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FEASIBILITY ANALYSIS AND COMPARATIVE EVALUATION OF SUSTAINABLE HEAD-TRUCK SYSTEMS USING LIFE CYCLE ASSESSMENT (LCA), OPERATIONAL COST ANALYSIS, AND ANALYTIC NETWORK PROCESS (ANP) IN THE LOGISTICS OPERATIONS OF PT XYZ

Keywords:

analytic network process;
electric head-truck; life cycle
assessment; operational cost
analysis; port logistics;
sustainability

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Abstract

The transition toward sustainable port logistics requires evaluating head-truck technologies from environmental, economic, technical, and social perspectives. This study evaluates the feasibility and sustainability of diesel and electric (EV) head-truck systems at PT XYZ by integrating Life Cycle Assessment (LCA), Operational Cost Analysis, Sensitivity Analysis, and Analytic Network Process (ANP). LCA was conducted using SimaPro 9.0, ecoinvent 3.9, and ReCiPe 2016 Midpoint (H), while operational costs were compared based on actual energy consumption. ANP integrated technical, economic, environmental, and social criteria to determine the overall priority of the alternatives. The results show that the EV system has a lower aggregated environmental burden, despite trade-offs in several impact categories. Its annual operational cost is approximately Rp 258.1 million per unit, compared with Rp 808.1 million for diesel, yielding potential annual savings of approximately Rp 550 million per unit. The ANP results also indicate a higher overall priority for the EV alternative. These findings demonstrate the potential of electric head-truck technology to support more sustainable and economically efficient internal container transportation at PT XYZ.

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1. Introduction

The increasing complexity of global port logistics requires transportation systems that are both operationally efficient and environmentally sustainable. Heavy-duty vehicles, particularly head-trucks used for container hauling, are significant sources of energy consumption and greenhouse gas emissions in port operations, making their decarbonization an important priority (Wang et al., 2023; de Saxe et al., 2023; Alamoush et al., 2020, 2022). Electrification of port vehicles has emerged as a promising pathway to reduce emissions and improve energy efficiency (Penchev et al., 2025; Link & Plötz, 2022; Sharifi et al., 2024). Studies have also shown that battery-electric heavy-duty trucks can reduce CO₂ emissions compared with diesel alternatives, although their environmental performance depends on battery production, electricity sources, and operational conditions (Wang et al., 2023; Penchev et al., 2025).

Life Cycle Assessment (LCA) is widely used to evaluate the environmental impacts of diesel and electric vehicles, while Operational Cost Analysis provides insight into differences in energy and operating expenditures (Miklausch & Woschank, 2022; Eriksson & Pernestål, 2025). Previous studies generally indicate lower operational emissions and costs for electric heavy-duty vehicles, although higher upstream impacts from battery production and mineral extraction remain important trade-offs (Penchev et al., 2025; Link & Plötz, 2022). In port environments, technological developments such as smart charging, digital optimization, and renewable-energy integration can further

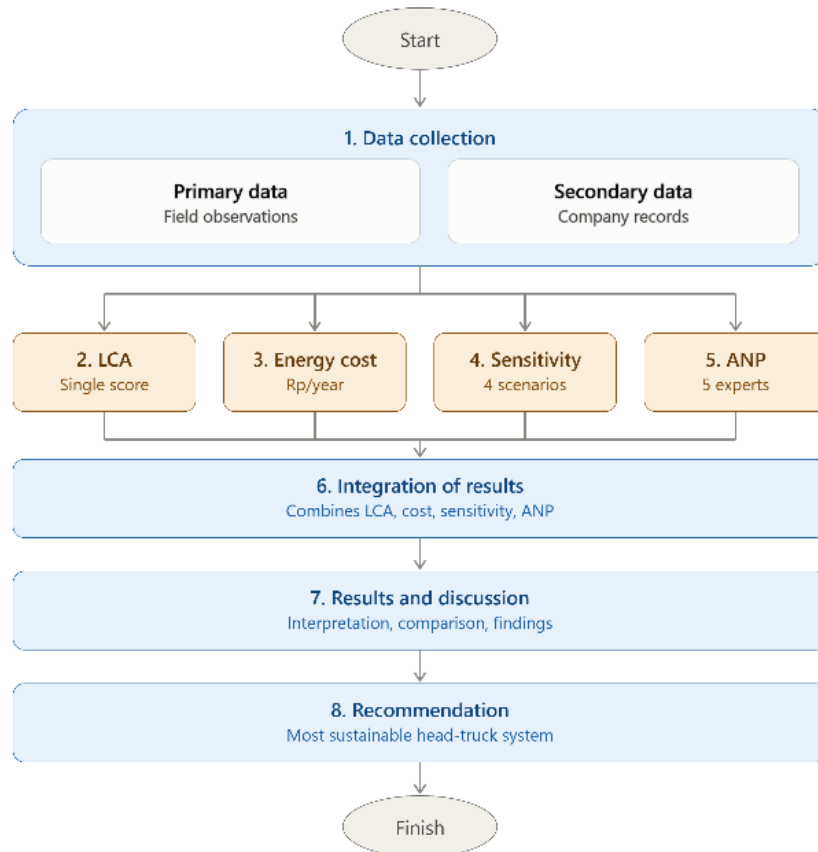


Figure 1. Research Framework For The LCA, Operational Energy Cost Analysis, Sensitivity Analysis, And ANP Evaluation Of Head-Truck Systems At PT XYZ

improve the feasibility of vehicle electrification (Kastner et al., 2024; Ramasan et al., 2025; Gao et al., 2023; Adegbahun et al., 2023; Miao et al., 2025).

Despite these developments, the adoption of sustainable transportation systems still faces challenges related to charging infrastructure, technical performance, policy support, and social acceptance (Homayouni et al., 2024; Nicoletti & Appolloni, 2024; Saeed & Kersten, 2020). Therefore, sustainability assessment should consider environmental, economic, technical, and social dimensions rather than relying on a single performance indicator (Okay et al., 2024; Saeed & Kersten, 2020).

Considering these gaps, this study evaluates diesel and electric head-truck systems in the logistics operations of PT XYZ by integrating Life Cycle Assessment (LCA), Operational Energy Cost Analysis, Sensitivity Analysis, and Analytic Network Process (ANP). The study assesses environmental performance, operational economic performance, and multi-dimensional sustainability while examining the robustness of the economic comparison under changes in key assumptions. The results are expected to support PT XYZ in evaluating the transition toward lower-emission and more energy-efficient internal container transportation.

2. Methods

This study employs a quantitative comparative approach to evaluate the feasibility and sustainability of diesel and electric (EV) head-truck systems at PT XYZ. The analysis integrates Life Cycle Assessment (LCA), Operational Energy Cost Analysis, Sensitivity Analysis, and ANP across environmental, economic, technical, and social dimensions. Primary data were collected through field observations and interviews with PT XYZ's technical and operational divisions, covering vehicle specifications, energy consumption, operating hours, transportation activities, and load capacity. Secondary data were obtained from company records, technical documents, relevant literature, and life-cycle inventory databases.

The research consists of five stages: (1) collecting and validating technical and operational data; (2) conducting LCA using a gate-to-gate system boundary focused on the operational phase of internal container transportation; (3) comparing annual operational energy costs; (4) conducting sensitivity analysis based on changes in electricity tariffs, diesel prices, electricity emission factors, and battery lifetime; and (5) applying ANP to integrate technical, economic, environmental, and social criteria and determine the overall priority of the alternatives. The research stages are presented in greater detail in **Figure 1**.

The research framework begins with collecting and validating technical and operational data for diesel and electric head-trucks, including vehicle specifications, energy consumption, load capacity, operating hours, and distance.

Table 1. Technical Specifications of Diesel and Electric Head-Truck Systems

Parameter	Diesel Head-Truck	Electric Head-Truck (EV)
Manufacturer	Volvo Trucks	Volvo Trucks
Model/variant	Volvo FM 330 4×2	Volvo FM Electric 4×2
Vehicle configuration	4×2 tractor	4×2 tractor
Powertrain	Internal combustion engine	Battery-electric powertrain
Energy source	Diesel fuel	Grid electricity
Engine displacement	10.8 L	N/A
Maximum power	330 hp (246 kW)	450 hp (332 kW)
Motor/engine	Volvo D11 diesel engine	Electric motor
Battery capacity	N/A	Up to 540 kWh
Gross combination weight	Up to 44 tonnes	Up to 44 tonnes
Transportation application	Container transportation	Container transportation
Functional unit	1 km of internal container transportation	1 km of internal container transportation
Operating period	360 days/year	360 days/year

Source: Volvo Trucks technical specifications

Life Cycle Assessment (LCA) was conducted using SimaPro 9.0 and the ecoinvent database with a gate-to-gate system boundary focused on internal container transportation operations. Vehicle manufacturing, infrastructure construction, and end-of-life processes were excluded due to limited primary data. The functional unit was defined as 1 km of head-truck operation to enable equivalent environmental comparisons between alternatives.

The LCA followed four phases: goal and scope definition, life-cycle inventory (LCI), life-cycle impact assessment (LCIA), and interpretation. Environmental impacts were assessed across Human Health, Ecosystem Quality, and Resources, including characterization and single-score results. Operational Energy Cost Analysis compared annual energy expenditures, while a complete Total Cost of Ownership (TCO) assessment was excluded due to insufficient data on acquisition, maintenance, battery replacement, charging infrastructure, and residual value.

The ANP was applied using Super Decisions 3.0 to integrate technical, economic, environmental, and social criteria and determine alternative priorities. The model comprised four main criteria and eight sub-criteria developed from literature reviews and expert consultations. Pairwise comparisons were conducted with five logistics and energy experts from PT XYZ using Saaty's 1–9 scale, with a Consistency Ratio (CR) threshold of ≤ 0.1 .

Data validation used triangulation among calculated results, company secondary data, and previous studies (Okoye et al., 2022; Penchev et al., 2025; Savadogo et al., 2023). The integrated LCA, operational energy cost analysis, sensitivity analysis, and ANP generated environmental impact indicators (CO₂-eq and MJ/km), annual operational energy costs, criterion priority weights, and the final ranking of head-truck alternatives to support sustainability-based decision-making at PT XYZ.

2.1 Technical Specifications of Diesel and Electric Head-Truck Systems

The diesel and electric head-truck systems were characterized based on technical and operational specifications relevant to vehicle performance, energy consumption, and operational suitability. The comparison covered vehicle type, power output, weight, payload, dimensions, energy source, operating hours, and service life, including engine and fuel specifications for diesel and battery and charging characteristics for electric systems. Both alternatives were evaluated for equivalent internal container transportation at PT XYZ. The specifications are presented in **Table 1**, using representative Volvo FM configurations, with operational energy and cost data obtained from PT XYZ.

2.2 Life Cycle Assessment (LCA)

LCA was conducted to compare the environmental performance of diesel and electric head-trucks using SimaPro 9.0, ecoinvent 3.9, and the ReCiPe 2016 Midpoint (H) method. A gate-to-gate boundary was applied to the terminal operation phase because reliable data for vehicle manufacturing, battery production, infrastructure, and end-of-life were unavailable. The assessment included energy consumption, transportation, equipment operation, lubrication, maintenance, and tyre wear. Diesel and electricity were used as the primary energy inputs for the respective systems. The functional unit was **1 km of internal container transportation**, allowing both alternatives to be compared based on the same transportation service. The assessment covered global warming, ozone depletion, terrestrial acidification, freshwater and marine eutrophication, particulate matter formation, and fossil resource scarcity. The resulting indicators were used as inputs for the ANP sustainability assessment.

2.3 Life Cycle Inventory (LCI)

The LCI quantified material and energy inputs for both head-truck systems using PT XYZ operational data and relevant ecoinvent 3.9 datasets. The diesel inventory included diesel consumption, supporting electricity, lubrication, maintenance, and tyre wear, while the electric inventory included electricity consumption, charging losses, lubrication, maintenance, and tyre wear. All data were normalized to the functional unit of **1 km of internal container transportation** and entered into SimaPro using the same system boundary. Where primary data were unavailable, the

Table 1. Life Cycle Inventory of Diesel Head-Truck System

Process	Input	Quantity	Unit
STS Crane Operation	Electricity, medium voltage	3.50	kWh
Shuttle Transport – Diesel	Diesel transport, freight, lorry 16–32 t, EURO5	0.80	km
RTG Operation – Diesel	Diesel, low sulphur	0.998	kg
Lubrication	Lubricating oil	0.00020	kg
Maintenance	Maintenance process	0.00100	p·km
Tyre Wear	Tyre production/wear process	0.00001	unit
Lubricant Replacement	Lubricating oil	0.00085	kg

Table 3. Life Cycle Inventory of Electric Head-Truck System

Process	Input	Quantity	Unit
STS Crane Operation	Electricity, medium voltage	3.50	kWh
Shuttle Transport – EV	Electricity, medium voltage	1.20	kWh
Charging Loss	Electricity, medium voltage	0.04	kWh
Lubrication	Lubricating oil	0.00017	kg
E-RTG/RMG Operation	Electricity, medium voltage	6.00	kWh
Maintenance	Maintenance process	0.00050	p·km
Tyre Wear	Tyre production/wear process	0.00001	unit
Lubricant Replacement	Lubricating oil	0.00017	kg

Table 4. Sustainability Criteria and Sub-Criteria

Dimension	Sub-Criterion	Definition	Main Indicator	Data Source	Reference Source
Technical	Performance	Ability of the head-truck to perform the required transportation activities effectively	Power and operational capability	Technical specification	Syre & Göhlich (2023)
Technical	Reliability	Ability of the system to operate continuously with minimum disruption	Operational reliability	Expert assessment	Li et al. (2024)
Economic	Operational Cost	Expenditure required to operate the vehicle, particularly energy expenditure	Rp/year	Operational data	Muller (2023)
Economic	Investment Cost	Initial expenditure required to acquire the vehicle system	Rp/unit	Technical/financial reference	Goodarzi et al. (2024)
Environmental	Global Warming Potential	Potential contribution of the system to climate change	kg CO ₂ -eq	SimaPro	Eduardo et al. (2023)
Environmental	Energy Consumption	Energy required to provide the transportation service	kWh/km	LCA inventory	Osorio et al. (2022)
Social	Safety	Ability of the system to support safe operations for operators and workers	Expert assessment	ANP questionnaire	Nicoletti & Appolloni (2024)
Social	Technology Acceptance	Degree to which the technology is accepted by operators and relevant stakeholders	Expert assessment	ANP questionnaire	Sobczuk (2024)

closest relevant ecoinvent datasets were applied. Further details of the inventory data and inputs are presented in **Table 2** and **Table 3**.

2.4 Sustainability Criteria and Sub-Criteria

The ANP framework consisted of four sustainability dimensions: technical, economic, environmental, and social. These represented operational capability and reliability, operating costs, energy and emission impacts, and operational safety and stakeholder acceptance, respectively.

The criteria and sub-criteria were incorporated into the ANP model to determine their relative importance and the overall priority of the alternatives. Environmental indicators were derived from LCA, economic indicators from Operational Energy Cost Analysis, and technical and social indicators from expert judgments.

2.5 Analytic Network Process (ANP)

The ANP was applied to integrate technical, economic, environmental, and social dimensions into a sustainability decision framework. The model consisted of four main dimensions with relevant sub-criteria, while diesel and electric head-trucks were defined as the alternatives are presented in **Table 4**.

Table 5. Profile of ANP Expert Panel

Expert	Position/Role	Area of Expertise	Years of Experience
E1	Inventory Planning Manager	Inventory Planning and Logistics	12–15
E2	Terminal Equipment Manager	Terminal Equipment and Maintenance	15–20
E3	Facility Planning Manager	Facility Planning and Infrastructure	12–15
E4	Deputy Planning Manager	Planning and Operations	10–15
E5	Operations Manager	Terminal Operations and Logistics	15–20

Table 6. Operational Energy Cost Comparison

Cost Component	Diesel	EV
Daily energy consumption	134.416 L	377.43 kWh
Energy price	Rp16,700/L	Rp1,899.70/kWh
Daily operational energy cost	Rp2,244,747.20	Rp717,003.77
Annual operating days	360	360
Annual operational energy cost	Rp808,108,992.00	Rp258,121,357.56
Annual saving compared with diesel	—	Rp549,987,634.44
Cost reduction	—	68.06%

Pairwise comparisons used Saaty's 1–9 scale and were completed by five PT XYZ experts with relevant experience in logistics, transportation equipment, maintenance, energy, and terminal operations. All experts had more than 10 years of professional experience. The profiles and relevant expertise of the experts involved in the pairwise comparison are presented in **Table 5**. Individual judgments were aggregated into group comparison matrices and processed using Super Decisions 3.0 to obtain the unweighted, weighted, and limiting supermatrices. The limiting supermatrix determined the final alternative priorities. Consistency was assessed using the Consistency Ratio (CR), with $CR \leq 0.10$ considered acceptable for the criteria, sub-criteria, and alternative comparisons.

2.6 Operational Energy Cost Analysis

The economic evaluation compared the operational energy expenditure of diesel and electric head-trucks. A complete Total Cost of Ownership (TCO) assessment was not conducted because data on acquisition, financing, maintenance, battery replacement, charging infrastructure, and residual value were unavailable. Therefore, the analysis was limited to operational energy costs.

The results show that the electric head-truck has a lower annual operational energy cost than the diesel alternative. The detailed results of the Operational Energy Cost Analysis are presented in **Table 6**. Thus, the economic assessment is referred to as **Operational Energy Cost Analysis** rather than a complete TCO assessment, enabling a direct comparison without assumptions about unavailable lifecycle cost data.

For the diesel head-truck, daily operational energy cost was calculated by multiplying daily diesel consumption by the applicable diesel price:

$$C_{\text{diesel,day}} = Q_{\text{diesel}} \times P_{\text{diesel}} \quad (1)$$

where is daily diesel cost (Rp/day), is daily diesel consumption (L/day), and is diesel price (Rp/L). Based on the operational data, the daily diesel consumption was 134.416 L/day and the diesel price was Rp16,700/L. Therefore:

$$C_{\text{diesel,day}} = 134.416 \times 16,700 = 2,244,747.2 \text{ Rp/day}$$

Assuming 360 operating days per year, the annual operational diesel cost was calculated as:

$$C_{\text{diesel,year}} = C_{\text{diesel,day}} \times 360 \quad (2)$$

$$C_{\text{diesel,year}} = 2,244,747.2 \times 360$$

$$C_{\text{diesel,year}} = 808,108,992 \text{ Rp/year}$$

For the electric head-truck, the daily electricity cost was calculated using where represents daily electricity consumption and represents the applicable electricity tariff. Based on the operational data, electricity consumption was 377.43 kWh/day and the electricity tariff was Rp1,899.70/kWh:

$$C_{\text{EV,day}} = Q_{\text{EV}} \times P_{\text{kWh}} \quad (3)$$

$$C_{\text{EV,day}} = 377.43 \times 1,899.7 = 717,003.77 \text{ Rp/day}$$

The annual operational electricity cost was subsequently calculated using the same 360 operating days:

$$C_{\text{EV,year}} = C_{\text{EV,day}} \times 360 \quad (4)$$

$$C_{\text{EV,year}} = 717,003.77 \times 360$$

$$C_{\text{EV,year}} = 258,121,357.56 \text{ Rp/year}$$

Table 7. Sensitivity Scenarios for Operational Energy Cost

Scenario	Diesel Price Change (%)	Electricity Price Change (%)	Diesel Annual Cost (Rp)	EV Annual Cost (Rp)	Preferred Alternative
Base Case	0	0	808,108,992	258,121,358	EV
S1	-20	+20	646,487,194	309,745,629	EV
S2	-40	+20	484,865,395	309,745,629	EV
S3	-40	+40	484,865,395	361,369,901	EV
S4	-50	+50	404,054,496	387,182,036	EV
S5	-50	+100	404,054,496	516,242,715	Diesel

Table 8. Life Cycle Inventory (LCI) of Diesel Head-Truck per 1 km Operation

Process	Input	Qty	Unit	Output	Qty	Unit
STS Crane Operation	market for electricity, medium voltage {ID}	3.50	kWh	container handling, STS crane	1.00	move
Shuttle Transport – Diesel	transport, freight, lorry 16-32t, EURO5 {RER}	0.80	km	shuttle transport, diesel	1.00	leg
RTG Operation – Diesel	market for diesel, low-sulphur {RER}	0.998	kg	container stacking, RTG diesel	1.00	move
Maintenance	market for lubricating oil {GLO}	0.00020	kg	—	—	—
	maintenance, heavy duty vehicle, processing {GLO}	0.00100	p·km	—	—	—
Tyre Wear	light commercial vehicle tyre production {GLO}	0.00001	unit	—	—	—
Lubricant	market for lubricating oil {GLO}	0.00085	kg	waste oil	0.00085	kg

Table 9. Life Cycle Inventory (LCI) of Electric Head - Truck per 1 km Operation

Process	Input	Qty	Unit	Output	Qty	Unit
STS Crane Operation	market for electricity, medium voltage {ID}	3.50	kWh	container handling, STS crane	1.00	move
Shuttle Transport – Electric (EV)	market for electricity, medium voltage {ID}	1.20	kWh	shuttle transport, electric	1.00	leg
	market for electricity, medium voltage {ID} (<i>charger loss</i>)	0.04	kWh	—	—	—
	market for lubricating oil {GLO}	0.00017	kg	—	—	—
E-RTG / RMG Operation – Electric	market for electricity, medium voltage {ID}	6.00	kWh	container stacking, E-RTG	1.00	move
Maintenance	maintenance, passenger car, electric, processing {GLO} (<i>proxy EV</i>)	0.00050	p·km	—	—	—
Tyre Wear	light commercial vehicle tyre production {GLO}	0.00001	unit	—	—	—
Lubricant	market for lubricating oil {GLO}	0.00017	kg	waste oil	0.00017	kg

2.7 Sensitivity Analysis

A sensitivity analysis was conducted to assess the robustness of the operational energy-cost comparison under changes in diesel and electricity prices. The analysis used the base-case energy costs from Section 2.6 while varying energy prices under several scenarios, with energy consumption and operating periods held constant. The sensitivity scenarios and corresponding changes in diesel and electricity prices are presented in **Table 7** (Sensitivity Scenarios for Operational Energy Cost). Vehicle acquisition, battery replacement, and other lifecycle costs were excluded due to data limitations; therefore, the analysis focused only on operational energy costs. Under moderate price changes, the EV maintained its cost advantage. In S4, with a 50% decrease in diesel price and a 50% increase in electricity price, the annual EV energy cost remained lower at approximately Rp387.18 million compared with Rp404.05 million for diesel. However, in the more extreme S5, where the diesel price decreased by 50% and electricity price doubled, the EV cost increased to approximately Rp516.24 million, exceeding the diesel cost. Under the base case, the EV provided an annual energy-cost saving of approximately Rp549.99 million, or 68.06%. These results indicate that the EV advantage depends strongly on the relative prices and consumption of electricity and diesel.

3. Results and Discussions

3.1 Life Cycle Assessment (LCA) Results

The LCA compared the environmental performance of diesel and electric head-truck systems using 1 km of internal container transportation as the functional unit and a gate-to-gate operational boundary. The model was developed in SimaPro 9.0 using the ecoinvent 3.9 database and ReCiPe 2016 Midpoint (H).

The LCI data in **Table 8** and **Table 9** were used as the initial inventory for the diesel and electric head-truck systems, respectively, before simulation. **Table 8** presents the Life Cycle Inventory (LCI) of the diesel head-truck per

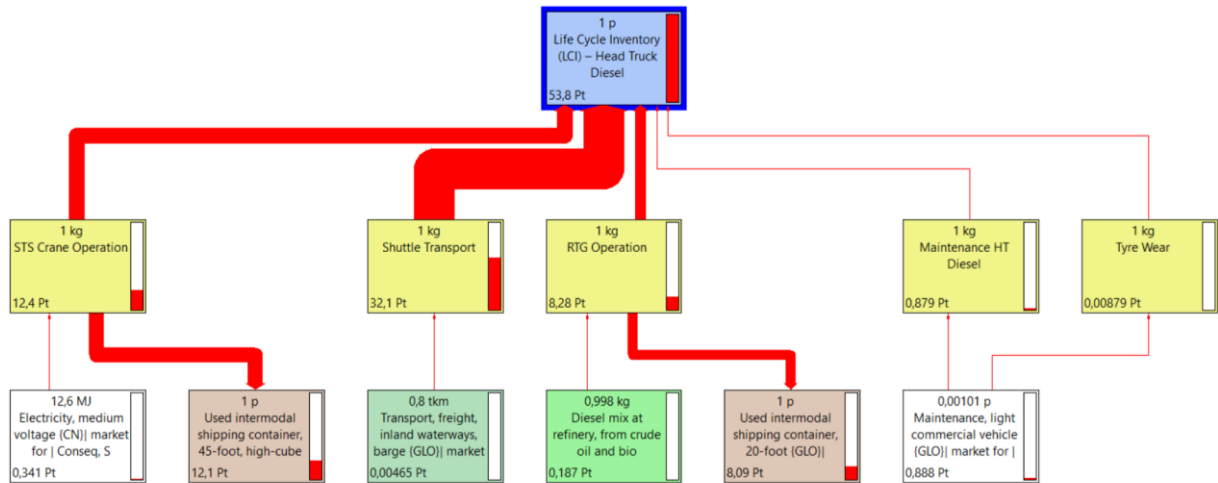


Figure 2. Overall Process Network Of The Diesel Head-Truck System

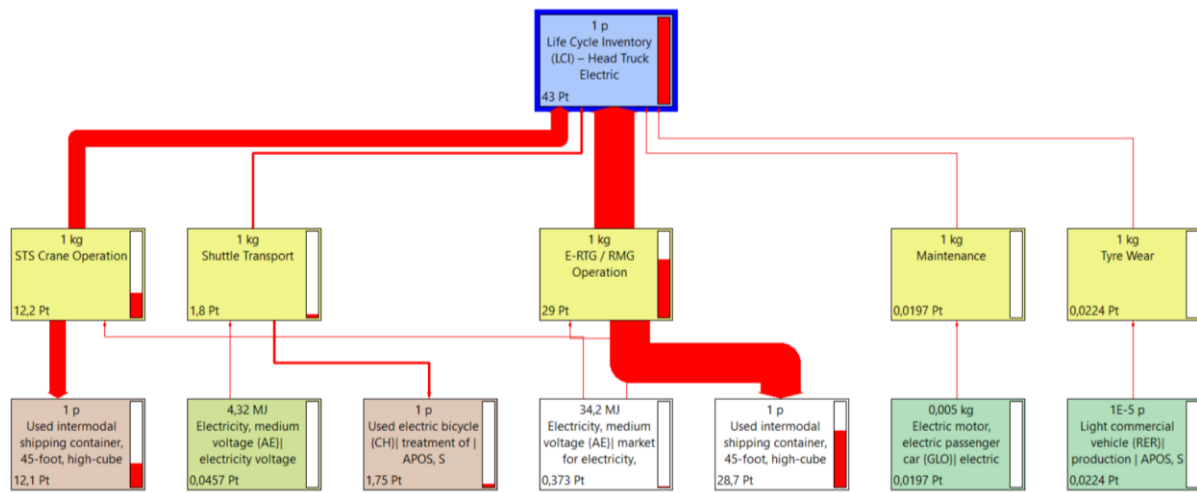


Figure 3. Overall Process Network Of The Electric Head-Truck System

1 km of operation, while **Table 9** presents the corresponding LCI for the electric head-truck per 1 km of operation. These inventories include the relevant material and energy inputs within the defined gate-to-gate system boundary. The analysis generated Characterization, Damage Assessment, Normalization, Weighting, and Single Score results. Characterization quantifies impacts in physical units, while the subsequent stages aggregate and normalize impacts into damage categories and overall environmental scores. The detailed LCIA results are presented in the following sections.

1) Diesel Head-Truck System

The SimaPro process network for the diesel head-truck is presented in **Figure 2**, showing the material and energy flows within the defined gate-to-gate operational boundary.

2) Electric (EV) Head-Truck System

The SimaPro process network for the electric head-truck is presented in **Figure 3**, illustrating the electricity supply, battery-related processes, and operational activities included in the assessment. The LCIA results show different performance across impact categories. The EV performs better in Human Health, while diesel performs better in Ecosystem Quality and Resources. After weighting, the EV obtained a lower single score of 43.00 Pt, compared with 53.80 Pt for diesel, indicating a lower overall environmental burden under the selected LCA method and boundary. However, the EV has a higher Resources score (12.30 Pt vs. 5.49 Pt), reflecting trade-offs associated with battery materials and electricity generation (Wang et al., 2023).

3.1.1 Characterization Results

The characterization results in **Table 10** show that the electric head-truck has lower impacts in respiratory organics and respiratory inorganics than diesel, at $1.18\text{E-}7$ and $8.08\text{E-}4$ DALY, compared with $1.26\text{E-}7$ and $8.22\text{E-}4$ DALY. However, the electric system has higher impacts in several other categories, including climate change, carcinogens, radiation, ozone depletion, ecotoxicity, acidification/eutrophication, land use, minerals, and fossil fuels. For climate change, the impact increases from $2.62\text{E-}5$ DALY for diesel to $5.92\text{E-}5$ DALY for electric, indicating that upstream electricity generation and related processes can offset some benefits of eliminating direct diesel combustion.

Table 10. Characterization Results of Diesel and Electric Systems

Impact Category	Unit	Diesel	Electric
Carcinogens	DALY	5.61E-5	8.82E-5
Respiratory organics	DALY	1.26E-7	1.18E-7
Respiratory inorganics	DALY	8.22E-4	8.08E-4
Climate change	DALY	2.62E-5	5.92E-5
Radiation	DALY	2.58E-7	5.22E-7
Ozone layer	DALY	2.17E-8	5.13E-8
Ecotoxicity	PDF·m ² yr	1.02E3	1.31E3
Acidification/Eutrophication	PDF·m ² yr	3.39	9.19
Land use	PDF·m ² yr	-0.898	6.06
Minerals	MJ surplus	1.29	3.30
Fossil fuels	MJ surplus	152	348

Table 11. Damage Assessment Results

Damage Category	Unit	Diesel	Electric
Human Health	DALY	0.000905	0.000453
Ecosystem Quality	PDF·m ² yr	105	147
Resources	MJ surplus	153	344

Table 12. Weighted Environmental Impact Results

Damage Category	Unit	Diesel	Electric
Human Health	Pt	41.00	20.50
Ecosystem Quality	Pt	7.31	10.30
Resources	Pt	5.49	12.30
Total	Pt	53.80	43.00

Table 13. Normalization Results of Diesel and Electric Head-Truck Systems

Damage Category	Diesel	Electric
Human Health	0.102	0.0513
Ecosystem Quality	0.0183	0.0256
Resources	0.0274	0.0614

Table 14. Single Score Results of Diesel and Electric Head-Truck Systems

Damage Category	Unit	Diesel	Electric
Human Health	Pt	41.00	20.50
Ecosystem Quality	Pt	7.31	10.30
Resources	Pt	5.49	12.30
Total Single Score	Pt	53.80	43.00

3.1.2 Damage Assessment Results

The characterization results were aggregated into Human Health, Ecosystem Quality, and Resources. The damage assessment results for these three impact categories are presented in **Table 11**. The electric head-truck has lower Human Health impacts (0.000453 vs. 0.000905 DALY), representing a 49.95% reduction. However, it has higher impacts in Ecosystem Quality (147 vs. 105 PDF·m²yr) and Resources (344 vs. 153 MJ surplus). The normalized results in **Table 13** show the same pattern. After weighting, the electric system obtains a lower Human Health score (20.50 vs. 41.00 Pt) but higher Ecosystem Quality (10.30 vs. 7.31 Pt) and Resources (12.30 vs. 5.49 Pt) scores. Consequently, as shown in **Tables 12 and 14**, the electric system achieves a lower total single score of 43.00 Pt, compared with 53.80 Pt for diesel. Overall, the results indicate an environmental trade-off: the electric head-truck reduces Human Health impacts but increases burdens in Ecosystem Quality and Resources under the defined system boundary.

3.1.3 Normalization Results

The normalization results in **Table 13** show that the electric head-truck has a lower Human Health value than diesel (0.0513 vs. 0.102). However, the electric system has higher values for Ecosystem Quality (0.0256 vs. 0.0183) and Resources (0.0614 vs. 0.0274). These results confirm the environmental trade-offs between the two propulsion systems.

3.1.4 Weighting Results

The weighting results in **Table 12** show a lower total score for the electric system (43.00 Pt) than diesel (53.80 Pt), representing a 20.07% reduction. The electric system has a substantially lower Human Health score (20.50 vs.

Table 15. Operational Energy Cost Comparison

Parameter	Diesel Head-Truck	Electric Head-Truck
Daily operational energy cost	Rp2,244,747.20	Rp717,003.77
Operating days per year	360 days	360 days
Annual operational energy cost	Rp808,108,992.00	Rp258,121,357.20
Annual cost saving	–	Rp549,987,634.80
Cost reduction	–	68.06%

41.00 Pt), but higher scores for Ecosystem Quality (10.30 vs. 7.31 Pt) and Resources (12.30 vs. 5.49 Pt). The results therefore indicate a lower overall weighted environmental burden for the electric system, while retaining trade-offs in Ecosystem Quality and Resources.

3.1.5 Single Score Results

The single-score results in **Table 14** show total scores of 43.00 Pt for the electric system and 53.80 Pt for diesel. The 20.07% lower score for the electric system is primarily associated with its lower Human Health impact. However, the higher Ecosystem Quality and Resources scores highlight the trade-offs that may be concealed by aggregation into a single score.

3.2 Operational Energy Cost Analysis

The economic evaluation initially considered a Total Cost of Ownership (TCO) approach. However, complete data on acquisition, maintenance, battery replacement, charging infrastructure, and residual value were unavailable for both alternatives. Therefore, the analysis was limited to operational energy costs.

As shown in **Table 15**, the annual operational energy cost was calculated using daily energy costs and 360 operating days per year. The diesel head-truck incurs Rp808.11 million annually, compared with Rp258.12 million for the electric system, resulting in an annual saving of Rp549.99 million or a 68.06% reduction for the electric alternative:

$$C_{\text{diesel,day}} = Q_{\text{diesel}} \times P_{\text{diesel}} \quad (1)$$

$$C_{\text{diesel,day}} = 134.416 \times 16,700 = 2,244,747.2 \text{ Rp/day}$$

The annual diesel operating cost is:

$$C_{\text{diesel,year}} = C_{\text{diesel,day}} \times 360 \quad (2)$$

$$C_{\text{diesel,year}} = 2,244,747.2 \times 360$$

$$C_{\text{diesel,year}} = 808,108,992 \text{ Rp/year}$$

The EV head-truck consumes 377.43 kWh/day of electricity with a tariff of Rp 1,899.7/kWh, leading to

$$C_{\text{EV,day}} = Q_{\text{EV}} \times P_{\text{kWh}} \quad (3)$$

$$C_{\text{EV,day}} = 377.43 \times 1,899.7 = 717,003.77 \text{ Rp/day}$$

Annual EV operating cost:

$$C_{\text{EV,year}} = C_{\text{EV,day}} \times 360 \quad (4)$$

$$C_{\text{EV,year}} = 717,003.77 \times 360$$

$$C_{\text{EV,year}} = 258,121,357.56 \text{ Rp/year}$$

The resulting annual operational savings from switching to EV are:

$$\text{Annual Savings} = C_{\text{diesel,year}} - C_{\text{EV,year}} \quad (5)$$

$$\text{Annual Savings} = 808,108,992 - 258,121,358$$

$$\text{Annual Savings} = 549,987,634.44 \text{ unit per year}$$

$$\text{Annual Savings} = \text{Rp } 549,987,634.44 \text{ per unit per year}$$

The results in **Table 15** show annual operational energy costs of Rp808.11 million for the diesel head-truck and Rp258.12 million for the electric head-truck. The electric system therefore saves approximately Rp549.99 million annually, equivalent to a 68.06% reduction. This finding is consistent with previous studies reporting lower operating energy costs for electric heavy-duty vehicles (Eriksson & Pernestål, 2025; Penchev et al., 2025). However, this represents only the operational energy-cost advantage, not a complete TCO comparison, as acquisition, maintenance, battery replacement, charging infrastructure, and residual value were excluded.

3.3 Analytic Network Process (ANP) Results

The ANP was applied to integrate environmental, economic, technical, and social considerations in evaluating diesel and electric head-truck systems. Five experts from PT XYZ participated in the pairwise comparison assessment, selected based on their managerial responsibilities and experience in inventory planning, terminal equipment, facility planning, and logistics operations. All experts had more than 10 years of professional experience. The expert profiles

Table 16. Expert Panel for ANP Assessment

Expert	Position/Role	Relevant Expertise	Years of Experience
E1	Inventory Planning Manager	Inventory and Logistics Planning	>10 years
E2	Terminal Equipment Manager	Terminal Equipment and Maintenance	>10 years
E3	Facility Planning Manager	Facility and Infrastructure Planning	>10 years
E4	Deputy Planning Manager	Planning and Logistics Operations	>10 years
E5	Operations Manager	Terminal and Logistics Operations	>10 years; approximately 20 years

Table 17. Consistency Analysis of ANP Pairwise Comparisons

Comparison Matrix	λ_{max}	CI	RI	CR	Status
Sustainability dimensions	4.083	0.028	0.900	0.031	Consistent*
Environmental criteria	4.112	0.037	0.900	0.041	Consistent*
Economic criteria	4.076	0.025	0.900	0.028	Consistent*
Technical criteria	3.051	0.026	0.580	0.045	Consistent*
Social criteria	3.067	0.034	0.580	0.058	Consistent*
Alternative comparison	2.021	0.021	0.000	—	Not applicable (2×2 matrix; inherently consistent)

Table 18. Global Weights of Sustainability Dimensions

Sustainability Dimension	Global Weight	Percentage (%)	Rank
Environmental	0.432	43.2	1
Economic	0.297	29.7	2
Technical	0.174	17.4	3
Social	0.097	9.7	4
Total	1.000	100.0	

Table 19. Final Priority of Head-Truck Alternatives

Alternative	Final Priority	Percentage (%)	Rank
Electric Head-Truck	0.732	73.2	1
Diesel Head-Truck	0.268	26.8	2
Total	1.000	100.0	

are presented in **Table 16**, while the consistency results are shown in **Table 17**. All applicable comparison matrices achieved a Consistency Ratio (CR) below 0.10, indicating acceptable consistency. The 2×2 alternative comparison was inherently consistent. The resulting judgments were used to determine the global weights of the four sustainability dimensions and the final priorities of the diesel and electric alternatives.

3.3.1 Consistency Analysis

The consistency of the pairwise comparison judgments was evaluated using the Consistency Ratio (CR). The consistency assessment was conducted to verify whether the judgments provided by the experts were sufficiently consistent before the synthesis of the ANP priorities. A comparison matrix was considered acceptable when $CR \leq 0.10$. The consistency analysis was performed for the sustainability dimensions and their respective criteria. The results of the consistency assessment are presented in **Table 17**.

3.3.2 Global Weights of Sustainability Dimensions

The ANP model evaluated four sustainability dimensions: environmental, economic, technical, and social. The resulting global weights are presented in **Table 18**. Environmental criteria have the highest weight (0.432; 43.2%), followed by economic (0.297; 29.7%), technical (0.174; 17.4%), and social (0.097; 9.7%). Together, environmental and economic dimensions account for 72.9% of the total weight, indicating their dominant contribution to the decision framework.

The high environmental weight is consistent with the study's sustainability focus and the LCA assessment of the two head-truck systems. Although the social dimension has the lowest weight, it remains relevant to implementation through considerations such as operator training, safety procedures, and adaptation to new technology.

The final ANP priorities are presented in **Table 19**. The electric head-truck obtains a final priority of 0.732 (73.2%), while the diesel alternative obtains 0.268 (26.8%). These priorities represent the aggregated results of the environmental, economic, technical, and social criteria considered in the ANP model.

3.3.3 Final Priority of Head-Truck Alternatives

The final ANP priorities are presented in **Table 19**. The electric head-truck obtains a priority of 0.732 (73.2%), compared with 0.268 (26.8%) for the diesel alternative. This result reflects the aggregated preferences across environmental, economic, technical, and social dimensions. The higher priority of the electric alternative is supported

Table 20. Integrated Evaluation of Diesel and Electric Head-Truck Systems

Evaluation Aspect	Diesel	Electric	Preferred Alternative
Human Health	41.00 Pt	20.50 Pt	Electric
Ecosystem Quality	7.31 Pt	10.30 Pt	Diesel
Resources	5.49 Pt	12.30 Pt	Diesel
LCA Single Score	53.80 Pt	43.00 Pt	Electric
Annual operational energy cost	Rp808.11 million	Rp258.12 million	Electric
Annual operational saving	–	Rp549.99 million	Electric
Operational cost reduction	–	68.06%	Electric
ANP final priority	0.268	0.732	Electric

Table 21. Sensitivity Analysis Scenarios

Scenario	Variable	Baseline	Scenario Change	Expected Effect
S0	Baseline condition	100%	–	Reference condition
S1	Electricity tariff	100%	+20%	EV cost increases
S2	Electricity tariff	100%	+40%	EV cost increases significantly
S3	Diesel price	100%	–20%	Diesel cost decreases
S4	Diesel price	100%	–40%	Diesel becomes more competitive
S5	Electricity emission factor	100%	–20%	EV environmental performance improves
S6	Electricity emission factor	100%	+20%	EV environmental advantage decreases
S7	Battery lifetime	Baseline	5 years	Higher battery replacement burden

particularly by the environmental and economic dimensions, which together account for 72.9% of the total decision weight. However, the ANP priority represents an overall multi-criteria preference and does not imply better performance in every individual criterion. The LCA results, for example, show environmental trade-offs between the two alternatives. The ANP result therefore reflects the combined effect of the criteria and their relative importance within the decision framework.

3.4 Integrated Evaluation of Diesel and Electric Head-Truck Systems

The LCA, Operational Energy Cost Analysis, and ANP provide complementary perspectives on the two head-truck alternatives.

The integrated results are presented in **Table 20**. The electric head-truck obtains a lower LCA single score (43.00 Pt vs. 53.80 Pt) and lower annual operational energy cost (Rp258.12 million vs. Rp808.11 million), corresponding to an annual saving of Rp549.99 million or 68.06%. The ANP also assigns a higher final priority to the electric alternative (0.732 vs. 0.268). Nevertheless, the LCA results indicate trade-offs, with the electric system performing better in Human Health but showing higher impacts in Ecosystem Quality and Resources. In addition, the economic analysis covers only operational energy costs and excludes acquisition, maintenance, battery replacement, charging infrastructure, and residual value. Therefore, the integrated results apply specifically to the defined system boundary, assumptions, and operating conditions.

3.5 Sensitivity Analysis

A sensitivity analysis was conducted to assess the robustness of the results under changes in key assumptions. The analysis considered electricity tariffs, diesel prices, electricity emission factors, and battery lifetime, as summarized in **Table 21**.

3.5.1 Sensitivity Scenario

The sensitivity analysis considers changes in electricity tariffs, diesel prices, electricity emission factors, and battery lifetime. These parameters were selected because they represent important sources of uncertainty in comparing conventional diesel and electric vehicle systems. The scenarios applied in the analysis are presented in **Table 21**.

3.5.2 Sensitivity of Operational Energy Cost

The sensitivity analysis evaluated changes in electricity and diesel prices while maintaining other operational parameters constant. The results show that changes in energy prices directly affect the operational cost advantage of the electric head-truck. The sensitivity results for annual operational energy costs under different electricity and diesel price scenarios are presented in **Table 22** (Sensitivity of Annual Operational Energy Cost). Under the baseline condition, the electric head-truck requires Rp258.12 million per year, compared with Rp808.11 million for diesel, resulting in annual savings of Rp549.99 million or 68.06%.

Table 22. Sensitivity of Annual Operational Energy Cost

Scenario	Diesel Cost (Rp million/year)	EV Cost (Rp million/year)	Difference (Rp million/year)	EV Cost Reduction (%)
Baseline	808.11	258.12	549.99	68.06
Electricity +20%	808.11	309.75	498.36	61.67
Electricity +40%	808.11	361.37	446.74	55.28
Diesel –20%	646.49	258.12	388.37	60.07
Diesel –40%	484.87	258.12	226.75	46.76

Table 23. Sensitivity of Electric Head-Truck Environmental Performance to Electricity Emission Factor

Scenario	Electricity Emission Factor	Relative Change (%)	Expected Effect on EV Environmental Performance
Low-emission electricity	80% of baseline	–20	Environmental burden decreases
Baseline	100%	0	Reference condition
High-emission electricity	120% of baseline	+20	Environmental burden increases

3.5.3 Sensitivity Analysis of Electricity Emission Factor

The analysis evaluated $\pm 20\%$ changes in the electricity emission factor while keeping other LCA parameters constant. The sensitivity scenarios and their expected effects on the environmental performance of the electric head-truck are presented in **Table 23** (Sensitivity of Electric Head-Truck Environmental Performance to Electricity Emission Factor). A reduction decreases the environmental burden of the electric head-truck, while an increase produces the opposite effect, indicating dependence on the electricity generation mix (Ramasan et al., 2025). Under the baseline, the electric head-truck obtained **43.00 Pt** compared with **53.80 Pt** for diesel, representing a **20.07% lower** aggregated environmental burden.

3.5.4 Sensitivity Analysis of Battery Lifetime

Battery lifetime was assessed as an uncertainty, with 8 years as the baseline and 6 and 5 years as alternative scenarios. Due to unavailable data on battery cost, degradation, replacement, and production inventory, battery replacement was excluded from the baseline analysis. Thus, battery lifetime does not affect the reported annual operational energy cost of Rp258.12 million, but remains a long-term uncertainty for investment decisions.

4. Conclusion

This study evaluated diesel and electric head-trucks at PT XYZ using LCA, Operational Energy Cost Analysis, sensitivity analysis, and ANP. The electric head-truck obtained a single score of 43.00 Pt compared with 53.80 Pt for diesel, representing a 20.07% lower aggregated environmental burden. However, the impacts varied across categories, with the EV performing better in Human Health, while diesel showed lower impacts in Ecosystem Quality and Resources. Annual energy costs were Rp258.12 million for the EV and Rp808.11 million for diesel, resulting in potential savings of Rp549.99 million or 68.06%. The ANP weights were 0.432 for environmental, 0.297 for economic, 0.174 for technical, and 0.097 for social dimensions. The EV received a final priority of 0.732 compared with 0.268 for diesel. Overall, the electric head-truck shows potential to reduce operational energy costs and aggregated environmental burden. However, the economic analysis does not represent a complete Total Cost of Ownership because vehicle acquisition, maintenance, battery replacement, charging infrastructure, and residual value were excluded. Future studies should incorporate these components and battery degradation for a more comprehensive assessment.

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Declaration of the Use of Artificial Intelligence (AI)

The authors declare that they used artificial intelligence (AI) tools in the preparation of this manuscript. The authors used ChatGPT (OpenAI) to assist with language editing, grammar correction, and improving the clarity of the manuscript. All ideas, interpretations, figures, data analyses, discussions, and conclusions presented in this manuscript were developed and determined by the authors. The authors take full responsibility for the accuracy, integrity, and originality of the manuscript.

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