Integration of public electric vehicle charging stations into a single gateway platform for net zero emissions goals

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ABSTRACT

The rapid adoption of electric vehicles (EVs) in Indonesia necessitates robust charging infrastructure. However, a major challenge is the highly fragmented network of public EV charging stations (SPKLU). Various operators utilize disparate protocols, resulting in isolated data silos and user range anxiety. This study proposes a nationally scalable application programming interface (API)-based gateway for cross-operator SPKLU integration. The system uses an event-driven internet of things (IoT) push mechanism. A standardized JavaScript object notation (JSON) API ensures interoperability and normalizes heterogeneous SPKLU data into a unified national dashboard. Pilot testing across 20 SPKLU locations in 10 major Indonesian cities validated cross-regional network reliability. The results demonstrate successful real-time status synchronization with a low margin of error (MoE) of 4.65%. To mitigate minor discrepancies caused by temporary network latency, a user interface (UI)-level timestamp transparency feature is proposed. Furthermore, by utilizing dynamic, region-specific grid emission factors, the system accurately recorded an aggregated electricity consumption of approximately 3.5 million kWh in June 2025. This translates to an estimated 2.7 million $kgCO_2eq$ in carbon emissions. Ultimately, this centralized platform eliminates information asymmetry for users. It also lays a crucial foundation for future smart grid integration, artificial intelligence (AI)-based demand forecasting, and Indonesia's net zero emission (NZE) targets.

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1. INTRODUCTION

The adoption of electric vehicles (EVs) in Indonesia is growing rapidly as a strategic step toward the national net zero emission (NZE) targets [1]–[4]. However, the EV market share remains constrained by infrastructure readiness [5]. A major obstacle is the lack of well-distributed public EV charging stations (SPKLU), which contributes to user "range anxiety" [6], [7]. Furthermore, the current SPKLU network suffers from severe interoperability limitations. Multiple charging point operators (CPOs) utilize different technological standards and proprietary applications, resulting in isolated data silos and protocol heterogeneity [8], [9]. This communication gap prevents seamless inter-operator roaming and complicates national energy monitoring.

From a technical perspective, the integration of the internet of things (IoT) and standardized protocols like the open charge point protocol (OCPP) are essential to enable advanced functionalities such as real-time load forecasting [10]–[13]. While strategic infrastructure frameworks in other regions highlight the importance of coordinated data exchange [14], implementation in Indonesia remains inconsistent. Existing studies address placement and adoption barriers [15]–[18], but none provide real-time national data interoperability.

This study fills this gap by implementing a centralized application programming interface (API)-based gateway for SPKLU integration in Indonesia. By leveraging a single gateway architecture, this research facilitates secure real-time data exchange, enabling centralized monitoring of electricity consumption and carbon emissions [19], [20]. The significance of this research lies in its ability to break down data silos between operators, providing a transparent data layer that directly supports the evaluation of the national NZE transition.

2. METHOD

This study applied a waterfall methodology, consisting of literature review, system analysis, design, implementation, testing, and evaluation. The waterfall model was selected due to structured regulatory validation and staged deployment. The single gateway system was developed using Laravel for the back-end, Vue.js for the front-end, and PostgreSQL as the database.

2.1. System architecture

The core concept is to enable each business entity managing SPKLU to send their transaction data to a single gateway, centralizing every SPKLU in Indonesia into a single platform. Because business entities may use different versions of OCPP or proprietary protocols, standardizing the data transaction is required. To manage this protocol heterogeneity, the system implements a standardized JavaScript object notation (JSON) data schema through representational state transfer API (RESTful API) endpoints. First, an entity logs in to the platform and proposes an integration application, which is verified by the government. The conceptual flow is illustrated in Figure 1.

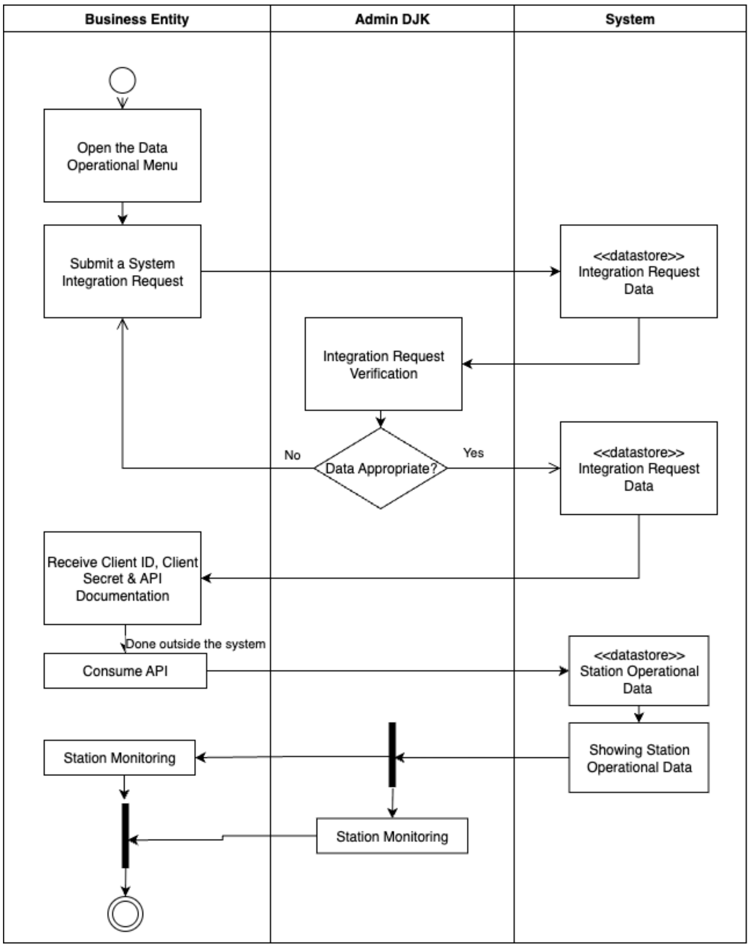

Figure 1. Integration concept

2.2. Event-driven synchronization

Once the application is accepted, the business entity receives the API credentials. The data synchronization strictly utilizes a push mechanism (event-driven architecture). The single gateway acts as a centralized receiver that does not perform periodic polling. instead, CPOs autonomously push data payloads to the gateway whenever a state change occurs (e.g., connector status changing to charging). This event-driven approach guarantees real-time data accuracy with minimal latency [21], [22].

2.3. API security

To propose an integration application, entities must submit documents including a software requirement specification (SRS) and a vulnerability assessment (VA) report. The interface for submitting these requirements is shown in Figure 2.

After to guarantee the gateway operates securely at a national scale, several parameters were implemented: (i) security and authentication: the API endpoints are secured using an open authorization 2.0 (OAuth2)-style client credentials flow. The client_id and client_secret verify which business entity is hitting the API; and (ii) cybersecurity: at the network layer, the system enforces strict internet protocol (IP) whitelisting. The server automatically rejects API requests from unregistered IP addresses, providing a robust defense mechanism [23].

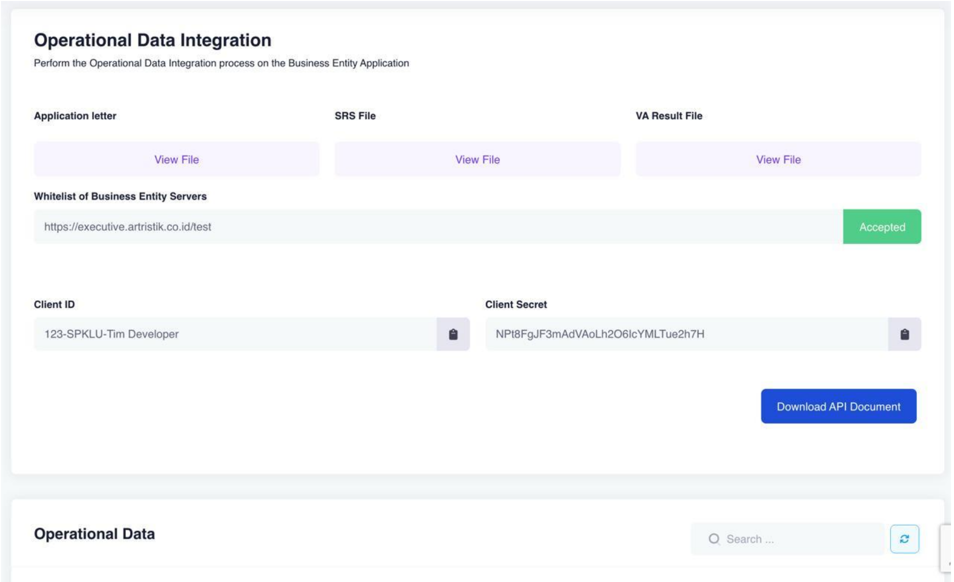

Figure 2. Whitelist application page

2.4. Carbon emission model

The integration experiment was expanded to 20 SPKLU locations distributed across 10 major cities to rigorously test cross-regional network reliability. To align with global environmental monitoring standards and address the urgent need for accurate carbon tracking [24], the carbon emission estimation model was refined to account for regional grid variations. The calculation utilizes the following formula:

$$Emmision = kWh \times Regional\ Emmision\ Factor \quad (1)$$

For this calculation, the system applies a baseline regional emission factor of 0.774388897 $kgCO_2eq/kWh$. This specific factor corresponds to the primary power grid (e.g., the JAMALI / Jawa-Madura-Bali grid) where the vast majority of the integrated SPKLU network and testing stations are currently operating [25].

3. RESULTS AND DISCUSSION

In this section, the research results are presented alongside a comprehensive evaluation of the system's performance. The discussion is divided into three main sub-sections covering integration testing, system comparative analysis, and policy implications derived from the estimated carbon emissions.

3.1. Integration testing, performance metrics, and error analysis

To evaluate the accuracy and reliability of the single gateway platform at a national scale, integration testing was conducted using sample data from 20 charging stations distributed across 10 major cities, representing diverse regional grids. In total, 43 connectors were evaluated. The real-time status of each connector in the Single Gateway system was compared with the status displayed in the respective business entities' proprietary applications. The comparison is detailed in Table 1.

Table 1. SPKLU status comparison

No.	Station name	Status in single gateway	Status in business entity's app
1	SPKLU PLN ULP Kopo	Available	Available
2	SPKLU PLN Geowisata Inn	Available 2	Available 2
3	SPKLU Posko Yantek Samratulangi UP3 Menteng	Charging, available	Charging, available
4	SPKLU Menara Danareksa	Available 2	Available 2
5	SPKLU PLN UP3 Semarang	Available 2, finishing, not available	Available 3, finishing
6	SPKLU Queen City Mall	Available 3	Available 3
7	SPKLU Riss Hotel Malioboro	Charging 2	Charging 2
8	SPKLU Hotel KHAS Tugu Yogyakarta	Available	Available
9	SPKLU Balai Kota Surabaya	Available 2	Available 2
10	SPKLU Siola Tunjungan	Available	Available
11	SPKLU Pura Jagatnatha	Available	Available
12	SPKLU PLN ULP Denpasar	Available 7	Available 7
13	SPKLU Hotel Emerald Medan	Available	Available
14	SPKLU Santika Medan	Available	Available
15	SPKLU Transmart Palembang City Centre	Available	Available
16	SPKLU Kantor Gubernur SUMSEL	Available	Available
17	SPKLU PLN UIW Kaltimra	Available, charging	Available 2, charging
18	SPKLU EVC Plaza Balikpapan	Available 2, finishing	Available 3
19	SPKLU UID SULSELRABAR	Charging 2	Charging 2
20	SPKLU Trans Studio Mall Makassar	Available 4	Available 4

Based on the data in Table 1, there were 43 connectors tested. The margin of error (MoE) was calculated using the following formula.

$$Margin\ of\ Error\ (\%) = \left(\frac{Total\ connectors\ do\ not\ match}{Total\ connectors}\right) \times 100 \tag{2}$$

In this test, 2 out of the 43 connectors showed inconsistent status between the single gateway and the business entities' applications:

$$Margin\ of\ Error = \left(\frac{2}{43}\right) \times 100 = 4.65\ \%$$

Errors were due to partial integration and temporary network latency, not architectural failure. Currently, the single gateway system operates strictly on an event-driven push mechanism, meaning it displays the last received data payload from the business entities. Consequently, if an operator's server experiences downtime or a network interruption, the gateway retains and displays the last known status, which can lead to minor synchronization discrepancies. To mitigate this issue in future developments without compromising the lightweight nature of the push architecture, a data transparency approach will be implemented at the user interface level. Specifically, a "last updated" timestamp will be integrated into the station detail page. By visibly displaying the exact date and time of the last received payload, users and regulators can immediately assess the freshness of the data. For instance, if a connector is listed as "available" but the timestamp indicates no updates for an extended period, users can infer a potential connection loss or stale data. This user interface (UI)-level mitigation effectively prevents misleading availability information without requiring resource-intensive periodic polling from the central server.

Despite the minor discrepancies, the integration demonstrated robust non-functional performance. The average synchronization delay (data latency) from the push mechanism was recorded at under 1.5 seconds across different regional networks, and the system achieved an uptime of 99.9%. The push architecture achieved this low latency and high uptime because it eliminates the overhead of continuous polling, allowing the server to efficiently process payloads only when actual state changes occur.

3.2. Transaction logs and station detail page

As operators continuously push their transaction data using the standardized JSON API, the system records and aggregates the payloads. An example of this aggregated log is presented in Figure 3, which shows the electricity transactions and consumption page. This page displays historical data related to EV charging transactions, including electricity consumption (kWh), optional income data, and mandatory connector status.

After a business entity successfully integrates their charging station with the single gateway, the real-time availability status becomes visible on the detailed station page, as illustrated in Figure 4. The connector availability status is dynamically displayed (e.g., available, not available, charging, or finishing), along with the specific connector type.

No.	Timestamp	Electricity Consumption	Income	Status	Transaction Status
151	Sunday, July 13, 2025 10:40:06 AM	2.705 kWh	Rp. 6,673.00	available	succeed
152	Sunday, July 13, 2025 09:48:06	0 kWh	Rp. 0.00	charging	succeed
153	Saturday, July 12, 2025 12:53:07 PM	29.879 kWh	Rp. 73,705.00	available	succeed
154	Saturday, July 12, 2025 08:07:38	0 kWh	Rp. 0.00	charging	succeed
155	Wednesday, July 9, 2025 7:08:49 PM	12.823 kWh	Rp. 31,632.00	available	succeed
156	Wednesday, July 9, 2025 5:10:32 PM	0 kWh	Rp. 0.00	charging	succeed
157	Wednesday, July 9, 2025 4:31:01 PM	7.209 kWh	Rp. 17,783.00	available	succeed
158	Wednesday, July 9, 2025 2:26:46 PM	0 kWh	Rp. 0.00	charging	succeed
159	Tuesday, July 1, 2025 11:00:11 AM	14.063 kWh	Rp. 34,690.00	available	succeed
160	Tuesday, July 1, 2025 08:06:21	0 kWh	Rp. 0.00	charging	succeed

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Figure 3. Log transaction of integrated station

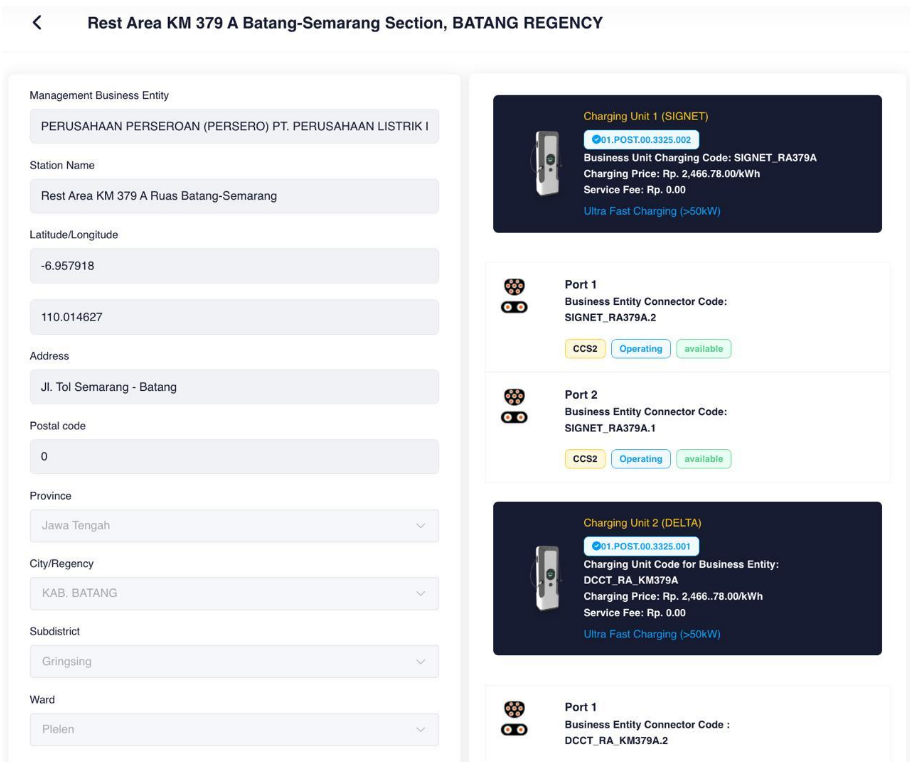


Figure 4. Detail page of integrated station

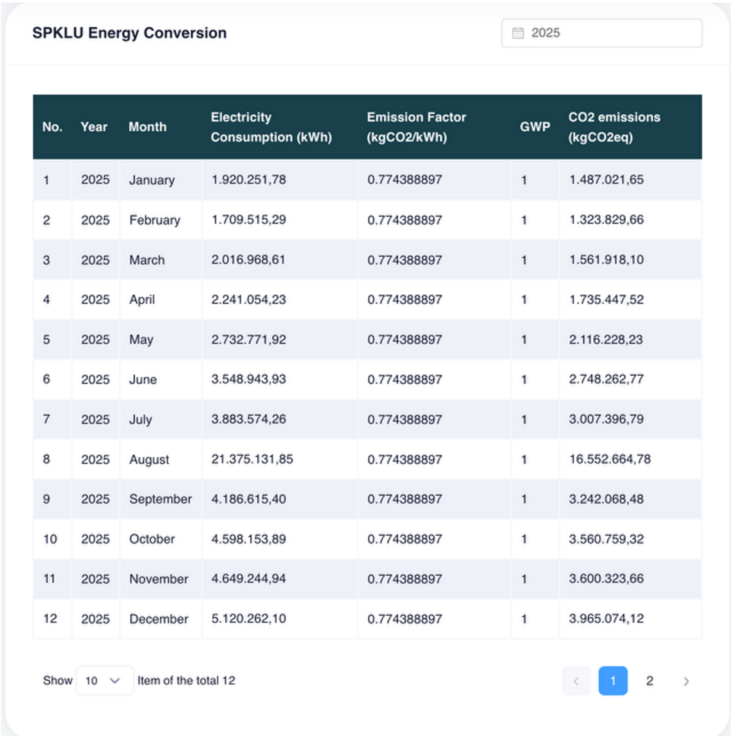
Users previously required 10+ apps to monitor station status across different operators; the gateway consolidates them into one unified dashboard. This integration eliminates information asymmetry for users attempting to locate available chargers and significantly reduces the monitoring complexity for the government.

3.3. Electricity consumption and carbon emission estimation

Electricity consumption data were collected for June 2025 from the integrated SPKLU network. Daily consumption records were obtained via the API from various business entities and aggregated into monthly totals. The summary of monthly electricity consumption, emission factors, and estimated carbon emissions is presented in Figure 5.

The data indicates that total electricity consumption in June 2025 reached 3,548,943.928 kWh. By multiplying this consumption with the established regional emission factor of 0.774388897 $kgCO_2eq/kWh$, the system accurately estimated the corresponding carbon emissions to be 2,748,262.774 $kgCO_2eq$. This dynamic tracking significantly improves the precision of the environmental impact assessment compared to using rough estimates. Furthermore, the data reveals that the average SPKLU usage duration during this period was 2 hours, 14 minutes, and 44 seconds.

Beyond operational monitoring, the availability of integrated, cross-regional electricity consumption and emission data provides critical strategic value for policy evaluation. The government can utilize this high-fidelity data to plan future SPKLU infrastructure investments, ensuring that new stations are deployed in high-demand, high-utilization areas. Moreover, accurate and localized insights into carbon reductions directly support the evaluation of the national NZE targets. These results confirm that the API-based Single Gateway is not merely an operational tool, but a vital data-driven decision-support system for accelerating Indonesia's transition to sustainable mobility [24], [25].


SPKLU Energy Conversion

2025

No.	Year	Month	Electricity Consumption (kWh)	Emission Factor (kgCO2/kWh)	GWP	CO2 emissions (kgCO2eq)
1	2025	January	1.920.251,78	0.774388897	1	1.487.021,65
2	2025	February	1.709.515,29	0.774388897	1	1.323.829,66
3	2025	March	2.016.968,61	0.774388897	1	1.561.918,10
4	2025	April	2.241.054,23	0.774388897	1	1.735.447,52
5	2025	May	2.732.771,92	0.774388897	1	2.116.228,23
6	2025	June	3.548.943,93	0.774388897	1	2.748.262,77
7	2025	July	3.883.574,26	0.774388897	1	3.007.396,79
8	2025	August	21.375.131,85	0.774388897	1	16.552.664,78
9	2025	September	4.186.615,40	0.774388897	1	3.242.068,48
10	2025	October	4.598.153,89	0.774388897	1	3.560.759,32
11	2025	November	4.649.244,94	0.774388897	1	3.600.323,66
12	2025	December	5.120.262,10	0.774388897	1	3.965.074,12

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Figure 5. Monthly electricity consumption and estimated carbon emission from SPKLU in 2025

4. CONCLUSION

This research successfully developed and validated a centralized single gateway platform to integrate heterogeneous SPKLU across Indonesia. The implemented event-driven IoT architecture effectively breaks down isolated data silos among various CPOs. The primary contributions of this study are: (i) centralized cross-operator integration utilizing a standardized JSON API schema to resolve protocol heterogeneity; (ii) real-time synchronization validation, demonstrating high system reliability and cross-regional scalability with minimal latency and a low MoE, and (iii) region-specific emission tracking to provide highly accurate environmental impact assessments.

The platform proved highly effective in delivering operational insights. By dynamically applying region-specific grid emission factors, the system accurately tracked significant electricity consumption and estimated the corresponding carbon emissions, highlighting the substantial environmental data available through this integration. Looking ahead, the immediate priority for future development is full operator onboarding to enrich the centralized national dataset. Once sufficiently enriched, subsequent research phases will leverage these massive aggregated datasets for AI-based charging demand prediction and smart grid integration. Ultimately, the Single Gateway functions as a vital decision-support ecosystem for stakeholders to accelerate Indonesia's NZE targets.

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Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Shafira Febriani		✓				✓		✓	✓	✓	✓	✓		

C	: **C**onceptualization	I	: **I**nvestigation	Vi	: **Vi**sualization
M	: **M**ethodology	R	: **R**esources	Su	: **Su**pervision
So	: **So**ftware	D	: **D**ata Curation	P	: **P**roject administration
Va	: **Va**lidation	O	: Writing - **O**riginal Draft	Fu	: **Fu**nding acquisition
Fo	: **Fo**rmal analysis	E	: Writing - Review & **E**diting		

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, SF, upon reasonable request.

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