibit the highest fuel demand, exceeding 8.2×10^8 MJ per year, due to continuous engine operation. The adoption of shore power reduces the reliance on onboard generation, with the OPS_BESS configuration achieving the lowest fuel consumption of about 7.1×10^8 MJ per year through increased use of port electricity and improved energy integration.
- Changes in the electrical supply also affect the thermal balance. In the baseline scenario, most thermal demand (4–17 MW) is covered by waste heat recovery from engines, while fired boilers provide additional heat during peak periods. As shore power reduces engine operation, the available waste heat decreases, increasing the use of auxiliary boilers and electric boilers in advanced OPS configurations.
- The reduction in engine operation also improves environmental performance. The baseline scenario results in the highest emissions, with approximately 64,000 ton/year of CO_2 and 1,720 ton/year of NO_x. Increasing the share of shore electricity gradually lowers emissions, reaching about 49,000 ton/year of CO_2 and 1,330 ton/year of NO_x in the OPS_BESS scenario.
- Finally, the economic analysis shows that the baseline configuration results in the highest annual cost of about 21,000 k$, mainly driven by fuel and emission costs. The OPS scenarios reduce total costs to approximately 19,000 k$ due to lower fuel consumption and compliance costs, although part of these savings is offset by port electricity expenses. Overall, integrating shore power with advanced onboard energy systems improves the operational, environmental, and economic performance of the vessel during berthing.

References

Abu Bakar, N. N., Bazmohammadi, N., Vasquez, J. C., & Guerrero, J. M. (2023). Electrification of onshore power systems in maritime transportation towards decarbonization of ports: A review of the cold ironing technology. Renewable and Sustainable Energy Reviews, 178, 113243. https://doi.org/10.1016/j.rser.2023.113243

Albo-López, A. B., Carrillo, C., & Díaz-Dorado, E. (2024). Contribution of Onshore Power Supply (OPS) and Batteries in Reducing Emissions from Ro-Ro Ships in Ports. Journal of Marine Science and Engineering, 12(10), 1833. https://doi.org/10.3390/jmse12101833

Ancona, M. A., Baldi, F., Bianchi, M., Branchini, L., Melino, F., Peretto, A., & Rosati, J. (2018). Efficiency improvement on a cruise ship: Load allocation optimization. Energy Conversion and Management, 164. https://doi.org/10.1016/j.enconman.2018.02.080

Bakar, N. N. A., Guerrero, J. M., C. Vasquez, J., Bazmohammadi, N., Othman, M., Rasmussen, B. D., & Al-Turki, Y. A. (2022). Optimal Configuration and Sizing of Seaport Microgrids including Renewable Energy and Cold Ironing—The Port of Aalborg Case Study. Energies, 15(2), 431. https://doi.org/10.3390/en15020431

Banaei, M., Ghanami, F., Khooban, M. H., & Boudjadar, J. (2021). Cost-effective control of Roll-on/Roll-off Emission-Free Ships. 2021 25th International Conference on Methods and Models in Automation and Robotics (MMAR), 315–320. https://doi.org/10.1109/MMAR49549.2021.9528473

Bischi, A., Taccari, L., Martelli, E., Amaldi, E., Manzolini, G., Silva, P., Campanari, S., & Macchi, E. (2014). A detailed MILP optimization model for combined cooling, heat and power system operation planning. Energy, 74, 12–26. https://doi.org/10.1016/j.energy.2014.02.042

CruiseMapper. (2025). Norwegian Gem. https://www.cruisemapper.com/ships/Norwegian-Gem-573

Deniz, C., & Zincir, B. (2016). Environmental and economical assessment of alternative marine fuels. Journal of Cleaner Production, 113, 438–449. https://doi.org/10.1016/j.jclepro.2015.11.089

entsoe. (2025). Transparency Platform. https://transparency.entsoe.eu/market/energyPrices?appState=%7B%22sa%22%3A%5B%22BZN%7C10YDK-2--------M%22%5D%2C%22st%22%3A%22BZN%22%2C%22mm%22%3Atrue%2C%22ma%22%3Afalse%2C%22sp%22%3A%22HALF%22%2C%22dt%22%3A%22MAP%22%2C%22df%22%3A%222025-12-07%22%2C%22tz%22%3A%22CET%22%7D

Fang, S., & Wang, H. (2021). Optimization-Based Energy Management for Multi-energy Maritime Grids (Vol. 11). Springer Singapore. https://doi.org/10.1007/978-981-33-6734-0

Glavinović, R., Krčum, M., Vukić, L., & Karin, I. (2023). Cold Ironing Implementation Overview in European Ports—Case Study—Croatian Ports. Sustainability, 15(11), 8472. https://doi.org/10.3390/su15118472

Hatef, M., Gholamian, E., Seyed Mahmoudi, S. M., & Saberi Mehr, A. (2024). Enhancing efficiency and reduced CO2 emission in hybrid biomass gasification with integrated SOFC-MCFC system based on CO2 recycle. Energy Conversion and Management, 313. https://doi.org/10.1016/j.enconman.2024.118611

Herrero, A., Ortega Piris, A., Diaz-Ruiz-Navamuel, E., Gutierrez, M. A., & Lopez-Diaz, A.-I. (2022). Influence of the Implantation of the Onshore Power Supply (OPS) System in Spanish Medium-Sized Ports on the Reduction in CO2 Emissions: The Case of the Port of Santander (Spain). Journal of Marine Science and Engineering, 10(10), 1446. https://doi.org/10.3390/jmse10101446

Hou, Q. (2011). Life cycle assessment of cruising ship superstructure. https://www.diva-portal.org/smash/get/diva2:451090/FULLTEXT01.pdf

Ingwersen, A., Hahn Menacho, A. J., Pfister, S., Peel, J. N., Sacchi, R., & Moretti, C. (2025). Prospective life cycle assessment of cost-effective pathways for achieving the FuelEU Maritime Regulation targets. Science of The Total Environment, 958, 177880. https://doi.org/10.1016/j.scitotenv.2024.177880

Interactive App. (2025). Electricity Maps. https://app.electricitymaps.com/map/live/fifteen_minutes

Kwon, B., Jeong, B., Lee, S., Park, Y., Oh, S., & Shin, S. (2025). Comparative analysis of EU ETS, FuelEU maritime and IMO carbon pricing regulations: Strategic and economic implications for the shipping industry. Journal of Advanced Marine Engineering and Technology, 49(3), 224–238. https://doi.org/10.5916/jamet.2025.49.3.224

MA Nasser, MM Elgohary, M Abdelnaby, & MR Shouman. (2022). Environmental and economic performance investigation of natural gas and methanol as a marine alternative fuel. https://doi.org/10.21203/rs.3.rs-1947354/v1

Nasser, M. A., Shouman, M. R., & Ghoneim, N. I. (2023). A Comparative Study of Alternative Fuels for Reducing Marine Emissions: Environmental, Technical, and Economic Assessment. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.4655134

Peng, Y., Li, X., Wang, W., Wei, Z., Bing, X., & Song, X. (2019). A method for determining the allocation strategy of on-shore power supply from a green container terminal perspective. Ocean & Coastal Management, 167, 158–175. https://doi.org/10.1016/j.ocecoaman.2018.10.007

Prenc, R., Vučetić, D., & Cuculić, A. (2018). High Voltage Shore Connection in Croatia: Network configurations and formation of the connection point to the Utility power grid. Electric Power Systems Research, 157, 106–117. https://doi.org/10.1016/j.epsr.2017.12.011

Prousalidis, J., D'Agostino, F., Manos, A., & Bosich, D. (2023). The SSE-ID Card of Ships in the Sustainable Maritime Framework. 2023 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), 1–6. https://doi.org/10.1109/ESARS-ITEC57127.2023.10114812

Qiu, J., Tao, Y., Lai, S., & Zhao, J. (2022). Pricing Strategy of Cold Ironing Services for All-Electric Ships Based on Carbon Integrated Electricity Price. IEEE Transactions on Sustainable Energy, 13(3), 1553–1565. https://doi.org/10.1109/TSTE.2022.3157645

Saadeldin, M. A., Elgohary, M. M., Abdelnaby, M. M., & Shouman, M. R. (2023). Effects of Direct Water Injection on the Nitrogen Oxide Emission Characteristics of Marine Diesel Engines. Journal of Marine Science and Technology (Taiwan), 31(2). https://doi.org/10.51400/2709-6998.2692

Saadeldin, M. A., Elgohary, M. M., Abdelnaby, M. M., & Shouman, M. R. (2024). Advanced Simulation and Environmental Impact Assessment of Combustion in Maritime Energy Systems. Marine Technology Society Journal, 58(3), 36–55. https://doi.org/10.4031/MTSJ.58.3.3

Saadeldin, M. A. N., Elgohary, M. M., Abdelnaby, M., & Shouman, M. R. (2023). Biofuels and Electrofuels as Alternative Green Fuels for Marine Applications: A Review. Marine Technology Society Journal, 57(3). https://doi.org/10.4031/MTSJ.57.3.2

Saadeldin, M., Vasylyev, A., Rivarolo, M., & Sorce, A. (2026). Feasibility analysis of hydrogen fuel cell-powered passenger vessels: a multi-criteria and MILP-based analysis for sustainable inland navigation. Ocean Engineering, 349, 124186. https://doi.org/10.1016/j.oceaneng.2026.124186

Sciberras, E. A., Zahawi, B., Atkinson, D. J., Juandó, A., & Sarasquete, A. (2016). Cold ironing and onshore generation for airborne emission reductions in ports. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 230(1), 67–82. https://doi.org/10.1177/1475090214532451

TE-FINAL-EU. (2024). Status for onshore power supply in selected EU ports . https://www.transportenvironment.org/uploads/files/2025_06_27-TE-FINAL-EU-report_rev1.docx.pdf

Vasylyev, A., Passalacqua, M., Mantelli, L., Rivarolo, M., & Sorce, A. (2024). Piecewise-linear MILP optimization for energy system design onboard hybrid ships. Journal of Physics: Conference Series, 2893(1), 012040. https://doi.org/10.1088/1742-6596/2893/1/012040

Yuksel, O., Bayraktar, M., & Seyhan, A. (2025). Environmental and economic analysis of cold ironing using renewable hybrid systems. Clean Technologies and Environmental Policy, 27(8), 3489–3517. https://doi.org/10.1007/s10098-024-03065-w

Zhang, W., He, Y., Wu, N., Zhang, F., Lu, D., Liu, Z., Jing, R., & Zhao, Y. (2023). Assessment of cruise ship decarbonization potential with alternative fuels based on MILP model and cabin space limitation. Journal of Cleaner Production, 425. https://doi.org/10.1016/j.jclepro.2023.138667

Zhou, X., Li, T., Chen, R., Wei, Y., Wang, X., Wang, N., Li, S., Kuang, M., & Yang, W. (2024). Ammonia marine engine design for enhanced efficiency and reduced greenhouse gas emissions. Nature Communications, 15(1). https://doi.org/10.1038/s41467-024-46452-z

Zis, T. P. V. (2019). Prospects of cold ironing as an emissions reduction option. Transportation Research Part A: Policy and Practice, 119, 82–95. https://doi.org/10.1016/j.tra.2018.11.003