International Journal Of Humanities Education And Social Sciences ***(IJHESS)*** *E-ISSN:* **2808-1765**
Volume 6, Number 1, August 2026, *Page. 239 – 247*
Email : editorijhess@gmail.com

Integrated Renewable Power and Traffic Evaluation for an Automated Railway Crossing in Indonesia

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Abstract

This study examines the feasibility of using renewable energy to power an automated railway level crossing and evaluates its operational effect on adjacent urban traffic. The case study was conducted at the officially recognized but unguarded crossing on Jl. Rawa Simprug III, South Jakarta. Methodologically, this study applied a quantitative simulation-based approach. Field observations were conducted to identify electrical load parameters and baseline traffic conditions. These primary data were evaluated using the PKJI 2023 framework for macroscopic capacity, while HOMER Pro and PTV VISSIM were utilized for microgrid energy simulation and microscopic traffic evaluation, respectively. The proposed crossing system had an installed connected load of 770 W, equivalent to approximately 17.20 kWh/day. Four hybrid energy scenario families were compared. The most attractive configuration was a grid-assisted system consisting of 5.55 kW solar PV, six battery units, and grid backup, which produced the lowest reported net present cost of about IDR 40.9 million and electricity cost of about IDR 427.12/kWh. Under existing traffic conditions, the site operated at 1,752 pcu/h with a degree of saturation of 1.14, average delay of 29.31 s/veh, and level of service D. After implementation and traffic engineering, the best scenario reduced the degree of saturation to 0.74 and average delay to 12.59 s/veh, improving the level of service to B. The findings show that solar-led hybrid power is technically suitable for the study site, while traffic benefits depend on coordinated operation with the surrounding road network.

Keywords: Automated Railway Crossing, Hybrid Renewable Energy, Homer Pro, Vissim, Urban Traffic Operations

INTRODUCTION

Distributed renewable-energy systems are increasingly deployed for relatively small yet operationally critical loads because modular generation, storage integration, and hybridization can improve supply reliability in decentralized applications (Bajpai & Dash, 2012;Chauhan & Saini, 2014;Eriksson & Gray, 2017). This is particularly crucial for modern land transportation infrastructure, where grid dependency can introduce vulnerabilities during power outages, directly compromising public safety at critical intersection nodes. By transitioning to localized, renewable-driven microgrids, traffic control devices—such as automated crossing gates and early warning signals—can maintain uninterrupted continuous operation regardless of municipal grid stability. The literature on hybrid renewable-energy systems has established a mature foundation for techno-economic design, including optimization methods (Baños et al., 2011), uncertainty treatment (Kumar & Saravanan, 2017), system sizing (He et al., 2023;Twaha & Ramli, 2018;Yu et al., 2023), and simulation-based assessment across off-grid and grid-connected contexts (Oladeji et al., 2021; Arunachalam et al., 2023;(Kebede et al., 2020). Additional studies have examined small hybrid systems (Ndukwe et al., 2019), dynamic off-grid modelling (Khalid et al., 2024), autonomous architectures (Singh & Bansal, 2019;Kazem et al., 2017), and investment-oriented HOMER Pro applications (Chisale et al., 2023; Rahmat et al., 2022). For transport infrastructure with modest but mission-critical electricity demand, this body of work confirms that renewable-energy systems can be designed as dependable operational assets rather than merely as supplementary power sources.

Railway level crossings are operational conflict points at which rail priority disrupts road traffic, often generating delay, queue spillback, and interference with nearby intersections. Microsimulation has been widely applied to assess railway-crossing operations (Anagnostopoulos, 2025;Tey et al., 2012), evaluate delay-reduction treatments (Larue et al., 2020), investigate pre-emption and transitional control strategies (Cho et al., 2011), and analyse clearance-oriented performance. Complementary studies have examined crash risk, accident prediction, and behavioural factors at level crossings (Restuputri et al., 2022;Das et al., 2022;Liang et al., 2018), while other work has linked delay management to broader transport sustainability (Pasha et al., 2021) and supporting warning or interconnection measures (Haces-Garcia et al., 2021).

Recent advancements have further expanded the scope of railway crossing safety and optimization. For instance, (Blagojević et al., 2021) developed predictive modeling frameworks to evaluate crossing safety risks and prioritize cost-effective interventions based on complex traffic interactions. In terms of alternative power integration at such nodes, (Pandya et al., 2025) demonstrated the viability of localized renewable harvesting by utilizing piezoelectric sensors on tracks to capture train vibration energy, successfully powering signaling systems without grid access. Additionally, contemporary analytical models have been formulated to complement microsimulation platforms, offering structured methods to estimate specific maximum queue lengths and time loss for irregular, non-cyclical railway closures (Szczepanek & Kruszyna, 2026). Collectively, these studies indicate that crossing upgrades should be evaluated as part of the surrounding traffic system rather than as isolated field devices.

Despite this progress, the literature remains fragmented across two largely separate streams. Renewable-energy studies typically concentrate on component sizing, optimization, and lifecycle feasibility, whereas railway-crossing studies focus mainly on traffic operations, safety, or control timing. Integrated assessments that simultaneously examine renewable power-supply adequacy and post-implementation traffic performance are still limited, particularly for officially recognized but unguarded crossings in dense Indonesian urban settings.

This study addresses that gap through a case study of the Jl. Rawa Simprug III crossing in South Jakarta. The site is located on the Tanah Abang-Rangkasbitung commuter line and experiences 203 train movements per day according to the study dataset. By integrating HOMER Pro-based energy simulation with VISSIM-supported traffic analysis, the study aims to determine a technically feasible renewable-energy configuration for automated crossing equipment and to evaluate how the proposed intervention influences adjacent traffic performance. In doing so, the paper offers a practical planning workflow for renewable-energy-powered railway crossing upgrades in Indonesia.

RESEARCH METHODS

This study employed a quantitative, single-site case-study methodology combined with discrete-event simulation modeling. According (Yin et al., 2018), a case-study design is the most appropriate research method when addressing complex "how" and "why" operational phenomena within real-life contexts, allowing for an in-depth empirical inquiry of localized infrastructure. Furthermore, as emphasized by simulation methodology experts, integrating field data with computational modeling provides a rigorous scientific framework to evaluate alternative system configurations and traffic behaviors without disrupting the existing physical environment (Yin et al., 2018;Shanon, 1998). The empirical investigation was conducted at the railway level crossing on Jl. Rawa Simprug III and the adjacent Jl. Kramat Putal Senayan intersection in South Jakarta. Primary data consisted of a field inventory of signs and road equipment, traffic surveys conducted over two weekdays and one weekend day, measurements of crossing-closure duration and queue length, and electrical load identification for the proposed automatic crossing system. Secondary data included local climatological information, train-operation frequency, and supporting design inputs derived from the underlying research dataset.

Traffic performance was analysed using the (Pedoman Kapasitas Jalan Indonesia, 2023) framework. The main indicators were traffic flow, degree of saturation, average control delay, queue probability, and level of service. Existing conditions were compared with two post-implementation traffic-management scenarios. To strengthen the interpretation of the analytical results, the operating scenarios were also examined through PTV VISSIM microsimulation, consistent with earlier studies on railway crossing operations and pre-emption analysis (Anagnostopoulos, 2025;Tey et al., 2012;Larue et al., 2020; Chen et al., 2022;Cho et al., 2011). The electrical demand of the proposed system was estimated from the operating characteristics of each field device, including barrier motors, audible warning devices, flashing lamps, proximity sensors, barrier lamps, a control unit, and communication auxiliaries. Both intermittent and continuous loads were considered in order to estimate installed power, daily energy use, and the demand profile that the storage system had to support. HOMER Pro was then used to compare four power-system families: PV-battery-grid, PV-wind-battery-grid, off-grid PV-battery, and off-grid PV-wind-battery. The principal input parameters were average solar radiation of 4.76 kWh/m2/day, average wind speed of 3.38 m/s, average temperature of 29.27 C, and daily energy demand of approximately 17.20 kWh/day.

The simulated energy architecture used a coupled AC/DC bus configuration in which the main crossing load, the grid, and the micro wind turbine were connected to the AC bus, while the solar PV array and the battery storage system were connected to the DC bus through a bidirectional converter. The overall workflow linked the field-derived load profile and local renewable-resource inputs to HOMER Pro for power-supply sizing, while traffic survey data and operational scenarios were evaluated in VISSIM. The two simulation domains were interpreted jointly to assess whether the proposed crossing upgrade could be supported by a feasible renewable-energy configuration without degrading adjacent traffic performance.

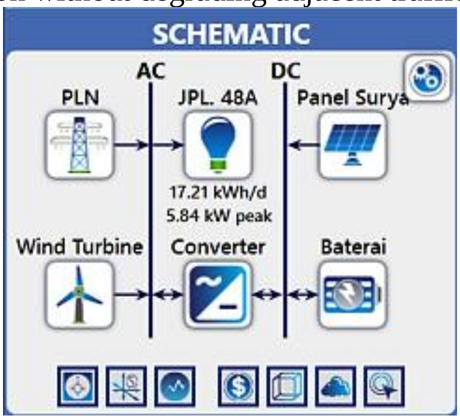

Figure 1. Schematic diagram of the proposed hybrid renewable energy architecture modelled in HOMER Pro.

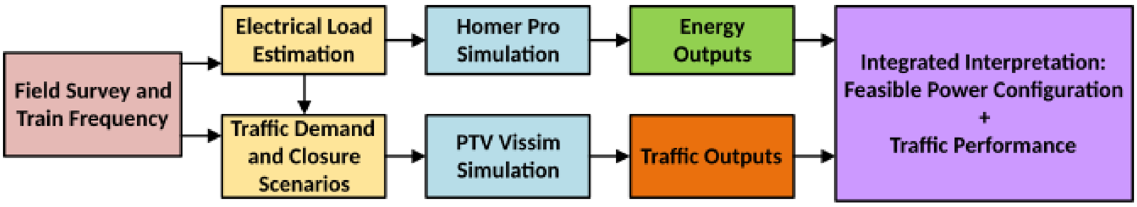

Figure 2. Integrated energy-traffic simulation workflow used in this study.

Table 1. Study-site characteristics and main input parameters

Parameter	Value
Study location	Jl. Rawa Simprug III, South Jakarta

Crossing type	Official unguarded railway level crossing
Commuter train frequency	203 train movements/day
Traffic survey period	2 weekdays + 1 weekend day
Existing traffic flow	1,752 pcu/h
Average solar radiation	4.76 kWh/m2/day
Average wind speed	3.38 m/s
Average temperature	29.27 C
Installed connected load	770 W

Table 2. Electrical load profile of the proposed automatic crossing system

Component	Quantity	Average power	Operating mode
Barrier DC motor	2 units	250 W	Intermittent
Siren / speaker	2 units	30 W	Intermittent
Flashing lamps	4 units	15 W	Intermittent
Proximity sensor	4 units	5 W	Continuous
Barrier lamps	6 units	10 W	Intermittent
Controller unit	1 set	40 W	Continuous
Communication auxiliary	1 set	30 W	Continuous
Total	-	770 W	-

RESULTS AND DISCUSSION

Results

Before intervention, the study site operated under constrained traffic conditions. Baseline flow reached 1,752 pcu/h, the degree of saturation was 1.14, average control delay was 29.31 s/veh, queue probability ranged from 53% to 106%, and the corresponding level of service was D. These values indicate that the crossing already functioned within a stressed urban traffic environment, so the proposed improvement needed to be evaluated in relation to the surrounding intersection rather than as an isolated device installation.

The energy analysis showed that the installed load of 770 W translated into a daily demand of approximately 17.20 kWh/day. Because several loads were intermittent and synchronized with train arrivals, storage support remained necessary even though the average daily energy requirement was moderate. HOMER Pro identified the most attractive grid-assisted configuration as 5.55 kW solar PV with six battery units and grid backup. This option yielded the lowest reported net present cost of approximately IDR 40.9 million and the lowest electricity cost of approximately IDR 427.12/kWh. By contrast, the grid-only benchmark reached an NPC of about IDR 93.8 million and a cost of energy of about IDR 1,143/kWh, while the addition of a micro wind turbine increased both NPC and electricity cost under local resource conditions.

Table 3. Candidate HOMER configuration sizing results

Scenario	PV (kW)	Micro wind (unit)	Battery (unit)	Grid backup	Converter (kW)
PV-battery-grid (optimal)	5.55	0	6	Yes	3.26
PV-wind-battery-grid	5.25	1	6	Yes	3.19
Off-grid PV-battery	6.73	0	9	No	6.18
Off-grid PV-wind-battery	6.65	1	9	No	5.83

Table 4. Selected HOMER outputs for the compared power configurations

Configuration	Reported NPC	Electricity cost	Interpretation
Grid only	IDR 93.8 million	IDR 1,143/kWh	Operationally simple, but highest lifecycle cost
Solar PV 5.55 kW + 6 batteries + grid backup	IDR 40.9 million	IDR 427.12/kWh	Best-performing configuration
Solar PV + micro wind + grid	IDR 45.6 million	IDR 493.31/kWh	Wind addition did not improve site efficiency

The comparison also showed that off-grid alternatives required larger PV and battery capacities than grid-assisted options. This result indicates that the local solar resource is adequate for the site, while grid backup reduces storage requirements and improves the practical suitability of the system for a dense urban crossing. The operational stability of the optimal configuration is further illustrated by the simulated power-dispatch profile, which shows that the system consistently serves the load while renewable penetration increases during daylight hours.

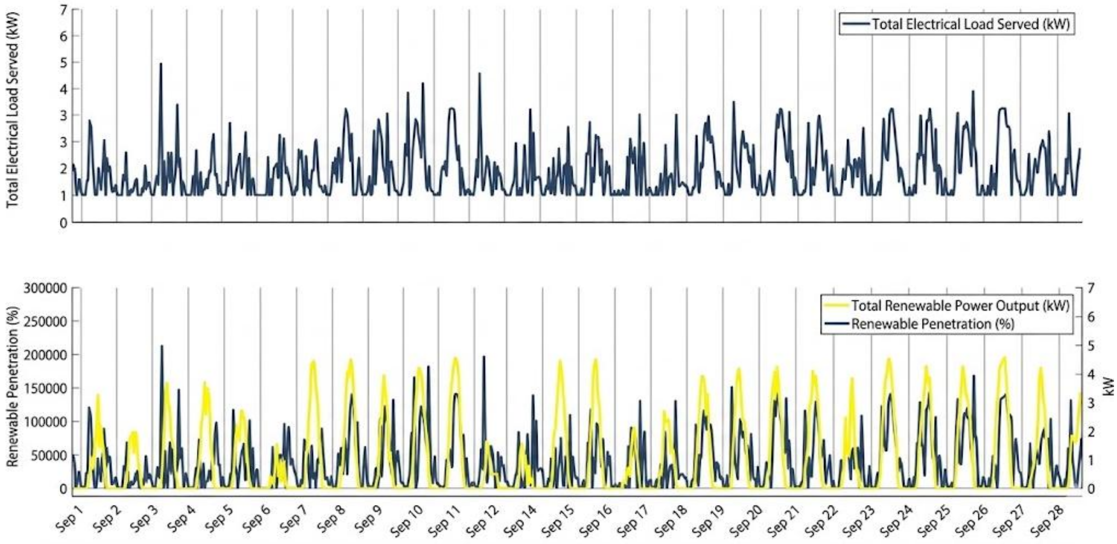

Figure 3. Dynamic performance profile illustrating total electrical load served and renewable energy penetration for the optimal configuration.

The integration of automated gate operation with traffic engineering produced substantial operational improvement. Scenario 1 reduced the degree of saturation from 1.14 to 0.81 and average delay from 29.31 to 13.66 s/veh. The best result was obtained in Scenario 2, in which the degree of saturation fell further to 0.74 and average delay to 12.59 s/veh, corresponding to level of service B. Reported service time also decreased from 177 s under existing conditions to 146 s after implementation.

Table 5. Traffic performance comparison before and after implementation

Condition	Flow (pcu/h)	Degree of saturation	Delay (s/veh)	Level of service
Existing	1,752	1.14	29.31	D
Scenario 1	1,752	0.81	13.66	B
Scenario 2	1,328	0.74	12.59	B

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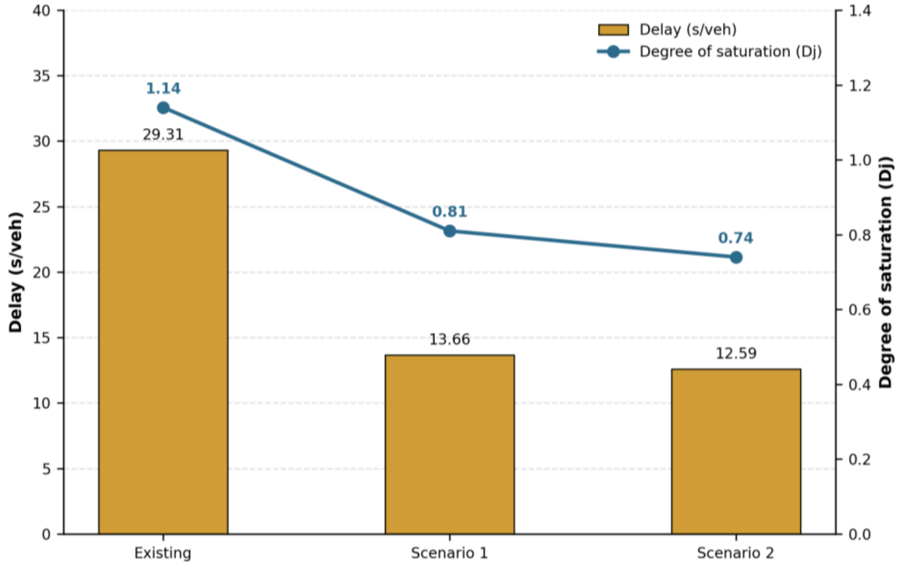

Figure 4. Traffic performance before and after implementation of the proposed system.

Queue-length results further clarify the effect of the intervention. Under the existing condition, maximum queues reached 147.8 m on the major approach and 118.0 m on the minor approach. In Scenario 1, the reported major-approach queue dropped to 39.3 m, indicating that the combination of automation and traffic management can substantially reduce blockage on the dominant stream. However, some approaches still exhibited long queues, including 120.5 m on the reported minor approach under Scenario 1 and 118.4 m on the reported major approach under Scenario 2. This suggests that no single operating strategy optimises every approach simultaneously.

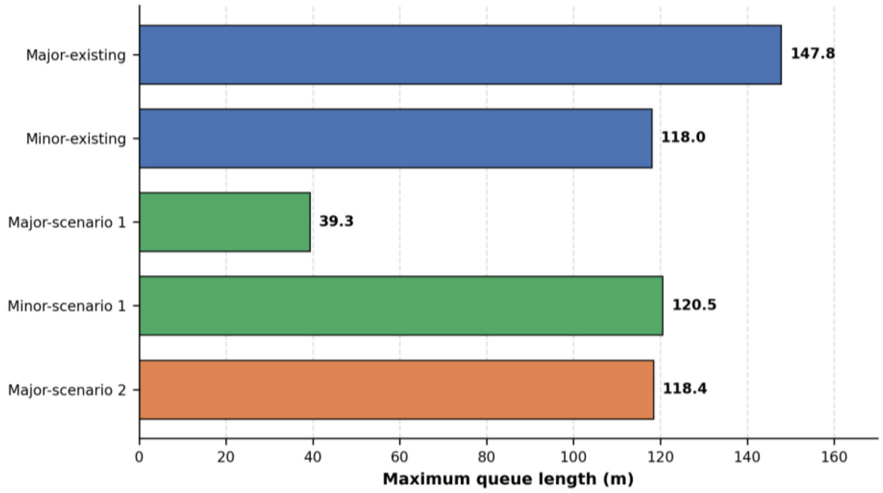

Figure 5. Maximum queue length across reported approaches and scenarios.

Discussion

The combined results indicate that renewable-energy-based automation is technically feasible for the study site because the electrical demand is modest, the local solar resource is sufficient to support daily charging, and grid backup enhances operational resilience. The comparison among HOMER scenarios also shows that adding wind generation does not automatically improve system performance; technology choice remains sensitive to site-specific resource conditions.

From the traffic perspective, the study shows that automation alone is not enough to guarantee network improvement. The benefits emerged when automated gate operation was accompanied by traffic engineering, indicating that closure timing, intersection coordination, and route distribution must be managed together. This interpretation is consistent with earlier findings on delay-reduction treatments, pre-emption strategies, and corridor signal coordination near railway crossings (Larue et al., 2020; Cho et al., 2011; Chen et al., 2018; Chen et al., 2022; Pasha et al., 2021).

These findings suggest that renewable-energy-powered automation can be a viable upgrading strategy for officially recognized but unguarded crossings in dense urban environments. At the same time, the study remains limited to one site, so the results should not be generalized mechanically to all Indonesian crossings. Even so, the integrated HOMER Pro-VISSIM framework offers a replicable planning approach for other locations with comparable load profiles, surrounding network conditions, and implementation objectives.

CONCLUSION

This study demonstrates that integrated renewable-energy simulation and traffic-performance analysis are essential for planning automated railway level crossings in dense urban environments. At the study site, the existing traffic condition was already saturated, while the proposed system presented a modest but mission-critical electrical demand. From the energy perspective, the site favored a solar-led hybrid configuration rather than a wind-augmented alternative, with the optimal HOMER Pro result consisting of 5.55 kW solar PV, six batteries, and grid backup. From the traffic perspective, automation alone was not sufficient; the best outcome emerged when automated gate operation was combined with traffic engineering, reducing the degree of saturation from 1.14 to 0.74, lowering average delay from 29.31 to 12.59 s/veh, and improving the level of service from D to B. These findings support renewable-energy-powered crossing automation as part of a broader operational intervention. Future studies should extend meteorological observations, validate the configuration under field operation, and compare multiple crossing typologies across Indonesian cities.

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