Sustainable Marine Structures
https://journals.nasspublishing.com/index.php/sms

ARTICLE

Sustainable Maritime of Onshore Power Supply Systems for Ships in Thai Ports

Phatthawut Kanokwannakhon , ***Thanyaphat Muangpan**** , ***Kittisak Makkawan***

Faculty of Logistics, Burapha University, Mueang Chonburi 20131, Thailand

ABSTRACT

Maritime transport faces escalating decarbonization pressure, prompting ports and shipping lines to evaluate onshore power supply (OPS) as a near-term abatement option for hoteling (at-berth) emissions. This study assesses the feasibility of implementing OPS for ship berthing at Bangkok Port, Thailand, using a sequential mixed-methods design. Qualitative evidence from semi-structured interviews with 26 shipping lines and 3 Port Authority of Thailand (PAT) respondents, combined with a Strengths, Weaknesses, Opportunities, and Threats (SWOT)-based contextual assessment, identifies readiness conditions and adoption constraints. A 30-year discounted cash-flow appraisal evaluates investor-side performance (NPV, IRR, and payback) for a pilot at container berths 20A and 20F and tests tariff mark-up sensitivity under 2022–2024 fuel and electricity price conditions. A socio-economic appraisal monetizes avoided air pollutants ($PM_{2.5}$, NO_x, SO_x) and CO_2 using AIS-based hoteling profiles and recognized emission-factor approaches, and reports EIRR. Results show that OPS is financially unattractive for the port operator in all scenarios (base case: NPV = −4.61 million USD; IRR = −3.38%); breakeven would require an ~115% tariff mark-up, which may reduce uptake. In contrast, the economic case is positive (EIRR = 7.78% at a 7% social discount rate), yielding an estimated net social benefit of 417,885 USD/year and avoiding 885.46 tCO_2/year for a pilot demand of ~1.25 GWh/year. These findings indicate a coordination gap between infrastructure investment and vessel uptake, implying a need for targeted public co-financing, transparent tariff design, and phased deployment linked to demonstrated demand. The study contributes policy-

*CORRESPONDING AUTHOR:
Thanyaphat Muangpan, Faculty of Logistics, Burapha University, Mueang Chonburi 20131, Thailand; Email: thanya.donut@gmail.com

ARTICLE INFO
Received: 19 November 2025 | Revised: 4 February 2026 | Accepted: 24 February 2026 | Published Online: 5 March 2026
DOI: https://doi.org/10.36956/sms.v8i1.2935

CITATION
Kanokwannakhon, P., Muangpan, T., Makkawan, K., 2026. Sustainable Maritime of Onshore Power Supply Systems for Ships in Thai Ports. Sustainable Marine Structures. 8(1): 199–214. DOI: https://doi.org/10.36956/sms.v8i1.2935

relevant evidence for medium-scale ports in emerging policy settings where social benefits may exceed private returns.

Keywords: Onshore Power Supply (OPS); Feasibility Study; Green Port; Sustainable Port; Port Decarbonization; Shore-to-Ship Power; Thailand

1. Introduction

Maritime transport underpins international trade and port-centric logistics networks, yet it remains a material source of greenhouse gas (GHG) emissions and air pollutants [1]. Recent maritime research continues to reaffirm the sector's systemic importance to trade and logistics performance, while highlighting accelerating technology adoption and decarbonization pressure across shipping and ports [2,3]. International shipping contributes approximately 3% of global greenhouse gas emissions, reinforcing the urgency of credible mitigation pathways in both ship operations and port interfaces [4]. In response, the International Maritime Organization (IMO) adopted the IMO 2023 [5] GHG Strategy, articulating a sectoral trajectory toward net-zero GHG emissions around mid-century.

Decarbonization research and practice have largely emphasized at-sea propulsion and fuel transitions(e. g., Very Low Sulphur Fuel Oil (VLSFO), Low Sulphur Marine Gas Oil (LSMGO), Liquid Natural Gas (LNG), and emerging low-/zero-carbon fuels such as biofuels, hydrogen, ammonia, and methanol) [3,6]. However, emissions are not only a function of the main engines during navigation. Hoteling (at-berth) operations, where vessels rely on auxiliary engines to supply onboard electricity, can generate concentrated nitrogen oxides (NO_x), sulfur dioxide (SO_2), fine particulate matter ($PM_{2.5}$), and GHG emissions in port areas, with disproportionate exposure risks for nearby communities [7,8]. Methodological advances in emission quantification from ship-level time-series modeling [9] to AIS-based evaluation of emission-control policy impacts in the Gulf of Thailand [7] further indicate that robust feasibility assessments should explicitly address berth-level emission sources and local policy contexts.

Onshore Power Supply (OPS), referred to as shore-side electricity or cold ironing, enables a vessel to switch off auxiliary engines at berth and draw electricity from the onshore grid through standardized connections, thereby reducing at-berth emissions and local nuisance impacts [9–11]. Global regulatory momentum has strengthened OPS relevance; for example, the European Union has introduced regulatory instruments to accelerate shore-side electricity readiness and operational uptake in ports, alongside fuel/energy compliance frameworks for shipping decarbonization [10]. Nevertheless, outside leading regions, OPS deployment remains uneven, and Thailand has not yet implemented OPS for commercial vessels, creating a distinct empirical and policy gap for Thai ports.

This gap is particularly relevant for Bangkok Port, an urban river port adjacent to dense residential and commercial districts. Official air-quality monitoring in Bangkok indicates recurrent episodes of elevated particulate concentrations; across Bangkok's monitoring network, 24 h mean $PM_{2.5}$ exceeded 37.5 μg/m^3 on approximately 9.7%–18.4% of station-days during 2020–2024 [11]. While ambient PM levels are driven by multiple sources beyond port activity, this evidence supports the policy salience of localized emission mitigation in dense urban contexts [12].

Thailand's principal container gateways, i.e., Bangkok Port and Laem Chabang Port (deep-sea gateway supporting the Eastern Seaboard/EEC industrial hinterland), provide two contrasting operational and spatial contexts for OPS considerations. **Figure 1** presents the location of major ports under the Port Authority of Thailand [13], including Bangkok Port and Laem Chabang Port, to support international readers unfamiliar with the Thai port system. Despite being smaller than global mega-hubs, these ports represent consequential national gateways and a policy-relevant setting for berth-level emission reduction and OPS investment appraisal [14]. Accordingly, this study assesses the feasibility and implications of OPS implementation in Thailand through a case-driven evaluation anchored in Bangkok Port, while situating findings against recent international evidence.

Recent OPS studies, including Amaral et al. [9], have primarily focused on estimating port-side power needs using historical berth/call data and vessel-type energy profiling. In this respect, our study converges with prior literature in the technical planning objective of OPS deployment. However, it diverges by extending the analysis beyond power sizing to an integrated three-phase framework that combines stakeholder-based operational diagnosis, technical–economic feasibility assessment, and private and social viability evaluation using Net Present Value (NPV), Internal Rate of Return (IRR), and Economic Internal Rate of Return (EIRR), under Thai port conditions. This interpretation is consistent with recent green-port transition literature showing that financial, institutional, and coordination barriers jointly shape implementation outcomes [15]. Accordingly, this paper contributes a context-specific feasibility framework for medium-scale ports in emerging policy environments and provides empirical evidence on when OPS may be socially desirable yet financially constrained without targeted policy support.

Figure 1. Location of the Bangkok Port and Laem Chabang Port in Thailand.

Source: Natural Earth [13].

2. Materials and Methods

This study employed a sequential mixed-methods design, integrating qualitative and quantitative evidence to assess the feasibility of implementing Onshore Power Supply (OPS) for ship hoteling (at-berth) operations in Thailand. The methodology comprised three phases aligned with the study objectives: (i) desk-based contextual analysis, (ii) primary stakeholder feasibility assessment; and (iii) quantitative financial and economic appraisal.

Bangkok Port (operated by the Port Authority of Thailand: PAT) was selected as the primary case study because it is an urban river port adjacent to dense residential and commercial districts. The quantitative appraisal was structured around a proposed OPS pilot at container berths 20A–20F, with berths 20A and 20F treated as representative installation points for pilot sizing and investment appraisal. **Figure 2** shows the berth layout and pilot locations [16].

The overall research workflow and the linkage between the three phases and objectives are summarized in **Figure 3**.

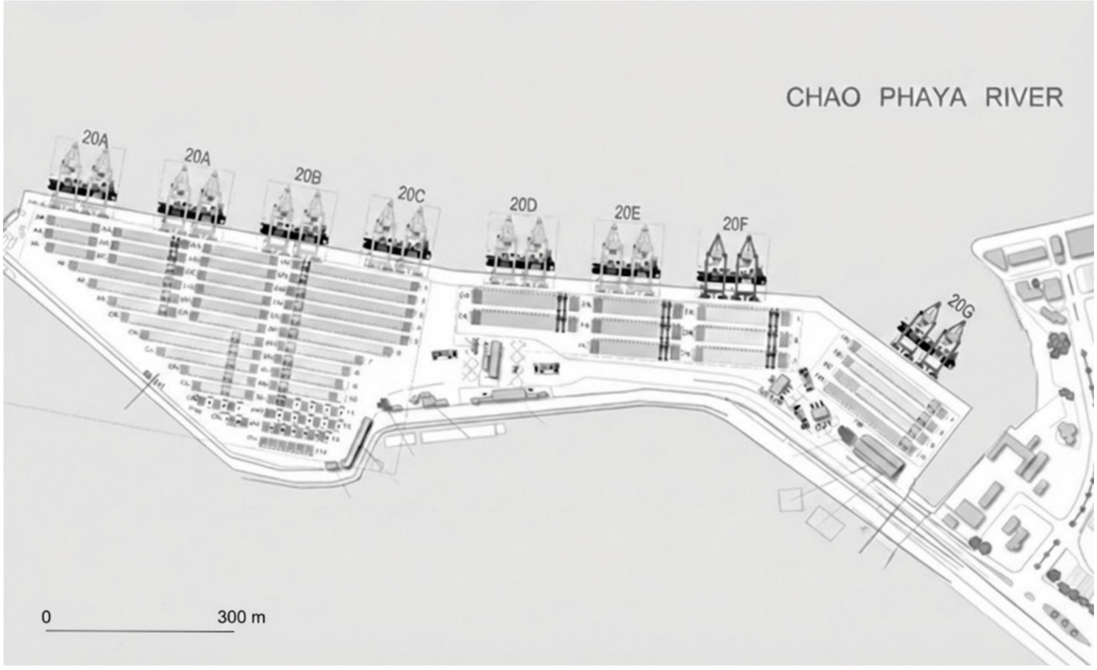

Figure 2. Bangkok Port berth layout highlighting the pilot berths (20A and 20F) within the 20A–20F berth group.

Source: Port Authority of Thailand [16].

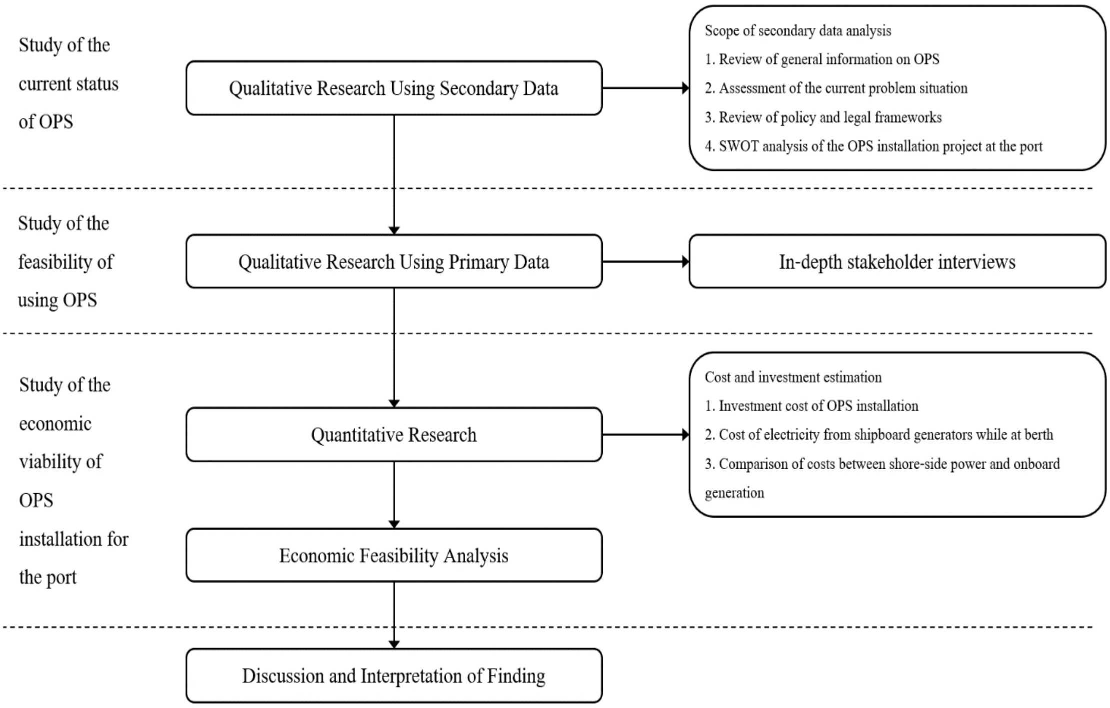

Figure 3. Framework of the research approach.

Source: Authors Developed.

2.1. Phase 1: Secondary Qualitative Analysis and Contextual Study

To address the first objective (assessing the current situation and readiness for OPS), a systematic desk-based synthesis of secondary sources was conducted. The review covered: national strategy and policy documents (e.g., the 20-Year National Strategy [17] and the BCG Economy Model); relevant legislation and power-sector planning documents (e.g., power development plans); international maritime decarbonization instruments and OPS-related policy frameworks (e.g., IMO GHG Strategy 2023 [5] and EU Fuel EU Maritime [8]); existing academic literature on OPS; and critical technical standards (e.g., the IEC/IEEE 80005 series) [18]. The synthesized evidence was analyzed using a SWOT (Strengths, Weaknesses, Opportunities, Threats) framework to evaluate policy alignment, institutional readiness, technical constraints, and implementation gaps for OPS in Thailand.

2.2. Phase 2: Primary Qualitative Analysis and Stakeholder Feasibility

The second phase considered practical feasibility and stakeholder acceptance through in-depth, semi-structured interviews with purposively selected decision-makers from two principal stakeholder groups. A total of N = 29 interviews were completed, including: (1) 3 PAT senior executives and engineering/operations personnel (investor/operator perspective) and (2) 26 executives and operations managers from 26 shipping lines that regularly call at Bangkok Port (end-user perspective) [19]. The interview guide was designed about feasibility dimensions commonly used in OPS appraisal market demand, technical feasibility, environmental impacts, financial considerations, legal compliance, and stakeholder acceptance, and focused on decision conditions for OPS uptake (e.g., OPS readiness, berth-operational constraints, and tariff expectations).

Interviews were conducted in Thai, either in-person or via online meetings as appropriate. To support structured responses for selected factual items (e.g., fleet readiness and operational practices), a Microsoft Forms questionnaire (QR-code access) was used as a supplementary instrument where needed. With participant consent, interviews were audio-recorded and transcribed. Transcripts were analyzed using qualitative content analysis to identify recurring themes, barriers (technical, financial, organizational), enabling factors, and required policy or commercial arrangements. Findings from Phase 2 were used to parameterize the quantitative scenarios and to interpret the feasibility results. Interview transcripts were coded into convergent themes (shared across both groups) and divergent themes (group-specific differences). The resulting thematic synthesis is presented in Section 3.1.

Ethics and confidentiality: This study was approved by the Human Research Ethics Committee, Burapha University (approval no. IRB3-169/2567; approved on 13 December 2024). All participants provided informed consent and could withdraw at any time. Interview data were anonymized at source and stored securely; the manuscript does not disclose personally identifiable information or commercially sensitive details.

2.3. Phase 3: Quantitative Cost-Effectiveness Analysis

The third phase quantified the cost-effectiveness of an OPS pilot at Bangkok Port using a structured appraisal comprising: (i) baseline energy cost comparison; (ii) investor-side financial appraisal; and (iii) societal economic appraisal.

2.3.1. Baseline Cost Comparison

A baseline comparison was developed between the unit cost of onboard electricity generation (USD/kWh) using marine fuels (VLSFO and LSMGO) and the unit cost of shore electricity supplied under PAT's published electricity tariff structure [13]. Fuel-price inputs were taken from the study's referenced market series for 2022–2024, and the shore electricity cost reflected the applicable tariff components during the same period. This baseline "price gap" assessment establishes the economic context for shipping-line adoption decisions and for feasible tariff setting.

2.3.2. Financial Analysis (Project Viability)

A discounted cash-flow model was developed from the investor perspective (PAT) over a 30-year project life. Key financial indicators were calculated, including Net Present Value (NPV) [20], Internal Rate of Return (IRR) [18], and Payback Period (PB), using a 7.00% discount rate (WACC). The revenue model reflects electricity sales to vessels using OPS, while costs include capital expenditure (CAPEX) and recurring operating expenditure (OPEX) required to operate and maintain the system. CAPEX inputs were derived from aggregated project-level estimates provided by PAT and relevant suppliers; where detailed itemized breakdowns were constrained by confidentiality, CAPEX was modelled as a single up-front investment. OPEX was represented using annual allowances consistent with typical utility-interface operation and maintenance activities (e.g., routine inspections, preventative maintenance, and administration).

Scenario analysis (Base/Best/Worst) was used to test sensitivity to key uncertainties (e.g., CAPEX level, achievable tariff mark-up under competitive constraints, and fuel–electricity price differentials). A dedicated sensitivity analysis examined the relationship between service price mark-up and payback performance, reflecting the central role of tariff competitiveness in OPS uptake.

2.3.3. Economic Analysis (Societal Viability)

The authors conducted an economic appraisal to evaluate societal viability by monetizing positive externalities from reduced air pollutants ($PM_{2.5}$, NO_x, SO_x) and greenhouse gas emissions (CO_2) attributable to reduced auxiliary-engine use during hoteling. At-berth activity reports were derived from AIS-based hoteling durations for vessel calls at Bangkok Port, together with recognized emission-factor approaches used in the ship-emission literature. The emission reductions were valued using monetary factors reported in peer-reviewed studies and policy analyses cited in the manuscript, and the Economic Internal Rate of Return (EIRR) was calculated to determine whether total societal benefits justify public investment.

3. Results

3.1. Stakeholder Sample and Representativeness

This section reports empirical evidence from the sequential mixed methods design, covering (i) stakeholder interview evidence and (ii) the quantitative financial and economic appraisal of the OPS pilot. To maintain confidentiality, shipping lines are anonymised (SL-01 to SL-26), and Port Authority respondents are reported at an aggregated role level (**Tables 1–3**).

Table 1. Profile of shipping-line interview respondents (n = 26).

Attribute	Category	Count
Gender	Male	23
Gender	Female	3
Position	Operation Manager	15
Position	General Manager	5
Position	Manager	4
Position	Owner	1
Position	President	1

Table 2. Vessel-call coverage of interviewed shipping lines (anonymised) (n = 26).

Line ID	Respondent Position	Call Share (%)	Cumulative (%)	Rank Group
SL-01	Operation Manager	58.01	58.01	Top-10
SL-02	Operation Manager	5.53	63.54	Top-10
SL-03	Manager	4.72	68.26	Top-10
SL-04	Operation Manager	4.24	72.50	Top-10
SL-05	Manager	2.73	75.23	Top-10
SL-06	Manager	2.65	77.88	Top-10
SL-07	Manager	2.31	80.19	Top-10

Table 2. *Cont.*

Line ID	Respondent Position	Call Share (%)	Cumulative (%)	Rank Group
SL-08	Operation Manager	2.24	82.43	Top-10
SL-09	Operation Manager	2.12	84.55	Top-10
SL-10	Owner	1.80	86.35	Top-10
SL-11	Operation Manager	1.61	87.96	Others
SL-12	President	1.51	89.47	Others
SL-13	Operation Manager	1.44	90.91	Others
SL-14	Operation Manager	1.12	92.03	Others
SL-15	Operation Manager	1.05	93.08	Others
SL-16	General Manager	0.90	93.98	Others
SL-17	Operation Manager	0.80	94.78	Others
SL-18	Operation Manager	0.73	95.51	Others
SL-19	Operation Manager	0.68	96.19	Others
SL-20	General Manager	0.66	96.85	Others
SL-21	Operation Manager	0.63	97.48	Others
SL-22	General Manager	0.61	98.09	Others
SL-23	General Manager	0.58	98.67	Others
SL-24	General Manager	0.54	99.21	Others
SL-25	Operation Manager	0.44	99.65	Others
SL-26	Operation Manager	0.34	99.99	Others

Note: Call-share represents the proportion of vessel calls attributable to each interviewed shipping line during the study period used in the OPS appraisal. The top 10 lines account for approximately 86.35% of calls, indicating strong coverage of dominant traffic.

Table 3. Port Authority of Thailand (PAT) interview respondent profile (aggregated) (n = 3).

Respondent ID	Role Level	Functional Domain	Notes (Aggregation)
PAT-1	Director, Bangkok Port	Executive Management	Reported in aggregated form (no personal identifiers)
PAT-2	Director, Ship and Cargo Operations Department	Port/Terminal operations	Reported in aggregated form (no personal identifiers)
PAT-3	Director, Support Services Department	Strategy/Sustainability	Reported in aggregated form (no personal identifiers)

3.2. Interview Findings: Convergences and Divergences across Feasibility Dimensions

Qualitative findings are presented as a structured thematic synthesis aligned with the semi-structured interview guide (Q1–Q10) and the feasibility dimensions (market, technical, environmental, financial, legal, and acceptance). Because the evidence base is reported as consolidated interview synthesis to protect commercial confidentiality, results are expressed using qualitative prevalence terms (e.g., “most”, “some”, “a minority”) rather than respondent-level frequency counts (**Table 4**).

3.3. Quantitative Appraisal: Baseline Costs, Financial Viability, and Economic Viability

The quantitative appraisal evaluates an OPS pilot at Bangkok Port (berths 20A and 20F as representative installation points within the 20A–20F berth group) under a 30-year life and a 7.00% discount rate (WACC). Scenario and sensitivity analyses are used to reflect uncertainty in CAPEX, achievable service mark-up under competitive constraints, and fuel–electricity price differentials (**Figure 4, Tables 5** and **6**).

Table 4. Thematic synthesis of stakeholder evidence (Q1–Q10) with qualitative prevalence tags.

Interview Prompt	Cross-Cutting Synthesis	Shipping-Line Emphasis	PAT Emphasis	Prevalence Tag
Q1: Current practice for onboard electricity while at berth	Hoteling electricity is primarily supplied by auxiliary engines; OPS use was mainly reported for overseas calls where shore power is available and mandated/incentivised.	Operational constraints; compatibility; prior exposure in EU/US.	Baseline for emissions and service design.	Most (AE baseline); some (OPS experience abroad)
Q2: Current and potential demand for OPS	Current demand is low and contingent on tariff competitiveness; potential demand is higher among international services and vessel types facing stricter environmental requirements.	Willingness-to-use depends on delivered price per kWh and operational certainty.	Demand-risk is central to investment justification.	Mixed; generally low at present
Q3: Technical feasibility and constraints	Key constraints include voltage/frequency compatibility (50/60 Hz), standardised connection interfaces, berth space, and integration with port operations; frequency converter requirements are a dominant cost driver.	Onboard retrofit readiness varies; operational downtime for connection matters.	Grid interface, safety, and infrastructure reliability.	Most raised (technical + CAPEX linkage)
Q4: Environmental impacts and perceived benefits	Stakeholders consistently recognised local air quality and noise benefits from eliminating auxiliary engine emissions at berth; some noted that net GHG benefits depend on grid generation mix.	Reputation and compliance value, especially for global services.	Urban exposure and public-health relevance around Bangkok Port.	Most (local benefits); some (grid-mix caveat)
Q5: Financial feasibility and pricing conditions	Economic attractiveness depends on a stable price gap where shore electricity is at or below onboard generation cost (VLSFO/LSMGO-based). A tariff band broadly equivalent to roughly 4–6 THB/kWh (context-specific) was discussed as a practical threshold.	Adoption conditional on tariff parity or savings vs. fuel-based generation.	Inability to recover high CAPEX under competitive tariffs.	Most conditional on tariff
Q6: Preferred policy instruments and incentives	Suggested instruments include capital subsidies/grants, transitional tariff support, tax incentives, and/or port dues discounts linked to OPS use, to overcome demand investment interdependence.	Prefer predictable incentives; avoid operational disruption.	Need public funding justification and policy mandate.	Several convergent proposals
Q7: Legal/regulatory feasibility	Absence of a domestic OPS mandate and local technical standards was viewed as a barrier; stakeholders emphasised the need for phased regulatory pathways to maintain competitiveness.	Concern about uneven playing field if costs rise.	Need alignment with national green-port policy and utility regulation.	Most (standards/mandate gap)
Q8: Stakeholder acceptance and adoption risk	Acceptance is conditional on reliability, safety assurance, berth assignment practicality, and clear responsibility allocation among port, utility, and ship operators.	Operational reliability and berth scheduling are decisive.	Risk management and service continuity.	Mixed (conditional acceptance)
Q9: Thailand-specific implementation requirements	Implementation must reflect Bangkok Port's space constraints, river port operations, and coordination with the metropolitan grid utility; phased pilots and learning by doing were emphasised.	Need operational simplicity and minimal turnaround impact.	Need institutional coordination and public communication.	Several consistent points
Q10: Strategic implications for Thai ports	OPS was framed as a strategic enabler for green-port positioning and future compliance, but requiring public sector support to resolve financial feasibility constraints under competitive tariffs.	Competitiveness and customer requirements.	Public infrastructure framing and policy leadership.	Most (strategic value; finance constraint)

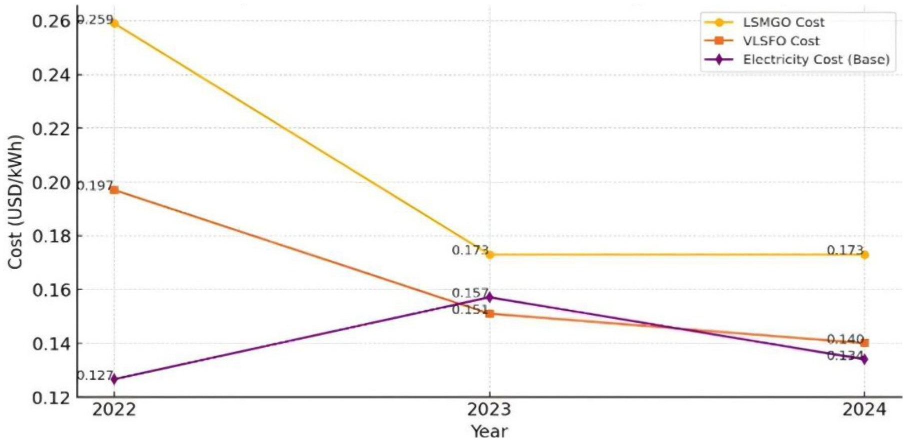

Figure 4. Comparison of Fuel Costs (VLSFO, LSMGO) versus Electricity Cost (Base) (USD/kWh).

Source: Authors' processing of market price data retrieved from Ship & Bunker (https://shipandbunker.com/prices).

Table 5. Baseline unit-cost comparison (USD/kWh), 2022–2024.

Energy Source	Min	Max	Interpretation
Shore electricity (PAT tariff)	0.134	0.157	Benchmark for OPS pricing
Onboard generation using VLSFO	0.140	0.197	Close to shore electricity (narrow price gap)
Onboard generation using LSMGO	0.173	0.259	Consistently higher than shore electricity

Table 6. Summary of financial appraisal results (NPV, IRR, and Payback) under scenario analysis (30-year project life; discount rate 7.00%).

Scenario	NPV (Million USD)	IRR (%)	Payback Period
Base Case	−4.61	−3.38	Not reached
Best Case	−3.38	−2.06	Not reached
Worst Case	−5.83	−4.41	Not reached

A sensitivity analysis on service-price markup indicates that the project only reaches a break-even payback point at approximately 115% markup. Such a mark-up would make OPS electricity materially more expensive than onboard generation and is therefore inconsistent with stakeholder tariff-competitiveness conditions (**Figure 5** and **Table 7**).

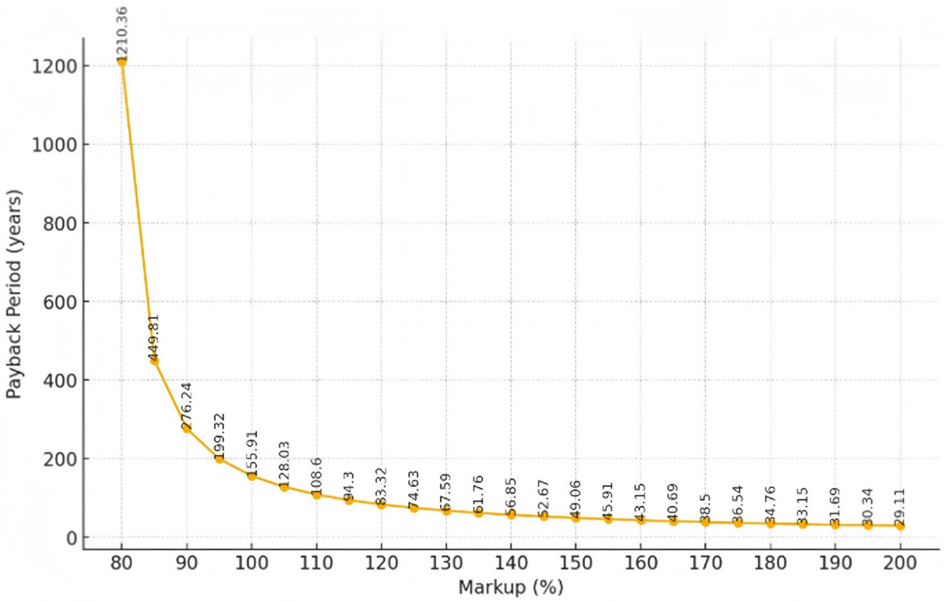

Figure 5. Sensitivity analysis of payback period (years) versus service price mark-up (%).

Source: Authors' processing of primary operational/project data provided by the Port Authority of Thailand (PAT).

Table 7. Economic Appraisal (Societal) Results for the Best Case Scenario (Externality Monetisation Included).

Metric	Value	Unit
Economic Internal Rate of Return (EIRR)	7.78	%
Social discount rate	7.00	%
Annual net benefit (monetised externalities—costs)	417,885.30	USD/Year
Avoided CO_2 emissions	885.46	Tonnes/Year
Avoided $PM_{2.5}$ emissions	0.1952	Tonnes/Year
Avoided SO_x emissions	2.61	Tonnes/Year
Avoided NO_x emissions	7.77	Tonnes/Year

The EIRR exceeds the assumed 7.00% social discount rate, indicating positive societal viability under the Best Case scenario when externalities are valued. Sensitivity tests show the EIRR is most responsive to CAPEX assumptions and the social cost values used for monetising emissions (**Tables 8** and **9**).

3.4. SWOT Analysis: Readiness and Implementation Context for OPS in Thailand

The SWOT analysis synthesizes the contextual evidence (policy alignment, technical constraints, and institutional readiness) known as Phase 1 outputs, and is presented to complement the interview and quantitative appraisal results (**Tables 10** and **11**).

Table 8. Sensitivity of EIRR to CAPEX assumptions (Best Case).

CAPEX Case	EIRR (%)
−20% CAPEX	9.12
Base CAPEX	7.78
+20% CAPEX	6.55

Table 9. Sensitivity of EIRR to Social Cost (Externality) Valuation (Best Case).

Social Cost Case	EIRR (%)
SCC −20%	7.12
Base SCC	7.78
SCC +20%	8.45

Table 10. SWOT analysis of OPS implementation in Thailand (internal factors: Strengths and Weaknesses).

Category	Key Factors	Implications for OPS Implementation
Strengths	1) Existing high-voltage grid infrastructure serving the Bangkok Port area. 2) PAT (state-owned enterprise) can lead a policy-driven pilot project.	Enables baseline technical feasibility and institutional leadership for a pilot.
Weaknesses	1) High initial investment cost (CAPEX), 2) Lack of domestic OPS technical standards and institutional experience.	CAPEX barrier and standardisation gap reduce bankability and operational readiness.

Table 11. SWOT analysis of OPS implementation in Thailand (external factors: Opportunities and Threats).

Category	Key Factors	Implications for OPS Implementation
Opportunities	1) International regulatory pressure and decarbonisation trajectories (IMO/EU) increase OPS relevance. 2) Alignment with the national Green Port/sustainability agenda supports reputational and policy benefits.	Creates policy rationale and competitiveness drivers for OPS readiness.
Threats	1) Volatility in fuel and electricity prices; narrowing of the “price gap” can remove user incentives. 2) Risk of low utilization without mandate or adequate incentives, reinforcing demand–investment interdependence.	Requires robust tariff/incentive design and phased scaling to manage utilization risk.

4. Discussion

4.1. Interpreting Feasibility Evidence: Investor–User Coordination and Adoption Conditions

The results indicate that OPS implementation at Bangkok Port is shaped less by a lack of technical awareness and more by a structural interdependence between the investor/operator (PAT) and the end users (shipping lines). Across stakeholder evidence (**Tables 1–3**) and the integrated synthesis (**Table 4**), the dominant adoption condition expressed by shipping lines is tariff competitiveness relative to onboard auxiliary generation using VLSFO/LSMGO. In parallel, PAT’s investment decision is constrained by high up-front capital expenditure, particularly for grid-interface and frequency-conversion assets, combined with uncertainty about sustained utilization. This pattern is consistent with a classic coordination failure in infrastructure adoption: demand cannot be credibly committed without a competitive tariff, while a competitive tariff cannot be offered without a level of investment that the investor cannot justify under commercial returns [21,22].

Importantly, the qualitative evidence suggests that 'technical readiness' is a necessary but insufficient condition for utilization. Several shipping lines reported OPS-ready capability on newer vessels driven by overseas regulatory readiness requirements; however, readiness does not automatically translate into use at Bangkok Port. Adoption is instead mediated by berth-assignment practices, operational flexibility (connection time and reliability), and the price gap between shore electricity and marine-fuel-based generation [23,24]. These findings imply that OPS uptake in Thailand should be evaluated as a system-of-systems decision involving port operations, utility-interface governance, and tariff design, rather than as a stand-alone engineering investment.

4.2. Explaining the Financial–Economic Divergence and the Role of Scale

The quantitative appraisal identifies a clear divergence between investor-side financial performance and societal economic performance. Under the scenarios evaluated for the Bangkok Port pilot, the financial indicators remain negative (**Table 6**): the Base Case yields an NPV of −4.61 million USD and an IRR of −3.38%, and even the Best Case remains financially unattractive (NPV −3.38 million USD; IRR −2.06%). The sensitivity analysis further shows that a breakeven payback would require an approximately 115% service price mark-up, a level that would undermine the tariff competitiveness required by end-users. This outcome is closely linked to scale and utilization intensity. The pilot demand profile used in the appraisal is anchored in observed vessel call volumes and hoteling electricity demand assumptions (**Table 7**), yielding an annual energy throughput on the order of 1.25 GWh/year (417 calls × 3000 kWh/call). In such a demand regime, the revenue base is limited, while the capital cost of OPS infrastructure—substation upgrades, switchgear, cable management, safety systems, and (where needed) frequency conversion exhibits substantial fixed-cost characteristics. For ports with modest throughput and/or low OPS utilization rates, these fixed costs can dominate the commercial business case [21,22]. This provides a direct response to Reviewer concerns regarding the implications of Bangkok Port's operational scale (approximately 1.5–1.7 million TEU/year): smaller or medium-sized ports may face stronger financial headwinds unless utilization is high, CAPEX is subsidized, or tariff competitiveness is supported through policy instruments. This interpretation is consistent with evidence from small and medium ports showing that cold-ironing implementation faces distinct economic and operational constraints compared with large hub ports [25].

Nevertheless, the scale effect does not preclude generalizability; rather, it clarifies the boundary conditions under which OPS projects can be financially viable [26]. Where other studies have reported more favorable commercial outcomes, the enabling conditions typically include one or more of the following: (i) larger and more concentrated berth-level demand (higher connection hours and higher kW loads); (ii) mandated usage for specific vessel categories, which reduces demand uncertainty; (iii) grant-funded or shared cost CAPEX structures that reduce the investor's capital burden; and/or (iv) a wider and more stable fuel electricity price spread [23]. The Bangkok Port case therefore, provides a transferable insight for similarly sized ASEAN ports: commercial viability is unlikely without explicit measures that address fixed-cost recovery and demand-risk allocation.

4.3. OPS as Urban Environmental Infrastructure: Externalities and Socio-Economic Justification

When externalities are monetised, the appraisal supports OPS as a socially justified intervention in an urban-port context. The economic assessment reports an EIRR of 7.78%, exceeding the applied social discount rate of 7.00% (**Table 7**). The estimated annual net benefit (monetised externalities minus costs) is 417,885 USD/year, associated with avoided emissions of approximately 885.46 tCO_2/year and reductions in local pollutants ($PM_{2.5}$, SO_x, NO_x). These magnitudes, while subject to uncertainty, indicate that the societal value of emission reductions in a dense urban environment can offset the financial deficit observed from the investor perspective.

This finding is particularly salient for Bangkok Port because urban proximity increases exposure and health-damage valuation per unit of emission reduction, compared with ports located in less densely populated industrial zones [12]. The results, therefore, support reframing OPS from a profit-seeking utility service to a form of 'green public infrastructure' whose primary return is improved air quality and climate-aligned port operation. This reframing also aligns with the stakeholder evidence: PAT interviewees characterized OPS as policy-driven and contingent on public support mechanisms, while shipping lines emphasised low tariff thresholds rather than willingness to pay for broader public benefits.

At the same time, the economic valuation relies on internationally sourced damage-cost values for pollutants and greenhouse gases. While this approach is consistent with common practice in port externality appraisal, its application to Thailand introduces transferability and parameter uncertainty. The implication for the manuscript is twofold: (i) the economic result is best interpreted as evidence of positive societal potential rather than a precise point estimate; and (ii) further work, such as a Thailand-specific health impact assessment and locally calibrated valuation parameters, would strengthen the robustness of the externality component.

4.4. Positioning against International OPS Literature and Methodological Contribution

The study's findings are consistent with a broad strand of OPS feasibility literature that identifies high CAPEX, tariff competitiveness, and utilization uncertainty as recurrent constraints on commercial viability [6,22]. However, the Bangkok Port case contributes by explicitly integrating three evidence layers: policy and readiness assessment (SWOT), stakeholder decision conditions, and financial/economic appraisal into a single feasibility narrative anchored at berth group 20A–20F, where implementation decisions are made. Compared with studies that focus primarily on power-needs estimation and infrastructure sizing (e.g., quay-level electrical demand planning) [8], the present approach places greater emphasis on adoption dynamics and investment appraisal under emerging market governance constraints. In particular, the integration of interview-derived decision thresholds with the sensitivity analysis of tariff mark-up provides an operational mechanism linking qualitative feasibility to quantitative outcomes: it shows that the tariff required for commercial payback is incompatible with the tariff required for utilization, thereby evidencing a structural mismatch rather than a parameter-choice artefact. This helps explain why studies may reach differing conclusions about OPS "need" versus OPS "viability," since demand estimation alone does not resolve financing feasibility when demand is price-elastic, and investment costs are front-loaded.

Therefore, the principal methodological contribution is not merely the calculation of NPV/IRR/EIRR, but the design of a feasibility logic that (i) captures berth-level hoteling profiles, (ii) makes adoption constraints explicit, and (iii) distinguishes investor returns from societal returns in a policy-relevant manner. This positioning also supports the transferability claim to other medium-sized ports facing similar coordination and tariff-competitiveness constraints [22].

4.5. Policy Implications for Practical Implementation

Given that the OPS pilot is financially unattractive under base-case assumptions but economically beneficial from a societal perspective, implementation should be designed as a coordinated public–private transition rather than a purely market-driven investment [22]. For the Port Authority of Thailand (PAT), a practical near-term pathway is to proceed with a pilot at berths 20A and 20F while testing tariff structures (including time-of-day or dynamic elements) to identify a commercially acceptable pricing range that remains competitive with onboard generation costs. In parallel, reducing unit electricity cost (USD/kWh) through long-term power procurement arrangements and/or renewable integration (e.g., warehouse rooftop solar) could improve project performance, as variable cost management emerges as a key financial lever in the sensitivity results.

For public agencies (e.g., Ministry of Transport, Ministry of Energy, and BOI), the evidence supports treating OPS as green public infrastructure with measurable external benefits; targeted CAPEX support (full or partial), tax incentives, or blended financing can help close the investor–user coordination gap identified in this study. Accelerating national OPS technical standards and legal frameworks aligned with IEC/IEEE 80005 would reduce interoperability uncertainty and improve long-term investment confidence [18], while non-financial instruments (e.g., priority berthing or fee differentiation for OPS-using vessels) may support early utilization [27]. For shipping lines, transition planning should include OPS-ready specifications for newbuilds and phased retrofitting for vessels serving routes linked to ports with stricter environmental requirements; active participation in pilot programs and structured feedback to PAT can improve operational practicality. A joint roadmap between port authorities and shipping lines, covering acceptable tariff bands, retrofit constraints, and support mechanisms, which would improve adoption conditions and reduce implementation risk. Overall, these implications are consistent with the study's core finding that OPS in Bangkok Port is socially desirable but financially constrained, and therefore requires coordinated policy design, cost-sharing mechanisms, and phased execution linked to demonstrated demand [15,22].

4.6. Limitations and Future Research Priorities

Several limitations must be recognized. First, CAPEX was modelled as an aggregated project estimate due to confidentiality constraints, and OPEX was represented using annual allowances rather than itemized maintenance and staffing schedules. While this approach is appropriate for early-stage feasibility appraisal, it limits engineering-level validation and complicates benchmarking against international cost structures. Second, the demand profile is based on AIS-derived activity and an assumed hoteling electricity requirement (3000 kWh per call); variation across vessel sizes and auxiliary loads may materially change throughput and, therefore, financial outcomes. Third, the externality valuation uses international damage-cost values; applying these values to the Thai context introduces uncertainty and may over- or under-estimate benefits. Finally, the analysis focuses on container berths and does not directly assess other vessel segments (e.g., passenger, Ro-Ro), which may have different load profiles and policy salience.

Future research should prioritize: (i) an engineering prefeasibility design to produce a transparent CAPEX/OPEX breakdown (including frequency conversion alternatives, cable management, and substation upgrade scope); (ii) a Thailand specific health impact assessment to calibrate pollutant damage costs and strengthen the economic appraisal; (iii) extended scenarios for utilization growth under phased policy uptake or conditional mandates; and (iv) comparative application to Laem Chabang Port to test how spatial context and vessel mix affect both financial and externality outcomes.

Overall, the Discussion supports a clear conclusion for policy: in an urban port setting such as Bangkok Port, OPS can be socially justified yet commercially unattractive under market conditions. Implementing OPS, therefore, requires explicit risk-sharing and policy support mechanisms that align tariffs with adoption conditions while recognizing the societal value of emission reductions. The subsequent Conclusions section should translate these findings into concise, actionable recommendations and a forward-looking agenda for Thailand and comparable ASEAN ports.

5. Conclusions

This study developed a Bangkok Port assessment of the feasibility of Onshore Power Supply (OPS) for ship hoteling (at-berth) operations in Thailand. The results show that Thailand's major ports have not yet implemented OPS in formal commercial operation, and vessels calling at Bangkok Port still rely on auxiliary engines using fossil fuels during berthing. Although national policy directions support clean energy transition and greenhouse gas reduction, practical policy and implementation gaps for OPS in maritime operations remain.

The findings indicate that OPS at Bangkok Port is technically feasible, but adoption is constrained by high upfront investment, demand uncertainty, interoperability requirements, and strong price sensitivity among shipping lines. In the financial appraisal, the pilot project is not commercially viable under base-case assumptions (negative NPV and IRR, with no payback within 30 years). Analysis shows that break-even would require an approximately 115% service mark-up, which may reduce tariff competitiveness and weaken user uptake.

In contrast, the socio-economic appraisal is positive (EIRR = 7.78%), suggesting that broader public-health and environmental benefits can outweigh project costs even when private returns are weak. Overall, the evidence suggests that OPS in Thailand is socially desirable but financially constrained. A practical pathway is targeted public co-financing for initial CAPEX, transparent and competitive tariff design, and phased implementation linked to demonstrated demand. This conclusion aligns with recent green port barrier evidence highlighting financial, institutional, and coordination constraints in implementation [15], and with recent OPS policy literature emphasizing coordinated deployment strategies and supportive policy design [22]. It is also consistent with Bangkok-area air-quality concerns reported in prior regional evidence [12], supporting the relevance of berth-level mitigation.

Author Contributions

Conceptualization, P.K. and T.M.; methodology, P.K. and T.M.; validation, T.M. and K.M.; formal analysis, P.K.; investigation, P.K.; resources, P.K. and T.M.; data curation, P.K.; writing—original draft preparation, P.K.; writing—review and editing, T.M. and K.M.; visualization, P.K.; supervision, T.M.; project administration, T.M. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

This study was approved by the Human Research Ethics Committee, Burapha University (approval no. IRB3-169/2567; approved on 13 December 2024).

Informed Consent Statement

Informed consent was obtained from all participants involved in the interview phase of this study.

Data Availability Statement

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical considerations.

Acknowledgments

The authors would like to thank the Faculty of Logistics at Burapha University and the Port Authority of Thailand for providing research facilities and support during this study.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The manuscript was proofread and language-edited using AI-assisted tools (ChatGPT, model GPT-5.2). The authors reviewed and take full responsibility for the content, ensuring its accuracy and originality.

References

[1] Bolat, F., 2025. Time series modeling of greenhouse gas emissions: A case study for a chemical tanker ship. Maritime Technology and Research. 8(1), 278949. DOI: https://doi.org/10.33175/mtr.2026.278949

[2] Breshanaj, M., Stringa, A., Ramosacaj, M., 2025. Applying Facebook Prophet to forecast the pas-

senger flow in a seaport. Maritime Technology and Research. 7(4), 277161. DOI: https://doi.org/10.33175/mtr.2025.277161

[3] Alamoush, A.S., Ölçer, A.I., 2025. Harnessing cutting-edge technologies for sustainable future shipping: An overview of innovations, drivers, barriers, and opportunities. Maritime Technology and Research. 7(4), 277313. DOI: https://doi.org/10.33175/mtr.2025.277313

[4] UN Trade and Development (UNCTAD), 2024. Review of Maritime Transport 2024: Navigating Maritime Chokepoints. UNCTAD: Geneva, Switzerland. Available from: https://unctad.org/publication/review-maritime-transport-2024 (cited 12 November 2025).

[5] International Maritime Organization (IMO), 2023. 2023 IMO Strategy on Reduction of GHG Emissions from Ships. IMO: London, UK. Available from: https://www.imo.org/en/ourwork/environment/pages/2023-imo-strategy-on-reduction-of-ghg-emissions-from-ships.aspx (cited 17 January 2026).

[6] Zhang, W., Wang, J., Qin, G., et al., 2025. Review of the state-of-the-art of alternative marine fuels: A viable approach to zero-carbon shipping. Cleaner Logistics and Supply Chain. 16, 100232. DOI: https://doi.org/10.1016/j.clscn.2025.100232

[7] Premsamarn, P., Win, T.K., Watanabe, D., 2025. Assessing the impact of emission control areas policy on ship emissions in the Gulf of Thailand using AIS data. Maritime Technology and Research. 7(3), 275311. DOI: https://doi.org/10.33175/mtr.2025.275311

[8] European Union (EU), 2023. Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (Text with EEA relevance). EU: Brussels, Belgium. Available from: https://eur-lex.europa.eu/eli/reg/2023/1805/oj/eng (cited 7 January 2026).

[9] Amaral, M., Amaro, N., Arsénio, P., 2023. Methodology for Assessing Power Needs for Onshore Power Supply in Maritime Ports. Sustainability. 15(24), 16670. DOI: https://doi.org/10.3390/su152416670

[10] European Union (EU), 2023. Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU (Text with EEA relevance). EU: Brussels, Belgium. Available from: https://eur-lex.europa.eu/eli/reg/2023/1804/oj/eng (cited 7 January 2026).

[11] Pollution Control Department, 2024. Air4Thai Air-Quality Monitoring Data ($PM_{2.5}$/PM_{10}), Bangkok Metropolitan Area. Available from: http://air4thai.pcd.go.th/ (cited 7 November 2025). (in Thai)

[12] Nounmusig, W., 2023. Bangkok port and coastal regions of Thailand under atmospheric $PM_{2.5}$ pollution: A hypothetical nuclear power plant accident. Maritime Technology and Research. 5(4), 264402. DOI: https://doi.org/10.33175/mtr.2023.264402

[13] Natural Earth, 2024. Free vector and raster map data at 1:10m, 1:50m, and 1:110m scales. Available from:https://www.naturalearthdata.com/ (cited 7 November 2025).

[14] Port Authority of Thailand (PAT), 2023. Annual Report 2023 (B.E. 2566). PAT: Bangkok, Thailand.

[15] Duc, N.M., Nguyen, L.H., 2025. Ranking barriers to green port development: A neutrosophic-fuzzy ISM approach. Maritime Technology and Research. 8(1), 281958. DOI: https://doi.org/10.33175/mtr.2026.281958

[16] Port Authority of Thailand (PAT), 2025. Port Safety Health and Environmental Management System Booklet. PAT: Bangkok, Thailand.

[17] National Strategy Committee of Thailand, 2018. National Strategy (B.E. 2561–2580) (2018–2037). Royal Thai Government Gazette: Bangkok, Thailand. (in Thai)

[18] Røed, N.M.A., 2018. IEC/IEEE International Standard—Utility Connections in Port—Part 1: High Voltage Shore Connection (Hvsc) Systems—General Requirements. IEEE: New York, NY, USA. DOI: https://doi.org/10.1109/IEEESTD.2019.8666180

[19] Port Authority of Thailand (PAT), 2023. State Enterprise Plan of the Port Authority of Thailand, Fiscal Years 2023–2027 (Revised Edition for Fiscal Year 2023). PAT: Bangkok, Thailand. (in Thai)

[20] Boardman, A.E., Greenberg, D.H., Vining, A.R., et al., 2018. Cost-Benefit Analysis: Concepts and Practice, 5th ed. Cambridge University Press: Cambridge, UK. DOI: https://doi.org/10.1017/9781108235594

[21] Yin, M., Wang, Y., Zhang, Q., 2020. Policy implementation barriers and economic analysis of shore power promotion in China. Transportation Research Part D: Transport and Environment.

87, 102506. DOI: https://doi.org/10.1016/j.trd.2020.102506

[22] Daniel, H., Trovão, J.P.F., Boulon, L., et al., 2025. Shore power deployment strategies and policies including alternative fuels. Transportation Research Part D: Transport and Environment. 148, 104999. DOI: https://doi.org/10.1016/j.trd.2025.104999

[23] Qi, J., Wang, S., Peng, C., 2020. Shore power management for maritime transportation: Status and perspectives. Maritime Transport Research. 1, 100004. DOI: https://doi.org/10.1016/j.martra.2020.100004

[24] Kim, A.-R., Seo, J., Seo, Y.-J., 2023. Key barriers to adopting onshore power supply to reduce port air pollution: Policy implications for the maritime industry in South Korea. Marine Policy. 157, 105866. DOI: https://doi.org/10.1016/j.marpol.2023.105866

[25] Innes, A., Monios, J., 2018. Identifying the unique challenges of installing cold ironing at small and medium ports—The case of Aberdeen. Transportation Research Part D: Transport and Environment. 62, 298–313. DOI: https://doi.org/10.1016/j.trd.2018.02.004

[26] Selén, V., 2023. Addressing Ship Emissions at Berth: Onshore power supply where it makes sense. IEEE Electrification Magazine. 11(1), 25–32. DOI: https://doi.org/10.1109/MELE.2022.3232979

[27] Konstantinidis, G., Paspatis, A., Karapidakis, E., 2023. An Optimal Scheduling Tool for the Realization of Onshore Power Supply at Seaports with Limited Power Supply from the Distribution Grid. In Proceedings of the 2023 IEEE Belgrade PowerTech, Belgrade, Serbia, 25 June 2023; pp. 1–5. DOI: https://doi.org/10.1109/PowerTech55446.2023.10202891