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TECHNO-ECONOMIC FRAMEWORK AND MICROGRID OPTIMIZATION FOR SMART RENEWABLE ENERGY LOGISTIC PORTS (SRE-LP) IN ARCHIPELAGIC MARITIME NETWORKS: A SCENARIO-BASED ASSESSMENT FOR INDONESIA

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ABSTRACT

Ports in Indonesian archipelagic logistics face growing demand for reliable terminal electricity and lower emissions from ships at berth. This study develops a transparent scenario-based techno-economic framework for a Smart Renewable Energy Logistic Port (SRE-LP) combining solar photovoltaics (PV), coastal wind generation, lithium iron phosphate battery energy storage (BESS), high-voltage onshore power supply (OPS), and an integrated energy management system (EMS). Official Indonesian maritime statistical publications are used to establish the policy and data context; technology architecture and evaluation metrics are grounded in traceable international standards and peer-reviewed research. The configuration assessed is a proposed 12.5-MWp PV system, 4.5-MW wind cluster, 8-MWh/4-MW BESS and two OPS connection points totaling 4.5 MW. Using the draft's hypothetical capital expenditure of US$18.45 million, constant annual net savings of US$3.42 million, a 20-year period and 8.5% discount rate, an arithmetic recalculation yields an illustrative net present value of US$13.91 million, internal rate of return of 17.84%, and discounted payback of 7.53 years. Direct vessel-at-berth emissions potentially avoided by OPS must be evaluated together with grid-generation emissions. Because audited tariff records, hourly metering, emission factors and field validation were not supplied, these results represent scenario calculations, not proven operational performance at Indonesian ports.

Keywords: Battery Energy Storage; Green Port; Indonesia; Onshore Power Supply; Port Microgrid; Renewable Energy; Shore Power.

1. Introduction

Maritime infrastructure is critical for an archipelagic economy. Indonesia's Badan Pusat Statistik (BPS) publishes annual information on cargo handling, ship visits, and passenger transport, providing an appropriate secondary-data basis for maritime planning [1], while its marine and coastal-resource series contextualizes the broader blue economy [2]. Neither publication alone, however, verifies the port-by-port power demand, equipment energy profiles, or project cost assumptions used in a particular microgrid feasibility study.

The International Maritime Organization adopted the 2023 GHG Strategy targeting net-zero emissions from international shipping by or around 2050, with indicative global 2030 and 2040 checkpoints [3]. Carbon Intensity Indicator (CII) ratings are vessel-level regulatory measures; they should not be equated directly with a port's grid emissions or a project-level lifecycle calculation [4]. Shore power can eliminate local combustion by connected onboard auxiliary generators but does not necessarily eliminate upstream electricity emissions [8].

This paper retains the proposed Indonesian SRE-LP concept from the submitted manuscript, focusing on the Tanjung Perak–Makassar logistics context, while separating verifiable knowledge, transparent scenario inputs and data still requiring field measurement. Its contribution is a reproducible power-balance, investment and emissions-accounting framework rather than an unsubstantiated claim that a microgrid has been installed or experimentally validated.

2. Literature Review

2.1 Shore power, port microgrids, and renewable integration

Abu Bakar et al. synthesize technical, standardization, economic and emissions challenges of shore power and explicitly discuss its interaction with port microgrids [8]. Binot et al. propose a combined cost-and-CO2 optimization approach for photovoltaic-based seaport microgrids, demonstrating that storage, grid imports, berth loads and lifecycle emissions must be modeled jointly [6]. Lamprinidi et al. evaluate how PV deployment, shore electricity tariffs and vessel load profiles affect the feasibility of cold ironing [7]. These results support the SRE-LP architecture, but do not verify the local costs or generation yields assumed for Indonesian ports.

2.2 Smart ports, EMS and digital monitoring

A scientific review of smart ports identifies digital logistics, security and green-port operations as active research themes [9]. Helo and Thai analyze practical tracking technologies and business-case considerations in Logistics 4.0 [10], while Zhang et al. discuss digitalization and environmental performance of maritime ports [11]. Energy monitoring and continuous improvement can additionally be organized under ISO 50001 [12]. Together these references justify telemetry, forecasting and dispatch functions without establishing any particular percentage reduction in port charges.

2.3 Interface standards and regulatory limits

IEC/IEEE 80005-1 describes high-voltage shore-connection system requirements, including converters, transformers, interlocks and the shore–ship interface [5]. A nominal 6.6-kV/60-Hz design cannot be asserted as universally compatible with all Indonesian vessels without berth-specific voltage and frequency surveys. Under IMO CII rules, a D rating for three consecutive years or E in one year prompts a corrective action plan; an OPS project alone cannot guarantee an A rating [4].

Table 1. Traceable literature and its relevance to the SRE-LP proposal

Evidence	Verified Topic	Application / Limitation
Abu Bakar et al. [8]	Review of OPS, economics and standards	Technical foundation; not Indonesian pilot evidence
Binot et al. [6]	PV-based seaport microgrid optimization	Model costs and emissions jointly
Lamprinidi et al. [7]	PV + OPS financial assessment	Tariffs and vessel demand are essential
Alzate et al. [9]; Zhang et al. [11]	Smart-port and green-port literature	Digital layer rationale; no local savings proof
IEC [5]; IMO [3], [4]	Shore connection and ship emissions rules	Specific engineering and regulatory constraints

3. Materials and Methodology

3.1 Study scope and provenance of inputs

This is a prospective engineering and financial scenario study. The Tanjung Perak (Surabaya) and Soekarno-Hatta (Makassar) port context, the 600-TEU feeder example, and all proposed power-system sizes were carried forward from the author-supplied draft; they have not been independently measured or presented as existing installed capacity. BPS maritime publications [1], [2] are verified as existing official sources, but numerical claims about 78.71 million tons of cargo, 893,258 vessels and port dwell times were not retained as sourced measurements because the corresponding original tables and definitions were not supplied or corroborated.

3.2 Load, dispatch and constraints

At each hour t, the port electricity demand is the sum of crane, yard, reefer and vessel shore-connection loads. Generation and storage dispatch must satisfy the power-balance identity, component ratings, battery-state-of-charge limits, availability of each vessel interface and relevant operating reserves [5]–[8].

$$P_{load}(t) = P_{cranes}(t) + P_{yard}(t) + N_{reefer}(t) \times P_{ref} + \Sigma P_{OPS,i}(t)$$

$$P_{PV}(t) + P_{wind}(t) + P_{dis}(t) + P_{grid}(t) = P_{load}(t) + P_{ch}(t) + P_{loss}(t)$$

P_loss explicitly captures conversion and distribution losses omitted from the original simplified expression. A time-indexed battery model must track charge and discharge efficiency and state-of-charge; simultaneous charging and discharging are prohibited. A robust EMS should minimize discounted electricity and equipment costs subject to berth service quality, demand-peak constraints and emissions objectives [6], [12].

3.3 Economic and environmental indicators

$$NPV = -CAPEX_0 + \Sigma[t=1\ldots N]\ (\text{Net cash flow}_t)/(1+r)^t$$

LCOE = (discounted capital + O&M + replacement costs − residual value) / discounted delivered energy

Internal rate of return (IRR) is the discount rate at which NPV equals zero. Discounted payback is the first period when cumulative discounted cash flows recover initial investment. Net lifecycle reduction requires subtracting indirect emissions from grid power, PV/wind/BESS supply-chain and losses from the auxiliary-engine baseline. These formulas cannot support an empirical LCOE or Well-to-Wake (WtW) percentage without time-series data and explicit system boundaries.

4. Results and Discussion

4.1 Proposed SRE-LP functional architecture

The draft's four functional layers can be organized as renewable/grid input, power conversion and BESS, predictive dispatch/EMS, and terminal/vessel loads. The proposed topology is shown in Figure 1, as an engineering concept, not an as-built diagram.

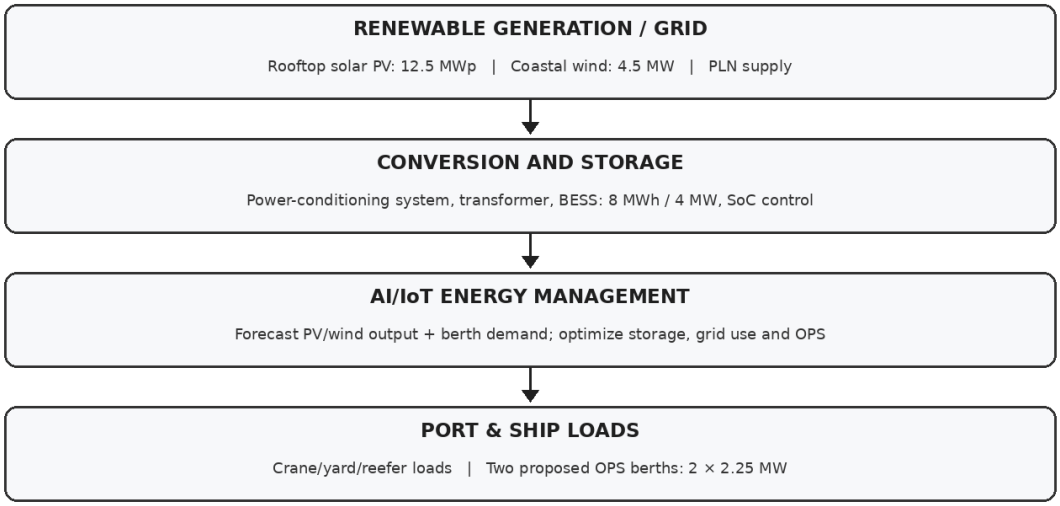


Figure 1. Conceptual four-layer SRE-LP microgrid; all ratings are draft design assumptions

4.2 Technical sizing and implied generation factors

Table 2 preserves the author's component sizing for reproducibility. Its annual energy figures imply a PV capacity factor of 16.67% and wind capacity factor of 22.48%, calculated as annual energy divided by rated capacity and 8,760 hours. These are internally consistent arithmetic assumptions but not measured yield estimates. The total CAPEX component sum equals US$18.45 million.

Table 2. Proposed equipment schedule and source status (not installed-system specifications)

Component	Scenario Rating	Output / Budget in Original Draft
Rooftop PV	12.5 MWp	18,250 MWh/yr; US$8,125,000
Coastal wind	3 × 1.5 MW	8,860 MWh/yr; US$4,950,000
LFP BESS	8 MWh / 4 MW	6,400 MWh annual throughput; US$2,800,000
Two OPS berths	2 × 2.25 MW	Peak 4.5 MW; US$2,100,000
EMS + metering	SCADA/EMS concept	US$475,000

Component	Scenario Rating	Output / Budget in Original Draft
TOTAL	17 MW nameplate generation	27,110 MWh/yr assumed; US$18,450,000

The BESS throughput should not be added to PV plus wind generation because it represents energy shifting rather than net primary electricity production. Curtailment, inverter losses, power-factor requirements, berth availability and any mismatch between vessel and shore frequencies are additional design issues that require study.

4.3 Transparent financial recalculation

Using the original draft's explicit baseline assumptions of US$18.45 million initial CAPEX, US$3.42 million constant annual NET cash benefit, 8.5% annual discount rate and a 20-year operating period, the recalculated values are NPV = US$13.915 million, IRR = 17.84%, and discounted payback = 7.53 years. Simple payback is 5.39 years. This cash-flow-only example excludes inflation, revenue escalation, replacement expenditures, salvage value, taxes and finance structure. Its figures supersede the draft's mathematically incompatible 16.8% IRR and 5.2-year discounted payback, but they are not verified investment forecasts.

Table 3. Audit of key techno-economic assumptions and results

Metric	Draft Assumption	Arithmetic / Interpretation
PV generation	12.5 MWp; 18,250 MWh/year	Implied capacity factor = 16.67%; not measured
Wind generation	4.5 MW; 8,860 MWh/year	Implied capacity factor = 22.48%; not measured
Total energy	27,110 MWh/year	18,250 + 8,860; excludes losses/curtailment
Capital cost	US$18.45 million	Sum of five draft component budget lines
Annual net savings	US$3.42 million/year	Assumption; needs tariff/load/maintenance breakdown
NPV (20 yr; 8.5%)	US$13.915 million	Uniform net annual cash flow, no degradation/replacements
IRR (20 yr)	17.84%	Uniform annual net cash flow assumption
Discounted payback	7.53 years	Linear interpolation between years 7 and 8

The source manuscript's LCOE of US$0.078/kWh cannot be reproduced from the listed aggregate inputs: it requires annual net electricity actually delivered and cost streams over the technology life, including BESS replacements and losses. Similarly, projected reductions in grid demand charges or electricity tariffs need published tariffs and load profiles, which were not provided.

4.4 Boundary-corrected assessment of berth emissions

The draft posits 48 port calls per vessel annually, 2.5 days at berth per call, and auxiliary fuel use of 2.85 t/day. Multiplication gives 342 t fuel/year; applying the draft's illustrative 3.206 t CO_2/t fuel gives 1,096.45 t CO_2/year per vessel and 14,253.88 t CO_2/year across 13 identical vessels. These figures are CONDITIONAL avoided *onboard combustion* values: they do not establish net avoided CO_2 or WtW performance, as emissions from OPS electricity and infrastructure must be accounted for. The initial paper's 14,280-t and 62.4% savings claims lack the necessary net electricity/emissions ledger.

Moreover, an asserted improvement from an EEOI of 18.45 to 11.32 g CO_2/(t·NM) does not automatically establish a change from IMO CII D to A: CII depends on vessel category, size, annual reporting and the applicable reference line [4]. A ship-level audit is required before assigning any rating.

5. Conclusion

The SRE-LP approach is technically plausible as a planning framework for archipelagic logistics ports, with a conceptual integration of 12.5-MWp PV, 4.5-MW wind, 8-MWh battery storage, 4.5-MW OPS and IoT-enabled EMS. Peer-reviewed literature supports investigating such hybrids, and internationally recognized shore-connection standards define essential safety and interoperability

controls [5]–[8]. However, the submission does not establish operational field validation at Tanjung Perak or Makassar.

Policy Recommendations

A transparent financial recalculation of the manuscript's unchanged assumptions yields an illustrative NPV of US$13.91 million, IRR of 17.84% and discounted payback of 7.53 years. No net GHG reduction, life-cycle intensity reduction or attained IMO CII rating can be substantiated without measured energy, fuel, grid emission factors and vessel records. Before investment or publication claims are finalized, the authors should collect at least one representative year of 15–60-minute load data, berth schedules, renewable resource measurements, tariff and hardware quotations, and a documented emissions baseline.

Acknowledgment

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