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Planning Sustainable Dry Port Supply Chains Through Renewable Energy Availability Assessment

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ABSTRACT

Dry ports have emerged as critical nodes in modern supply chains, yet their operations remain highly energy-intensive and largely dependent on fossil fuels. This study investigates the planned Jeneponto Dry Port in South Sulawesi, Indonesia, as a prototype of a "green by inception" logistics hub where renewable energy is embedded from the design stage. A mixed-methods approach was employed, integrating supply chain mapping, energy demand forecasting for the period 2025-2034, renewable resource assessment, and benchmarking with existing dry ports, such as Cikarang and New Priok. Results show that the Jeneponto Dry Port will require approximately 5.17 GWh of electricity in 2025, with demand projected to grow by 3.5% annually. This requirement can be met sustainably through hybrid systems that leverage abundant solar irradiation and wind energy, particularly from the Tolo Wind Farm. Comparative analysis highlights that a modular, medium-scale development strategy supported by renewable-powered equipment such as electric forklifts and solar reefer is technically feasible and environmentally beneficial. The study contributes theoretically by reframing dry ports as socio technical systems where renewable integration at the design stage prevents fossil-fuel lock-in, a departure from retrofitting approaches dominant in Western port studies. Practically, it establishes the first energy intensity benchmark (27.5 kWh/TEU) and phased decarbonization pathway for medium-scale dry ports in underrepresented Eastern Indonesian regions. Practically, it provides a transferable model for emerging economies to align dry port development with national energy transition targets and regional economic diversification.

1. INTRODUCTION

Ports and dry ports have long been recognized as pivotal nodes in global and domestic supply chains, facilitating multimodal connectivity and supporting international trade. However, their operations are highly energy-intensive, with cargo handling, warehousing, lighting, and refrigerated storage contributing significantly to energy demand and greenhouse gas (GHG) emissions [1, 2]. According to the International Maritime Organization (IMO, 2023), port-related activities account for nearly 3% of global GHG emissions, and without intervention, this share is expected to rise as global trade expands. To address these challenges, the IMO and the United Nations Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action), have emphasized the need for ports and dry ports to undergo a rapid energy transition.

In Indonesia, the strategic role of logistics infrastructure is formalized in Presidential Regulation number 26/2012 on the National Logistics System Blueprint, which envisions a "locally integrated and globally connected" network by 2025. Yet, logistics operations remain among the most energy-intensive sectors, with port activities alone estimated to contribute more than 12% of the transport sector's total emissions [3]. The Indonesian National Energy General Plan (RUEN) further mandates that by 2030, at least 15-20% of energy consumption in industrial and logistics zones must come from renewable sources [4]. This policy shift places ports and dry ports at the center of Indonesia's decarbonization agenda, demanding innovative approaches to align infrastructure development with energy transition targets.

Despite substantial progress in Western Indonesia, particularly Java and Sumatra, renewable integration in logistics infrastructure remains limited in Eastern regions. This imbalance is paradoxical given that provinces such as South Sulawesi possess abundant renewable resources, including solar irradiation exceeding 5 kWh/m²/day and proven wind potential through large-scale projects like the Sidrap (75 MW) and Tolo (72 MW) wind farms [5, 6]. These resources have not been systematically leveraged to support logistics infrastructure, with investments still concentrated in conventional energy systems.

Jeneponto as one of the regencies in South Sulawesi, Indonesia presents a promising potential for the establishment of a dry port due to its strategic location and growing energy infrastructure. The case of Jeneponto Regency illustrates both a challenge and an opportunity. On one hand, the region remains underserved in terms of large-scale logistics infrastructure, limiting its role in national and international trade networks. On the other hand, it is uniquely positioned with access to both conventional and renewable power plants, including Punagaya Steam Power Plant and Tolo Wind Power Plant, enabling the development of low-emission industrial zones and green logistics hubs [7]. Harnessing this dual energy capacity could transform Jeneponto into a prototype for sustainable dry port development in Eastern Indonesia.

From a theoretical perspective, this research builds upon sustainability transition theory and socio-technical systems analysis. Ports and dry ports are not merely infrastructural nodes but socio-technical systems where technological choices, institutional frameworks, and stakeholder dynamics intersect. Transition studies emphasize that embedding renewable energy "from inception" can prevent technological lock-in to fossil-fuel systems, accelerate learning curves, and enhance resilience [8]. Applying this perspective to dry port planning enables the reframing of energy availability not as an external constraint but as a constitutive variable in supply chain design.

Prior studies have examined renewable retrofitting in established facilities such as Cikarang Dry Port in Indonesia [4] and Jebel Ali Port in the UAE [9]. They primarily focus on technical feasibility or cost-benefit analysis. Few studies have addressed how new dry ports can be conceptualized as "green by inception," particularly in underrepresented regions of emerging economies. Moreover, there is limited integration of supply chain–oriented energy demand forecasting with renewable resource assessment, despite its importance in ensuring that logistics growth aligns with national and global sustainability targets [10, 11]. This gap is critical in the Indonesian context, where most research and investments remain Java-centric, leaving Eastern Indonesia largely unexplored in both academic and policy discourse [12, 13].

This study addresses these gaps by analyzing and optimizing renewable energy utilization in the planned Jeneponto Dry Port, South Sulawesi. Specifically, it aims to

1) What is the projected annual electricity demand range (in GWh) for Jeneponto Dry Port under a logistics growth scenario of 6% per year with 2-3% annual energy efficiency improvements over the period 2025–2034?
2) To what extent can locally available renewable energy capacity, specifically the Tolo Wind Farm (189 GWh/year) sustainably meet 100% of the dry port's operational electricity demand?
3) What is the potential CO_2 emission reduction (in tons/year) achievable by utilizing renewable energy instead of conventional grid electricity, based on Indonesia's grid emission factor?

The novelty of this study lies in its conceptualization of a dry port as "green by inception," embedding renewable integration into infrastructure design rather than retrofitting conventional systems. Theoretically, it extends the literature by situating dry port development within sustainability transition frameworks, highlighting the centrality of energy in supply chain resilience. Practically, it provides policymakers and practitioners with a scalable, regionally tailored model for green logistics hubs in emerging economies, offering insights transferable beyond Indonesia.

To guide the study, a conceptual framework is developed that connects the global and national policy context with the research gap, theoretical foundation, and objectives of this work. It positions Jeneponto Dry Port within sustainability transition theory, emphasizing the shift from fossil-based retrofitting to a "green by inception" model. The framework also outlines how energy demand forecasting, renewable integration, and benchmarking are combined to produce both theoretical and practical contributions. Figure 1 illustrates this logical sequence.

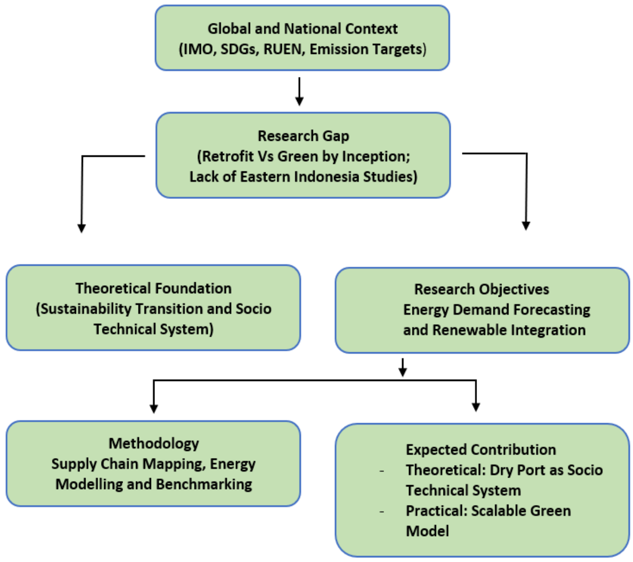

Figure 1. Conceptual framework

Figure 1 illustrates the conceptual framework of this study. It connects global and national sustainability agendas with the research gap, emphasizing the absence of "green by inception" dry ports in Eastern Indonesia. Guided by sustainability transition and socio-technical systems theory, the framework defines three main objectives: forecasting energy demand, integrating renewable resources, and formulating strategic pathways. These objectives are operationalized through supply chain mapping, energy modeling, and benchmarking, leading to both theoretical contributions framing dry ports as socio-technical systems and practical outcomes, namely a scalable model for renewable-powered logistics hubs in emerging economies. The framework also operationalizes research questions into measurable metrics which is annual energy demand (GWh), renewable availability ratio (%), and CO_2 reduction potential (ton/year).

2. METHOD

This study employed a mixed-methods approach, integrating quantitative forecasting with qualitative stakeholder analysis to ensure methodological triangulation. Primary data were obtained through field surveys and semi-structured interviews with 10 key informants, including local government officials, logistics operators, and port authorities, selected via purposive sampling. Secondary data were drawn from Statistics Indonesia, the Ministry of Energy and Mineral Resources, and technical reports on renewable capacity in South Sulawesi.

2.1 Research framework

The overall research process followed these sequential stages:

a. Supply Chain Mapping based on comparative benchmarking: Identification of operational nodes and activities in existing dry ports (e.g., Cikarang Dry Port, New Priok Container Terminal (NPCT), and Samudra Indonesia Container Port) including cargo handling, warehousing, storage, inventory management, and distribution.
b. Energy Demand Assessment and renewable potential analysis: Quantification of current and projected energy requirements for each operational stage, based on empirical data, equipment specifications, and throughput projections.

2.2 Data collection

Data was obtained from multiple sources:

a. Primary Data are field surveys in Jeneponto Regency, covering potential dry port sites, existing energy infrastructure, and transport connectivity. Semi-structured interviews were conducted with representatives from provincial and regency governments, logistics operators, port authorities, and local communities. Interview transcripts were analyzed using descriptive qualitative synthesis, a method appropriate for exploratory feasibility studies where the objective is to identify stakeholder perspectives rather than develop new theoretical constructs.
b. Secondary Data are published statistical reports, energy production and consumption data from the Ministry of Energy and Mineral Resources (ESDM) and Statistics Indonesia, as well as technical reports on renewable energy capacity in South Sulawesi.

3. RESULT AND DISCUSSION

3.1 Supply chain mapping

Dry ports function as inland extensions of seaports, facilitating the transfer of goods between maritime and land transport. The supply chain identification process in this study followed the conceptual framework of Rodrigue and Notteboom [14], mapping operational components such as:

a. Terminal operations and cargo handling systems.
b. Transportation connectivity (road and potential rail).
c. Warehousing and storage facilities.
d. Ancillary services such as customs clearance and value-added logistics.

The comparative analysis of dry port and container terminal facilities is shown in Table 1. This highlights the structural and operational differences among NPCT, Samudera Indonesia Container Port, and Cikarang Dry Port, each serving a distinct function within the logistics and supply chain network. New Priok Terminal emphasizes maritime-based transport connectivity (ship–crane–dock–truck system), supported by advanced lifting equipment such as eight container cranes (50-65 tons capacity) and 24 rubber tire gantries (40 tons capacity), indicating high operational throughput efficiency. In contrast, Samudera Indonesia Port, operating under a Build, Operate, and Transfer (BOT) scheme, integrates both maritime and land-based logistics with moderate equipment capacity (33-45 tons) and a smaller stacking field of 25,000 m², reflecting a more balanced but less intensive cargo handling approach. Meanwhile, Cikarang Dry Port demonstrates a comprehensive logistics model emphasizing inland transport integration, especially rail connectivity that links Jakarta's hinterland to East Java. Its vast stacking field (2,000,000 m²) and diversified equipment portfolio signify its strategic function as an inland logistics hub supporting multimodal freight movement.

These findings align with previous studies emphasizing the importance of infrastructure capacity and multimodal integration in determining dry port performance and supply chain efficiency. Bask et al. [15] argued that inland ports' efficiency depends heavily on their ability to connect seaports through well-coordinated intermodal systems and sufficient yard capacity.

Similarly, previous study highlighted that dry ports play a pivotal role in decongesting seaport terminals by relocating storage and customs clearance inland, improving overall logistics sustainability [16]. The observed distinction between seaport terminals and inland dry ports also reflects the strategic shift toward supply chain resilience and spatial optimization of logistics activities, as noted by Sdoukopoulos and Boile [16], who suggested that hinterland connectivity determines the success of port-centric supply chains.

Table 1. Dry port/container terminal supply chain

Dry Port / Container Terminal	Warehouse	Equipment	Stacking Field
New Priok Container Terminal	-	8 container cranes with single capacity of 50 tons and twin lift capacity of 65 tons, and 24 rubber tire gantry with single capacity of 40 tons.	5,877 m^2
Samudera Indonesia Container Port	-	4 units of container cranes with 33- and 36-tons capacity, 5 units of RTG with 40 tons capacity and 5 units of reach stacker with 45 tons capacity.	25,000 m^2
Cikarang Dry Port	Bonded logistics warehouse of 11,960 m^2, Consolidated warehouse of 82,293 m^2.	Reefer plug 128 pieces, for 20 and 40 feet, container crane 2 pieces 40 tons capacity, Rubber Tired Gantry (RTG) 5 pieces 40-50 tons capacity, reach stacker 9 pieces 45 tons capacity, side loader 2 pieces 35 tons capacity, forklift 15 pieces 10-32 tons capacity, terminal tractor and chassis 50 pieces for 20- and 40-feet container.	2,000,000 m^2

Table 2. Comparison of existing dry port and adaptation strategy for Jeneponto

Aspects	Existing Dry Port	Adaptation Strategy for Jeneponto
Location	Jabodetabek industrial area	Potential industrial and agricultural areas in South Sulawesi
Mode Connectivity	Road and rail (Surabaya-Jakarta)	Highway (Makassar-Takalar-Bantaeng), potential future rail
Logistics Warehouse Area	11,960 m² (bonded logistics), 82,293 m² (consolidation)	Minimum 5,000 m² for initial phase, phased according to cargo volume
Stacking Field	2,000,000 m²	Medium scale (100,000-250,000 m²), depending on growth
Operational Equipment	RTG, reach stacker, forklift, crane, reefer plug	Renewable energy-based modular equipment (solar-powered reefer, electric forklift)
Energy and Emissions	Using conventional energy (electricity and solar)	Solar panel integration, hybrid microgrid, battery storage
Business Model	Private (integration with national logistics operator)	Local government-private collaboration (PPP or BOT scheme)
Service Functions	Export-import, domestic distribution, warehouse	Agrologistics, export of fishery and agricultural products, warehouse

In terms of energy and sustainability perspectives, the infrastructure utilization observed in these facilities suggests a growing potential for renewable energy integration within logistics operations. Optimizing energy consumption in cargo handling, warehousing, and transport modes is crucial for achieving carbon reduction targets within supply chain systems [17].

Therefore, mapping supply chain activities through infrastructure and equipment analysis provides not only a spatial understanding of logistics flow but also a foundation for assessing renewable energy adoption potential, particularly in energy-intensive nodes like Cikarang Dry Port.

By examining the supply chain structure of existing dry ports, adaptive strategies can be formulated for developing the Jeneponto Dry Port.

The adaptation strategy for developing a dry port in Jeneponto, as outlined in Table 2, illustrates a context-sensitive approach that aligns with both regional characteristics and sustainable logistics objectives. Unlike existing dry ports located in the Jabodetabek industrial zone that primarily serve dense industrial and trade activities, Jeneponto's proposed dry port leverages its strategic position in South Sulawesi's emerging industrial and agricultural corridor. The location's proximity to both agricultural production areas and Makassar's main logistics routes positions it as a potential agro-logistics hub. This approach mirrors findings by Bask et al. [15] and Bergqvist and Monios [18], which emphasize that successful dry port models must be adapted to regional economic profiles and resource potentials rather than merely replicating existing structures.

From a logistics and infrastructure standpoint, the Jeneponto dry port design proposes scalable development to accommodate phased growth in cargo volume. This incremental model supports flexible expansion based on trade demand, consistent with Nguyen and Notteboom [19], who observed that adaptive capacity in dry port infrastructure is key to maintaining economic feasibility in emerging regions.

Operationally, Jeneponto's strategy introduces renewable-energy-based modular equipment, including solar-powered reefers and electric forklifts, representing a shift toward low-carbon logistics systems. This transition aligns with Hasnat [20] and Parhamfar et al. [21], who advocate for integrating renewable technologies into port operations to reduce emissions and operational costs while enhancing long-term sustainability.

Energy management is central to Jeneponto's adaptation framework. Unlike the conventional energy systems used in existing dry ports, the proposed model incorporates solar panel integration, hybrid microgrids, and battery storage systems that are suitable for regions with high solar potential such as South Sulawesi. This approach supports the concept of energy-resilient dry ports described by Khaslavskaya and Roso [22], where decentralized renewable systems ensure energy security while minimizing environmental impact.

The business model further emphasizes public-private collaboration (PPP or BOT schemes), promoting investment sharing and institutional synergy [23]. Finally, by focusing on agro-logistics and the export of fishery and agricultural products, the Jeneponto dry port expands the traditional function of dry ports from purely industrial logistics into a driver of rural economic transformation, ensuring alignment with sustainable regional development goals.

3.2 Energy demand and availability

The annual energy requirement data from the NPCT is used as a reference to illustrate the energy requirements of a small-scale dry port as shown in Table 3. The annual energy consumption profile of this dry port facility, totaling 89,373,325 kWh per year. The breakdown indicates that energy use is heavily concentrated in operational and administrative activities, revealing critical insights for energy optimization and renewable energy integration strategies.

The largest energy consumer is the office buildings, accounting for 42,931,651 kWh/year, or nearly 48% of total energy consumption. This dominance suggests that administrative operations, lighting, air conditioning, and information systems represent major energy loads. This result is consistent with findings by Kong et al. [24], who noted that non-transportation facilities in logistics complexes often contribute significantly to overall emissions due to continuous operation and limited energy efficiency measures.

The loading and unloading equipment category follow as the second largest consumer, at 31,326,160 kWh/year (35%), reflecting the intensive electricity demands of cranes, reach stackers, and forklifts used in container handling. Studies have emphasized that transitioning this equipment to electrified or hybrid renewable-powered systems (e.g., solar-assisted RTGs, electric forklifts) can dramatically reduce both energy use and CO_2 emissions [25, 26].

Other notable contributors include warehouse and workshop operations, consuming 3,029,098 kWh and 3,732,731 kWh respectively, highlighting opportunities for implementing solar rooftop systems and energy-efficient lighting or HVAC technologies. In contrast, supporting infrastructure such as yard lighting, street lighting, and reefer containers collectively consume less than 6% of total energy, but their continuous 24-hour operation makes them ideal for dedicated renewable microgrid integration (e.g., solar-powered lighting systems). Worshipatively smaller consumption by onshore power supply, cellular BTS, and worship facilities suggests marginal impact but potential for full renewable substitution.

Energy utilization at NPCT is shown in Table 4.

The annual electricity demand for Jeneponto Dry Port was estimated using an energy intensity scaling approach based on empirical data from NPCT, a comparable small-scale dry port facility in Indonesia. The methodology follows three sequential steps:

$$EI_{NPCT} = \frac{E_{NPCT}}{A_{NPCT}} = \frac{89.37\ GWh/year}{32\ ha} = 2.739\frac{GWh}{ha}/year$$

where,

EI_{NPCT} = Energy intensity of NPCT,

E_{NPCT} = Total annual energy consumption of NPCT (89.37 GWh/year) from Table 3,

A_{NPCT} = Total operational area of NPCT (32 ha) from Table 4.

Apply intensity to Jeneponto Dry Port area

$$E_{Jeneponto} = EI_{NPCT} \times A_{Jeneponto} \times (1 + \sigma)$$

$$E_{Jeneponto} = 2.793\ {}^{GWh}/_{ha.year} \times 1.85\ ha \times (1 + 0.20)$$

$$E_{Jeneponto} = 5.17\ GWh/year$$

where,

$A_{Jeneponto}$ = Planned operational area of Jeneponto Dry Port 1.85 ha (as shown in Table 5).

Table 3. Energy requirements of New Priok Container Terminal

No	Description	Annual Energy Consumption (kWh)
1	Loading and Unloading Equipment	31,326,160
2	Onshore Power Supply	133,166
3	Cellular BTS	273,004
4	Warehouse	3,029,098
5	Workshop	3,732,731
6	Office Buildings	42,931,651
7	Container Office	683,528
8	Retail Area	104,627
9	Worship Facility	334,538
10	Vessels	10,176
11	Factory	1,808,625
12	Street Lighting	477,796
13	Yard Lighting	2,820,060
14	Reefer	1,708,165
	Total Energy Consumption	**89,373,325**

Table 4. Energy utilization at NPCT 1

No	Description	Details
1	Dry Port Area	32 hectares
2	Number of Loading/Unloading Equipment	32 units
3	Annual Container Throughput	1,322,086 Teus
4	Container Yard Area	5,877 m^2
5	Energy Consumption	89.37 GWh (Table 3)

The total dry port area of 32 hectares indicates a medium-sized facility capable of accommodating significant logistics operations while maintaining manageable energy and spatial efficiency. This land allocation aligns with typical dry port scales observed in emerging logistics hubs, where land utilization efficiency is a critical determinant of throughput and service capacity. The presence of 32 units of loading and unloading equipment suggests a high operational capacity relative to the yard area, implying that the terminal is designed for intensive container handling operations. This equipment density supports an annual throughput of 1,322,086 TEUs, reflecting a performance level comparable to secondary maritime terminals or large-scale inland ports. However, the container yard area of only 5,877 m² appears relatively compact compared to the throughput volume, which suggests that efficient stacking systems, dynamic container flow, and high equipment utilization are employed to optimize spatial constraints.

Table 5. Estimated energy consumption of Jeneponto dry port (Based on NPCT comparison)

No	Description	Details
1	Dry Port Area	1.85 hectares
2	Number of Loading/Unloading Equipment	9 units
3	Annual Container Throughput	188,041 Teus
4	Container Yard Area	1,279 m^2
5	Estimated Energy Consumption	5.17 GWh

The annual energy consumption of 89.37 GWh underscores the energy-intensive nature of dry port operations. The significant energy use is primarily attributed to cargo handling machinery, lighting systems, and office operations. When correlated with the throughput data, this results in an approximate energy intensity of 67.6 kWh per TEU, a metric that can serve as a benchmark for evaluating energy efficiency improvements in future dry port developments. As emphasized in previous study, such data-driven assessments are essential for identifying opportunities to integrate renewable energy technologies and hybrid power systems to reduce operational costs and carbon emissions [27].

Table 6 presents an estimation of electrical load composition based on the operational categories of a dry port, including office buildings, cargo handling equipment, warehouses, yard lighting, reefer containers, and other supporting facilities. This data is used as a basis for planning electricity demand and for developing renewable energy systems at Jeneponto Dry Port.

Based on the estimated energy demand of the Jeneponto Dry Port, the subsequent analysis focuses on assessing the availability of energy resources in South Sulawesi that can supply and sustain the port's operational energy requirements.

Table 7 provides an overview of the major power generation facilities in South Sulawesi, consisting of a mix of steam, hydro, and wind power plants with a total combined capacity of approximately 1,362 MW. The largest contributor is the Bakaru Hydropower Plant, generating 400 MW, followed by the Punagaya Steam Power Plant with 260 MW, and the Larona Hydropower Plant with 165 MW. These three facilities alone account for more than 60% of the total installed capacity in the region. Among all the regions, Jeneponto emerges as a strategic location. It is home to a significant conventional power source (Punagaya steam power plant) and a renewable one (Tolo wind power plant). This dual capability opens vast potential for developing low emission industrial zones, smart logistics hubs, or green dry ports, which are a hybrid of renewable and conventional sources.

Table 7 shows projected renewable energy from Tolo wind power. With a total annual production of 189 GWh, the available energy capacity is sufficient to meet the estimated energy demand of the Jeneponto Dry Port, which is 5.17 GWh per year, as shown in Table 5. This indicates that the existing power generation in Jeneponto regency provides a strong potential for integrating renewable energy sources into the development of the Jeneponto Dry Port.

Table 6. Estimated load composition for Jeneponto dry port (2025)

Category	Consumption (GWh)	% of Total	Avg Load (kW)	Peak Load (kW)	Electrification Rate
Office Buildings (HVAC, lighting, IT)	2.48	48	283	435	100%
Cargo Handling Equipment	1.81	35	207	400	30% (forklift 40%, RTG 10%, reach stacker 20%)
Warehouse Operations	0.39	7.6	45	70	100%
Yard & Street Lighting	0.19	3.7	22	35	100% LED
Reefer Containers	0.10	1.9	11	25	100%
Ancillary (BTS, retail, worship)	0.2	3.8	23	35	100%
TOTAL	5.17	100	591	1,000	-

σ = Variations in energy intensity across Southeast Asian dry ports (15-25%) as reported by Nguyen and Notteboom [19] for emerging logistics hubs with comparable scale and climatic conditions.

Table 7. Power plants in South Sulawesi

No	Name	Type of Plant	Capacity
1	Punagaya	Steam Power	260 MW
2	Barru	Steam Power	100 MW
3	Larona	Hydro Power	165 MW
4	Malea	Hydro Power	90 MW
5	Bakaru	Hydro Power	400 MW
6	Balambano	Hydro Power	110 MW
7	Karebbe	Hydro Power	90 MW
8	Sidrap	Wind Power	75 MW
9	Tolo	Wind Power	72 MW

Table 8. Projected renewable energy supply at dry port Jeneponto

Component	Value	Description
Capacity	72 MW	Tolo wind power capacity/year
Production	189 GWh	Tolo wind power production capacity/year
Factor Capacity	30%	Tolo wind power factor capacity/year

Ten-Year Projection (2025-2034) on green energy supply and demand at the Jeneponto Dry Port estimate using basic assumption:

a. Initial renewable energy capacity (2025) 5.17 GWh per year (according to the estimated consumption during Dry Port development)
b. Logistics volume expansion: +6% per year (based on Indonesia's national logistics growth projection under Presidential Regulation No. 26/2012 and Statistics Indonesia's regional trade forecasts for Eastern Indonesia)
c. Energy efficiency improvements: 2.5% per year (midpoint of 2-3% range, reflecting progressive adoption of electric equipment, smart grid deployment, and LED lighting retrofits as outlined in Table 8 descriptions)
d. The net growth rate is calculated using the multiplicative energy decomposition formula [27]

$$(1 + r_{net}) = (1 + r_{volume}) \times (1 + r_{efficiency})$$
$$(1 + r_{net}) = (1 + 0.06) \times (1 - 0.025)$$
$$(1 + r_{net}) = 1.06 \times 0.975$$
$$(1 + r_{net}) = 1.0335$$
$$r_{net} = 1.0335 - 1$$
$$r_{net} = 0.0335$$
$$r_{net} = 3.5\%/year$$

The projected energy demand of the Jeneponto Dry Port over a ten-year period is presented in Table 9. This data illustrates a gradual and controlled growth pattern from 5.17 GWh in 2025 to 7.00 GWh by 2034 corresponding to an annual net increase of approximately 3.5%. This trend reflects a realistic estimation of energy escalation driven by rising logistics volume and the progressive adoption of electrified port operations.

Table 9. Projected energy demand at Jeneponto dry port

Year	Energy Requirements (GWh)	Description
2025	5.17	Dry port initial load (fully operational)
2026	5.33	Start of increased logistics activity
2027	5.51	Partial adoption of electric vehicles
2028	5.70	Expansion of the container stacking area
2029	5.90	Start of use of more reefer plugs
2030	6.11	Full implementation of smart grid phase 1
2031	6.32	Early-stage machine electrification
2032	6.54	Dry port internal electric vehicle dominance
2033	6.77	Achievement of 100% machine and vehicle electrification
2034	7.00	Addition of new logistics facilities

In the initial years, the increase is attributed to higher logistics activity and the introduction of electric vehicles, while in later years, the expansion of container areas, the addition of reefer plugs, and the implementation of smart grids contribute to higher demand. These findings are consistent with the pattern of port energy transition reported by Carrillo-Galvez et al. [27], who emphasize that energy consumption in modern ports increases gradually alongside digitalization and electrification initiatives rather than through abrupt surges.

The projection also aligns with the study of Lu et al. [28], which discusses the emergence of cyber-physical energy systems in port operations. Their research highlights that as ports adopt renewable integration, automation, and electric machinery, energy demand becomes increasingly dynamic and interconnected with logistics activities. The Jeneponto projection reflects these dynamics through its inclusion of smart grid deployment in 2030 and full electrification of machinery by 2033. These milestones correspond to the expected global transition toward energy-intensive but more efficient port infrastructures, where smart control and storage systems balance renewable generation with operational needs.

The installed capacity of Tolo Wind Farm (72 MW, around 189 GWh/year) is higher than the projected electricity demand of Jeneponto Dry Port (5.17 GWh in 2025). However, using this source for 100% renewable operation faces technical and regulatory constraints. The wind farm is connected to the 150 kV Sulawesi grid and has no dedicated line to the dry port, so electricity must be delivered through PLN's network. Under Ministerial Regulation No. 12/2023, such wheeling requires PLN approval and involves fees of 5-15% of the tariff, which could reduce economic benefits. Wind power is also intermittent, with a capacity factor of about 30%, while the dry port requires stable 24/7 electricity, especially for reefer containers. Without storage, periods of low wind could limit renewable contribution to about 40-60%. Supplying critical loads of 0.5 MW during a three-day low wind event would need roughly 2 MWh of battery storage, Therefore, a phased approach focused on rooftop solar PV which easier to implement, more feasible under current regulations is more practical in the near term, while the option of wheeling from Tolo Wind Farm should be assessed further in the detailed engineering stage.

From the statement above, based on Indonesia's grid emission factor of 0.65 kg CO_2/kWh [29], the potential CO_2 emission reduction from utilizing Tolo Wind Farm's renewable energy can be quantified as follows:

2025:

$$\frac{5.17\ GWh \times 1{,}000{,}000 \frac{kWh}{GWh} \times 0.65\ kg\ CO_2/kWh}{1000} = 3{,}361 \text{ tons } CO_2/year$$

2034:

$$\frac{7.00\ GWh \times 1{,}000{,}000 \frac{kWh}{GWh} \times 0.65\ kg\ CO_2/kWh}{1000} = 4{,}550 \text{ tons } CO_2/year$$

Over the 10-year projection period (2025-2034), the transition to renewable energy at Jeneponto Dry Port could avoid cumulative emissions of approximately 38,000 tons CO_2, contributing significantly to Indonesia's decarbonization targets under the National Energy General Plan (RUEN).

Table 10. Comparative analysis of renewable integration scenarios for Jeneponto dry port

Parameter	Scenario A: Grid Only	Scenario B: On-site Rooftop Solar+Grid	Scenario C: Grid+Wheeling from Tolo Wind Farm
Energy source	PLN grid mix (PLTU 60%, PLTA 30%, PLTB 10%)	0.75 MWp rooftop PV (5,000 m² warehouse roof) + PLN grid	PLN grid+allocated share from Tolo Wind Farm (72 MW) via wheeling
Renewable share	10-15%	20–25%	40-60%
Implementation timeline	Immediate (Year 0)	Short-term (Year 1-2)	Medium-term (Year 3-5, pending feasibility study)

Table 11. Comparative benchmarking of dry port energy studies

Indicator	[10]	[12]	[13]	Dry Port Jeneponto	Novelty Gap Addressed
Geographic focus	European seaports (retrofitting existing facilities)	Global intermodal corridors (literature review)	European dry ports with topographic constraints	New dry port in Eastern Indonesia	First energy feasibility study for planned dry ports in Indonesia's eastern provinces with high renewable potential
Methodology	Pilot implementation of green practices in operational ports	Systematic literature review of sea rail optimization	Monte Carlo simulation of road logistics under terrain constraints	Mixed-methods feasibility assessment (supply chain mapping+energy forecasting+stakeholder analysis)	Integrates supply chain topology with renewable resource assessment at planning stage rather than operational phase
Energy intensity	Not quantified (qualitative best practices)	Focus on transport time/cost efficiency, not energy metrics	CO_2 emissions from trucking, not facility level intensity	27.5 kWh/TEU (medium-scale dry port benchmark for Southeast Asia)	Provides first energy intensity benchmark for medium scale dry ports in emerging economies
Renewable share	< 15% (partial solar rooftop on existing facilities)	Not addressed	Not addressed	20-60% phased pathway (rooftop solar+wheeling from Tolo Wind Farm)	Demonstrates realistic pathway to > 60% renewable share through local resource integration, not just retrofitting
Decarbonization approach	Ex-post retrofitting of legacy infrastructure (high CAPEX, operational disruption)	Route optimization without energy source specification	Emissions reduction via logistics efficiency only	"Green by inception", renewable integration embedded at infrastructure design stage	Prevents fossil fuel lock in by designing energy systems before construction, avoiding costly retrofits
Theoretical framing	Operational best practices	Intermodal transport theory	Simulation based logistics optimization	Socio technical systems + sustainability transition theory	Positions dry ports as socio technical systems where energy sustainability enhances supply chain resilience

Table 10 shows a clear progression of renewable energy integration for Jeneponto Dry Port in terms of feasibility, impact, and timeline. Scenario A (Grid Only) is the simplest and can be implemented immediately, but it provides the lowest renewable share (10–15%) and minimal sustainability improvement. Scenario B (Rooftop Solar + Grid) offers a balanced solution, increasing renewable contribution to 20–25% with relatively short-term implementation (1–2 years). It is practical and utilizes existing infrastructure efficiently. Scenario C (Grid + Wind Wheeling) provides the highest renewable share (40–60%), supporting long-term sustainability goals. However, it requires more complex regulations and infrastructure, making it suitable for medium-term implementation (3–5 years).

Overall, the scenarios suggest a gradual transition from basic grid reliance to higher renewable integration, with Scenario B as a realistic intermediate step toward Scenario C.

Table 11 serves to validate the research contribution by explicitly identifying gaps in existing literature, such as the lack of renewable energy integration in emerging markets and the absence of planning-stage energy metrics. It justifies the study's necessity by advocating for a paradigm shift from reactive infrastructure modification to proactive, sustainable design.

4. CONCLUSION

This research represents an early-stage feasibility assessment emphasizing macro-level energy demand forecasting and renewable resource availability analysis. Detailed technical evaluations such as hybrid system sizing (PV–wind–battery ratios), reliability simulations, and levelized cost of energy (LCOE) optimization are beyond the scope of this study and will be addressed in subsequent engineering phases with relevant experts. The study positions Jeneponto Dry Port as a prototype for sustainable dry port development in Eastern Indonesia, integrating renewable energy as a core operational element. Energy demand is estimated at 5.17 GWh in 2025 and projected to reach 7.00 GWh by 2034, indicating that a phased decarbonization pathway is feasible. Initial deployment of rooftop solar PV could contribute 20-25% of demand with a 6–8-year payback, while future expansion through wheeling arrangements with the Tolo Wind Farm may further enhance renewable penetration. Nevertheless, achieving levels above 60% faces constraints related to grid regulation, intermittency management, and storage economics. These findings provide a strategic basis for decision-making, while comprehensive techno-economic validation including hourly load matching, storage optimization, and PPA structuring will be required in later stages in collaboration with PLN and renewable energy developers.

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