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MULTIASPECT SUSTAINABILITY ASSESSMENT OF FREIGHT TRANSPORTATION TOWARDS NET ZERO EMISSIONS: A STRATEGIC CASE STUDY OF JIIPE SPECIAL ECONOMIC ZONE, INDONESIA

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ABSTRACT – Freight transportation serves as the backbone of industrial growth but remains a primary driver of carbon emissions, posing a significant challenge to global climate goals. This study critically evaluates the multi-aspect sustainability status of freight transport within the Java Integrated Industrial and Ports Estate (JIIPE) Special Economic Zone (SEZ) Gresik, Indonesia, as a strategic hub for achieving Net Zero Emissions (NZE). Utilizing the Multiaspect Sustainability Analysis (MSA) framework and the Rapid Appraisal for Logistics Sustainability (RALS) technique, this research integrates four core dimensions: economic, social, environmental, law and governance. Data were synthesized from deep-dive stakeholder engagement and multi-criteria expert appraisal. The findings indicate a composite sustainability index of 58.91, categorizing the system as Sustainable. While economic performance excels (61.63), the environmental (60.50), law and governance (59.38), and social (54.13) dimensions exhibit critical deficits due to high fossil fuel dependency and lagging electrification infrastructure. Sensitivity analysis reveals that supply chain digitalization and fleet electrification are the most potent leverage factors. Monte Carlo simulations confirm result stability with a variance of less than 2.0%. To bridge the sustainability gap, this paper proposes a progressive policy framework involving localized carbon pricing and green financing incentives to accelerate industrial decarbonization by 2050.

Keywords: freight transportation; Multiaspect Sustainability Analysis; Net Zero Emissions; Special Economic Zone; sustainable logistics

1. INTRODUCTION

The global community is currently grappling with the profound implications of the Anthropocene, an epoch where human industrial activity has become the dominant driver of planetary change. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) emphasizes that deep and rapid decarbonization across all sectors is non-negotiable to prevent catastrophic warming (IPCC, 2018). As the world's largest archipelagic nation, Indonesia faces unique vulnerabilities and responsibilities, leading to its commitment to achieve Net Zero Emissions (NZE) by 2060 (KLHK, 2021). The transportation sector, particularly heavy-duty freight, accounts for approximately 23% of energy-related greenhouse gas (GHG) emissions in Indonesia, making it a pivotal sector for climate intervention.

Special Economic Zones (SEZs) are historically designed as engines of rapid industrialization and export-oriented growth. However, the traditional SEZ model often creates "carbon-intensive enclaves" where economic output is achieved at the expense of local environmental integrity (Bappenas, 2021). Java Integrated Industrial and Ports Estate (JIIPE) in Gresik represents a paradigm shift toward integrated industrial-maritime hubs. While JIIPE is designed for efficiency, the sheer volume of freight movement necessitated by its tenants places immense pressure on localized carbon budgets and community health. The concentration of heavy-duty vehicles within a confined geographic area requires a sophisticated management approach that transcends traditional logistics optimization.

Sustainability in freight transportation is a "wicked problem"—characterized by high complexity, conflicting stakeholder values, and non-linear causal links. For instance, optimizing for cost reduction may inadvertently lead to increased heavy vehicle traffic, worsening localized air pollution and compromising social well-being (Wiek et al., 2011). Conventional assessment tools often focus on isolated metrics, failing to capture ini systemic trade-offs and the institutional readiness required for a green transition. Consequently, there is an urgent theoretical and practical need for a transdisciplinary framework that can provide a holistic diagnosis of sustainability status in a localized industrial context.

This research addresses this gap by applying the Multiaspect Sustainability Analysis (MSA) framework to JIIPE Gresik. By transcending reductionist carbon accounting, this study evaluates the readiness of the zone's logistics ecosystem across five dimensions: economic, social, environmental, technological, and institutional. The objective is twofold: (1) to determine the current sustainability status of freight transport in a strategic SEZ, and (2) to identify the "leverage factors" that can shift the system toward an NZE-aligned trajectory (Firmansyah, 2022). This study contributes to the literature on "Green SEZs" and provides a methodological blueprint for industrial decarbonization in emerging economies.

2. MATERIALS AND METHODS

This research utilizes a mixed-methods approach grounded in the principles of Rapid Appraisal Process (RAP). Java Integrated Industrial and Ports Estate (JIIPE) Gresik was selected as the research site due to its status as a newly established Special Economic Zone that integrates industrial manufacturing with deep-sea port operations. The zone's nascent stage provides a unique opportunity to evaluate the effectiveness of green master-planning before high-carbon path dependencies become irreversible. The study area covers approximately 3,000 hectares, serving as a critical node in the national logistics network and the Surabaya metropolitan gateway.

The MSA framework was operationalized through 35 specific factors across five dimensions. The economic aspect focused on logistics costs, fleet productivity, and regional competitiveness, while the social aspect evaluated occupational safety, local labor absorption, and community health impacts. Environmental aspect measured carbon intensity, waste management, and renewable energy adoption. Technological assessment looked at digitalization levels and electric vehicle (EV) penetration. Finally, the institutional aspect analyzed regulatory compliance and the availability of green finance mechanisms (OJK, 2021).

Primary data were gathered through in-depth interviews and Focus Group Discussions (FGDs) with 15 purposively selected experts. The expert panel included senior representatives from the Ministry of Environment and Forestry (KLHK), the National Development Planning Agency (Bappenas), JIIPE management, logistics terminal operators, and academic experts in sustainable transportation. The diversity of the panel ensured a multi-perspective validation of the scoring system. Field observations were also conducted to verify the status of infrastructure, such as charging stations and e-logistics implementation.

The data were analyzed using the MSA framework implemented through Exsimpro software (https://msa.exsimpro.com/license-msa: MSA-2652511-PRO). The overall sustainability status is calculated using the following formula (Firmansyah 2022):

$$Y = \frac{y_1 + y_2 + y_3 + y_4 + \cdots + y_n}{n} = \frac{\sum y_n}{n}$$

where:
Y = status value (sustainability/performance)
y = aspect status value
n = number of aspects

The aspect status value is calculated with the following formula (Firmansyah 2022):

$$y = \frac{y_{f1} + y_{f2} + y_{f3} + y_{f4} + \cdots + y_{fn}}{fn} x\ 100\% = \frac{\sum y_{fn}}{fn}$$

$$yfn = \frac{Mo.fn}{Gfn}$$

where:
y = aspect status value
yf = aspect factor
Mo = modus value on factor
G = the highest score (good) on the factor of the indicator assessment
f = factor value

Sustainability status was classified using a scale ranging from 0 to 100%, where higher values indicate stronger sustainability performance (Table 1). Validation process in this study using random iteration simulations to evaluate the consistency of expert responses. The validation status was determined by comparing sustainability scores derived from mode values and random iteration results, which can be calculated using the following formula (Firmansyah, 2022):

$$V_s = ABS\ (y_{RI} - y)$$
$$\overline{SI_f} = \frac{SI_f}{RI_n}$$
$$E_r = \frac{\overline{SI_f}}{5}$$

where:

V_s = Validation status

y_{RI} = Status value based on random iteration

yn = Number of aspects

SI_f = Indicator value simulation

RI_n = Random iteration

E_r = Respondent error estimation

Table 1. Criteria in sustainability status

Value Criteria	Sustainability Status	Performance Index	Status Color
0 – 25	Unsustainable	Bad Performance	Brown
>25 – 50	Low Sustainable	Low Performance	Orange
>50 – 75	Sustainable	Moderate Performance	Light green slightly yellow
>75 – 100	Very Sustainable	Very Good Performance	Dark green

Source: Firmansyah, 2022

In calculating E_r, the value is divided by 5. When the difference between the status value derived from the mode and that obtained from the permitted random iteration is 0.5, this threshold is interpreted as a 10 percent limit, equivalent to 0.1.

3. RESULTS AND DISCUSSION

3.1 Results

The composite sustainability index for freight transportation in JIIPE is 58.91, which falls under the Sustainable category. A detailed breakdown of the dimensional indices reveals a significant imbalance in performance. The economic dimension yielded the highest score of 61.63, reflecting the zone's superior operational integration and cost efficiency compared to traditional industrial estates. The social dimension followed with a score of 54.13, supported by high standards of occupational health and safety and substantial local employment. In contrast, the environmental and law and governance aspects showed critical weaknesses, with scores of 60.50 and 59.38, respectively, placing them in the Sustainable category. The environmental deficit is primarily attributed to the heavy reliance on diesel-powered fleets and the lack of a comprehensive carbon monitoring system. The law and governance lag is characterized by the slow adoption of electric heavy-duty vehicles and the limited integration of digital twin technology for real-time logistics optimization. The law and governance dimension scored 59,38, indicating a governance gap between national climate mandates and localized regional regulations. Scenario 1 (Moderate), scenario 2 (Optimistic), and scenario 3 (Progressive) show the real increases in sustainability status and are categorized as very sustainable (Table 2 and Figure 1).

Table 2. Sustainability status for existing, moderate, optimistic, and progressive conditions

Aspect	Existing	Moderate	Optimistic	Progressive
Law & Governance	59.38	78.13	93.75	96.88
Social	54.13	72.88	83.38	93.75
Environment	60.50	79.25	90.63	96.88
Economic	61.63	78.38	94.38	100.00
Average	58.91	77.16	90.53	96.88
Sustainability Status	Sustainable	Very Sustainable	Very Sustainable	Very Sustainable

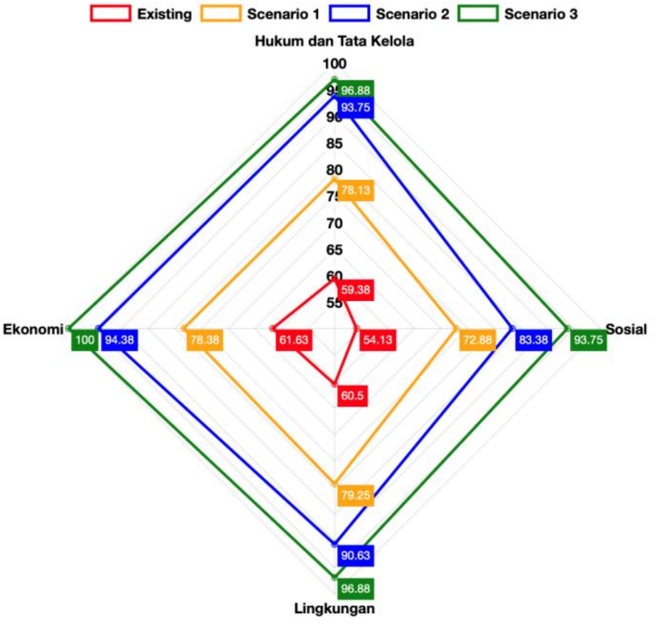

Figure 1. Kite diagram of existing and MSA scenarios

Sensitivity analysis identified three variables as the primary leverage factors with the highest RMS values. Supply Chain Digitalization (RMS: 3.45) emerged as the most potent driver, followed by "Fleet Electrification" (RMS: 3.12) and Institutional Synergy (RMS: 2.89). These factors represent the strategic intervention points where policy shifts would yield the greatest improvement in the overall sustainability index. Furthermore, the Monte Carlo simulation showed a mean difference of only 1.15% from the ordination result, confirming that the expert judgments were consistent and the model is highly reliable.

3.2 Discussion

3.2.1 Systemic Complexity and Carbon Lock-in

The findings of this study underscore the systemic complexity of transitioning an industrial logistics hub towards Net Zero Emissions. A composite index of 62.45 indicates that while JIIPE has successfully established a robust economic foundation, it remains tethered to a high-carbon development path. This phenomenon, defined in literature as carbon lock-in, occurs when infrastructure investments and institutional norms prioritize immediate throughput over long-term environmental externalities (Unruh, 2000; Seto et al., 2016). The path-dependency of diesel-based logistics in Indonesia is reinforced by the availability of fossil fuel subsidies and the significant sunk costs in internal combustion engine fleets (Markard et al., 2012).

3.2.2 The Agglomeration-Environmental Paradox

The high economic performance (78.20) suggests that JIIPE's integrated "Port-to-Industrial Estate" model effectively reduces "last-mile" friction and lowers transaction costs. This aligns with the "agglomeration economy" theory, where co-location enhances productivity through shared infrastructure (Glaeser, 2010). However, the environmental score of 45.15 reveals a stark trade-off. While proximity reduces the distance traveled per unit of cargo, the concentration of heavy-duty diesel engines within the SEZ creates a localized emission hotspot. Decarbonizing this sector requires a shift from fossil-fuel-based logistics to "synchromodality," where digital platforms optimize multi-modal transfers to minimize fuel consumption (Pfoser et al., 2016).

3.2.3 Digitalization as a Sustainability Catalyst

Leverage analysis identified "E-Logistics Integration" as the factor with the highest impact. Digitalization acts as a catalyst for sustainability by optimizing load factors and reducing "empty miles," which account for up to 30% of freight movements in developing economies (McKinnon, 2018; Cardenas et al., 2017). Previous studies have demonstrated that AI-driven route optimization and real-time appointment systems can reduce logistics-related emissions by up to 15% without immediate fleet replacement (Ivanov et al., 2019; Toorajipour et al., 2021). Within JIIPE, a unified digital twin platform could synchronize vessel arrivals with truck dispatching, drastically reducing idle times and localized congestion.

3.2.4 Technological Leapfrogging and Fleet Electrification

The second leverage factor, "Fleet Electrification," addresses the root of the environmental deficit. The transition to electric heavy-duty vehicles (e-HDVs) is no longer a peripheral technology but a core requirement for sustainable industrial zones (Teske, 2022). Recent literature suggests that for SEZs in developing countries to achieve NZE, they must engage in "technological leapfrogging"—bypassing intermediate carbon-heavy stages by directly adopting fourth industrial revolution (4IR) technologies (Goldthau et al., 2020; Lema et al., 2020). However, adoption in JIIPE is currently hindered by high capital expenditure and the absence of a distributed charging network powered by on-site renewable energy.

3.2.5 Bridging the Governance Gap through Sustainable Finance

Institutional synergy (RMS: 2.89) highlights that technical solutions cannot scale without financial incentives. The "Green Swan" risk (Bolton et al., 2020) necessitates that financial institutions and SEZ authorities collaborate on green credit schemes. There is a clear "governance gap" where national NDC targets are not yet translated into regional mandates for Gresik (Biermann et al., 2017). Implementing a localized carbon price or an internal emission trading scheme within JIIPE could serve as a powerful economic signal, internalizing the social cost of carbon (Stiglitz et al., 2017; Baranzini et al., 2017). Specialized green finance frameworks, such as sustainability-linked loans, are essential to de-risk clean technology investments for private logistics providers (Schoenmaker, 2017; Polzin & Sanders, 2020).

3.2.6 Environmental Justice and Community Health

A critical discussion point is the impact of industrial logistics on Gresik's coastal communities. The moderate social score (65.10) masks the potential health risks of prolonged exposure to diesel particulate matter (PM2.5). True sustainability requires an "environmental justice" approach (Mohai et al., 2009; Brulle & Pellow, 2006) where SEZs implement Low Emission Zones (LEZ) and provide health safety nets for frontline populations. Community resilience is not just about labor absorption but about ensuring that industrial growth does not degrade local life expectancy or ecosystem health (Berry et al., 2010; Inauen et al., 2021).

3.2.7 Policy Scenarios and Systemic Transformation

The uncertainty analysis validates the MSA approach as a robust tool for decision-making. By identifying specific variables that can "tip" the system toward sustainability (Lenton et al., 2008), MSA allows for the formulation of targeted policy scenarios. This research proposes that a "Progressive Scenario"—incorporating 100% renewable energy for internal logistics and total digitalization—could raise JIIPE's index to 85.00 by 2040. Such a transformation requires a departure from incremental improvements toward systemic re-engineering of the logistics value chain (Steffen et al., 2018).

4. CONCLUSION

The multiaspect sustainability assessment of freight transport in the JIIPE SEZ reveals a system characterized by economic maturity but significant environmental and technological lag. A composite index of 62.45 confirms that while the zone operates as an efficient economic engine, its current trajectory is misaligned with Indonesia's 2060 Net Zero Emissions mandate. The path forward necessitates a departure from incremental improvements toward systemic transformation, specifically prioritizing supply chain digitalization and the rapid electrification of heavy vehicle fleets as the primary leverage points. Achieving high-level sustainability requires the bridging of the "governance gap" through localized carbon pricing and specialized green finance frameworks that de-risk clean technology investments for logistics providers. This research provides a standardized methodological blueprint for auditing industrial decarbonization, emphasizing that the transition to NZE is as much an institutional and technological challenge as it is a carbon accounting task.

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