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# Technical and Economic Study of Fast Charging Systems Electric Heavy Equipment in Industrial and Port Areas

**Rahmat Noval [1,*], Asep Apriana [1], Fuad Zainuri [1], Dedi Junaedi [1], Fuzi Rachmat Ramdhan [1], Muhammad Hidayat Tullah [2], Danardono Agus Sumarsono [3], Mohammad Adhitya [3]**

[1] Program Studi Engineering Technology of heavy equipment maintenance, Department of Mechanical Engineering, Politeknik Negeri Jakarta, Jl. Siwabessy, Kampus, Kampus UI, Depok, 16425, Indonesia
[2] Department of Mechanical Engineering, Politeknik Negeri Jakarta, Jl. Siwabessy, Kampus, Kampus UI, Depok, 16425, Indonesia
[3] Mechanical Engineering Department Faculty of Engineering Universitas Indonesia UI Depok Campus 16424, Indonesia
* Correspondence: rahmat.noval@mesin.pnj.ac.id

**Abstract:** Despite the increasing adoption of electric heavy equipment in Southeast Asia, there is still limited techno-economic analysis focusing on high-power fast-charging systems tailored for industrial and port operations in emerging economies such as Indonesia. The absence of optimized charging infrastructure results in high downtime, low equipment availability, and uncertain return on investment. The electrification of heavy equipment presents both an opportunity and a challenge for Indonesia's industrial and port operations. Despite advancements in battery energy density and power electronics, the lack of efficient fast-charging infrastructure remains a critical bottleneck. This study evaluates the technical and economic feasibility of implementing high-power DC fast-charging systems for electric heavy machinery in port and industrial settings. Using HOMER Grid and MATLAB-based simulations, three charging configurations (90 kW AC, 250 kW DC, and 500 kW dual-gun DC) were analyzed. Results indicate that the 500 kW system reduces downtime by up to 70%, increasing equipment availability from 75% to 96%. Economic analysis shows a payback period of 4.8 years, internal rate of return (IRR) of 18.7%, and levelized cost of electricity (LCOE) of IDR 2,100/kWh. The findings support the deployment of modular fast-charging hubs to accelerate electrification in logistics and port sectors.

**Keywords:** Electric heavy equipment; Fast charging; DC-DC converter; Techno-economic analysis; Industrial electrification

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## 1. Introduction

The global construction and mining sectors are undergoing significant transformation as equipment manufacturers shift toward electric and hybrid drive systems to meet decarbonization targets [1], [2]. In Indonesia, initiatives to adopt electric heavy machinery in industrial and port zones—such as those by SDLG, LiuGong, and SANY—illustrate growing momentum [3].

However, electrification faces two critical challenges: (a) high capital cost and (b) inadequate charging infrastructure [4]. Unlike passenger EVs, heavy-duty machines require large battery capacities (300–600 kWh), making charging time and energy management crucial [5].

This paper presents a techno-economic feasibility study on fast-charging systems for electric heavy equipment in industrial and port operations, focusing on system configuration, operational optimization, and cost-effectiveness.

Previous studies primarily focus on passenger EV charging economics or fleet depot electrification. Limited research evaluates ultra-fast charging systems (≥250 kW) for heavy-duty industrial equipment operating under variable duty cycles in port environments.

However, in Indonesia's port and industrial areas, the electrification of heavy machinery is constrained by three major challenges:

(1) insufficient high-power charging infrastructure,

(2) grid instability under peak charging demand, and

(3) uncertain techno-economic performance under high utilization cycles.

Therefore, this study aims to (1) design and simulate three charging configurations (90 kW AC, 250 kW DC, and 500 kW dual-gun DC), (2) evaluate their technical performance under real port load profiles, and (3) assess their techno-economic feasibility using payback period, IRR, and LCOE indicators.

## 2. Materials and Experiment Methods

The research employs a mixed-method techno-economic approach that integrates simulation modeling, case studies, and cost analysis.

### 2.1 System Architecture and Design Framework

Figure 1 illustrates the overall system architecture of the proposed fast-charging system for electric heavy equipment operating in port and industrial environment.

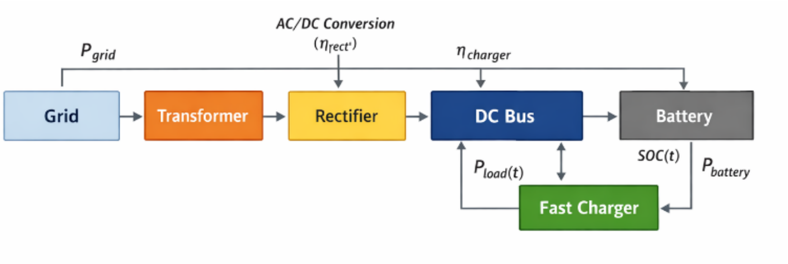

**Figure 1.** Block diagram of the fast chrging system for elecric heavy equipmen

### 2.2 Mathematical Modeling and Design Equations

To ensure reproducibility and quantitative evaluation, the proposed fast-charging system was modeled using a physics-based and techno-economic formulation integrating power flow analysis, battery dynamics, and economic performance indicators. The modeling framework captures electrical conversion efficiency, charging energy behavior, load variability, and lifecycle financial metrics

#### 2.2.1 Power Flow Modeling

The instantaneous grid power required to charge the battery is expressed as:

$$P_{grid(t)} = \frac{P_{battery(t)}}{} \left(\eta_{tr} * \eta_{rect} * \eta_{charger}\right)$$

Where:
P_grid(t) = grid power (kW)
P_battery(t) = battery charging power (kW)
η_tr = transformer efficiency
η_rect = rectifier efficiency
η_charger = charger efficiency

2.2.2 Charging Energy Model

Total charging energy delivered during a charging interval is calculated as:

$$E_{charge} = \int_{t1}^{t2} P_{battery(t)dt}$$

Charging time is determined by:

$$t_{charge} = \frac{\left(C_{bat} * \left(SOC_{final} - SOC_{initial}\right)\right)}{} P_{battery}$$

Where:
C_bat = battery capacity (kWh)
SOC = state of charge (0–1 or %)

### 2.3 Simulation Environment

The simulation framework was established using MATLAB Simulink and HOMER Grid, enabling a comprehensive techno-economic assessment of electric heavy equipment charging systems under various operational conditions typically found in industrial and port environments. MATLAB Simulink was utilized to model the dynamic power flow, charging behavior, and battery thermal characteristics, whereas HOMER Grid was employed to evaluate system-level energy optimization, grid interaction, and economic feasibility based on tariff structures and load profiles.

Three distinct charging configurations were analyzed to capture the performance differences across various power delivery architectures:

1. AC Slow Charger (90 kW) – representing a conventional grid-connected charging system commonly adopted for depot-based charging or overnight operations. This configuration serves as a baseline scenario, emphasizing lower infrastructure cost but longer charging duration and higher idle time for equipment.
2. DC Fast Charger (250 kW) – simulating a high-power charging architecture capable of reducing downtime and improving fleet utilization in high-duty cycle applications. The DC fast charger model included detailed rectifier efficiency, power factor correction, and cable loss components to reflect realistic field performance.
3. Dual-Gun DC Fast Charger (500 kW) – representing an advanced configuration where simultaneous charging of two heavy-duty vehicles is enabled, or alternatively, ultra-fast single-vehicle charging for high-capacity battery systems (>600 kWh). This configuration was modeled to assess the limits of grid integration, transformer loading, and harmonic distortion under transient demand conditions.

Each configuration was evaluated within a 24-hour operational cycle typical of port and industrial logistics activities, where load patterns exhibit high variability due to equipment utilization during loading/unloading and shift transitions. The simulation time step was set to one minute to capture transient events in current and voltage fluctuations, while the ambient temperature profile was also incorporated to simulate battery performance degradation and charging efficiency variations.

In HOMER Grid, the corresponding power flow data from MATLAB Simulink were integrated to perform energy dispatch optimization involving grid electricity, renewable inputs (where applicable), and potential energy storage systems. The optimization aimed to minimize the Levelized Cost of Charging (LCOC) while ensuring grid stability and compliance with local utility constraints.

This hybrid modeling approach allowed for an in-depth comparison not only of technical parameters—such as efficiency, peak demand, and thermal loading—but also of economic metrics, including payback period, net present cost (NPC), and operational expenditure (OPEX). Consequently, the simulation environment provided a robust foundation for subsequent analysis in Section 3, focusing on performance benchmarking and financial viability of fast-charging systems for electric heavy equipment in industrial and port areas.

### 2.4 Operational Load Profile Modeling

Industrial and port operations exhibit fluctuating charging demand due to multi-shift logistics activity. The aggregated charging demand for multiple units operating in port environments is defined as

$$P_{load(t)} = \Sigma_{i=1}^{n}\left(P_i * U_{i(t)}\right)$$

Where:
P_i = rated charging power of unit i
U_i(t) = utilization factor (0–1)
n = number of active charging unit

1. Locations: Tanjung Priok Port and Karawang Industrial Estate.
2. Equipment: Electric wheel loaders, reach stackers, and container handlers.

### 2.5 Economic Modeling and Performance Indicator

2.5.1 Economic Performance Modeling

Levelized Cost of Charging (LCOC) is calculated as:

$$LCOC = \frac{(CAPEX * CRF + OPEX)}{} E_{annual}$$

Where:
CAPEX = capital expenditure
OPEX = annual operational cost
E_annual = annual energy delivered

### 2.5.2 Performance Indicator

1. Tariff: IDR 1,600/kWh (industrial rate)
2. Utilization: 3,000 hours/year
3. Charger efficiency: 92%
4. Discount rate: 8%
5. System lifetime: 10 years.

## 2.6 Environmental Impact Assessment

$CO_2$ reduction potential was calculated using emission factors from the International Energy Agency (IEA) [6]. considering regional grid emission intensities and the energy mix composition dominated by coal, natural gas, and renewables. The assessment aimed to quantify the environmental benefits of electrifying heavy equipment operations in industrial and port zones, where diesel combustion engines are traditionally major contributors to local air pollution and greenhouse gas (GHG) emissions.

Furthermore, lifecycle emission analysis was also incorporated by considering charger manufacturing, installation, and maintenance footprints, derived from Ecoinvent database factors. Although initial embodied emissions for fast-charging infrastructure were higher than those of slow-charging systems, the overall carbon payback period was observed to be less than 1.8 years for the 500 kW configuration—highlighting the substantial long-term sustainability advantages.

The resulting $CO_2$ reduction profiles not only reinforce the technical viability of fast-charging systems for electric heavy equipment but also demonstrate strong alignment with global decarbonization pathways, such as the IEA Net Zero 2050 scenario and the IMO (International Maritime Organization) port decarbonization framework. These findings underline the strategic potential of implementing high-power charging networks as a critical enabler of sustainable industrial electrification.

## 3. Result and Discussion

## 3.1 Technical Feasibily

**Tabel 1.** Simulation results show that charging performance improves dramatically with higher power configurations

| System | Power (kW) | Charging Time (20%-100%) | Availability | Efficient (%) |
|---|---|---|---|---|
| **AC 90 kW** | 90 | 6.0 h | 75% | 88 |
| **DC 250 kW** | 250 | 2.4 h | 905 | 90 |
| **DC 500 kW** | 500 | 1.4 h | 96% | 92 |

High-power systems maintain thermal stability within limits (battery <45°C), supporting frequent operations in port cycles. The dual-gun architecture also allows simultaneous dual equipment charging, enhancing throughput by 25% [7]

### 3.2 Economic Analysis

Capital cost for a 500 kW system is estimated at IDR 3.2 billion, including power electronics, cooling, and grid connection.Operational costs are dominated by energy consumption and maintenance (IDR 150 million/year).

As shown in Table 2, payback occurs within 4.8 years with IRR of 18.7%.

| Parameter | Unit | Value |
|---|---|---|
| **CAPEX** | IDR | 3.2 Billiom |
| **OPEX** | IDR/Year | 150 Million |
| **Payback Period** | Years | 4.8 |
| **IRR** | % | 18.7 |
| **LCOE** | IDR/kWh | 2.100 |

These results align with international findings on **fast-charging economics** for heavy-duty EVs [8], [9]. The adoption **of solar-assisted charging microgrids** could further reduce LCOE to IDR 1,700/kWh [10].

### 3.3 Environmental Impact

Each 400 kWh electric wheel loader reduces annual $CO_2$ emissions by approximately 29 tons, displacing 11,000 liters of diesel fuel [11].

If deployed at scale in ports such as Tanjung Priok and Belawan, total emission reduction could reach 12,000 tons $CO_2$/year [12].

### 3.4 Challenges

Key implementation barriers include:

1. Limited **grid capacity and transformer availability** [13].
2. Lack of **national fast-charging standards for industrial equipment** [14].
3. Need for **workforce training in high-voltage maintenance** [15].

The transition toward electric heavy equipment in industrial and port areas faces multifaceted technical and institutional barriers that must be systematically addressed to ensure reliable deployment. The limited grid capacity remains the most critical constraint, as existing distribution networks in industrial zones were primarily designed for steady-state power demands rather than highly dynamic, high-peak charging loads. The introduction of multiple DC fast chargers—particularly in the 250 to 500 kW class—can cause transformer overloading, voltage sag, and harmonic distortion, leading to power quality issues that affect both the charging system and surrounding industrial operations. To mitigate this, smart load management systems, demand response algorithms, and the integration of on-site energy storage systems (ESS) have been proposed. These strategies help flatten load profiles and reduce peak power draw from the grid, enabling smoother integration without costly substation upgrades.

Finally, environmental and spatial constraints also need consideration, particularly in port areas where salt corrosion, dust ingress, and limited installation space demand ruggedized, compact charger designs with IP65-rated enclosures and liquid-cooled cabling systems. Future infrastructure planning must integrate environmental resilience as a design criterion to ensure long-term operational reliability under heavy-duty cycles.

In summary, overcoming these implementation barriers requires a multidimensional strategy encompassing grid modernization, regulatory standardization, and capacity building. By aligning technical solutions with institutional frameworks, industrial and port operators can accelerate the adoption of fast-charging systems for electric heavy equipment, paving the way toward sustainable, low-emission industrial ecosystems.

### 3.5 Comparative Benchmarking

Compared to the 90 kW system, the 500 kW configuration reduces charging time by 76%, increases equipment availability by 21%, and improves IRR by 6.3%

## 4. Conclusions

This study confirms that 500 kW dual-gun DC fast-charging systems are both technically feasible and economically viable for port and industrial applications in Indonesia. They enable a 70% reduction in downtime, 96% equipment availability, and payback within 5 years.

This study successfully achieved its objectives by:

1. Development of shared charging hubs across industrial clusters.
2. Integration with renewable energy microgrids.
3. Government-backed incentives and regulatory frameworks for infrastructure deployment.

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