Design architecture of interoperability between electric vehicle charging operators and regulators

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ABSTRACT

The rapid expansion of electric vehicle (EV) charging infrastructure has resulted in a fragmented ecosystem characterized by multiple charging station (CS) operators and limited interoperability between operator platforms and regulatory authorities. This fragmentation creates challenges for service continuity, user experience, and evidence-based policy development. To address these issues, this paper proposes a regulatory-centric interoperability framework that enables standardized data exchange across heterogeneous CS management systems. The proposed solution employs a lightweight representational state transfer (REST) application programming interface (API)-based interoperability model in which the regulator assumes a dual role as both verifier and national data aggregator, allowing operators to share essential operational and transaction data without requiring proprietary protocol alignment. The framework demonstrates that secure and standards-compliant data harmonization can be achieved by leveraging existing backend charging data, thereby improving network visibility, regulatory oversight, and coordination among operators. By supporting structured reporting and cross-operator information exchange, the proposed approach enhances service reliability and facilitates informed infrastructure planning. This study contributes a scalable and policy-aligned interoperability foundation that supports the sustainable development of EV charging infrastructure and provides a basis for future extensions toward advanced grid integration and data-driven mobility governance.

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1. INTRODUCTION

The increasing concentration of carbon emissions has driven many countries to adopt policies aimed at reducing greenhouse gas emissions, particularly in the transportation sector, which remains one of the largest contributors to local and global air pollution [1]. Indonesia, as one of the countries with a high volume of motorized vehicles, contributes significantly to transportation-related emissions [2]. In response, electric vehicles (EVs) are promoted as a key alternative to internal combustion engine vehicles (ICEVs) to reduce carbon dioxide emissions and improve air quality [3], [4].

As one of the world's major ecological regions, often referred to as the "lungs of the world," Indonesia has strengthened its commitment to sustainable transportation through national policies, including the acceleration of EV adoption as mandated by Presidential Decree No. 55 of 2019 [5], [6]. Following these policies, the number of EVs in Indonesia has increased steadily [7]-[9], reaching approximately 33,600 vehicles by the end of 2022 [8]. To support this growth, local governments have introduced incentives such as tax reductions, subsidies, and infrastructure development programs [10], resulting in the deployment of 1,081 public charging stations (PCSs) and 1,772 BSS nationwide by the end of 2023 [11]. Additionally, the Ministry of Energy and Mineral Resources issued Ministerial Regulation No. 13 of 2020, which governs the implementation of the PCS business [12]. Under this regulation, operators can legally establish and manage PCS businesses per the set provisions.

Several operators, including private companies and state-owned enterprises, have already obtained permits. This demonstrates the collaborative effort between the government, state-owned companies, and the private sector in expanding EV infrastructure. Each operator or business entity has been operating across various regions in Indonesia, but they follow independent business models, use different applications, and adopt distinct customer approaches. As a result, the lack of standardization among operators has made it difficult for the government to gather comprehensive data to assess the growth of the EV ecosystem since the regulation was introduced [13], [14]. Moreover, operators have deployed PCS stations with varying capacities and connector types in different locations [15]. This situation highlights the need for data integration and interoperability between multiple operators and the government. A unified system would help policymakers make informed decisions to support the long-term development of the EV ecosystem.

From a customer perspective, several issues have emerged, including difficulties in topping up balances across different operators, the limited availability of charging locations, and the inconvenience of installing multiple applications for payments. Additionally, the government currently lacks visibility into the usage of charging stations (CSs) operated by different providers. According to several studies, the lack of interoperability between various charge points operators (CPOs) and the government has led to a fragmented charging infrastructure, further complicating EV adoption and management.

Internationally, interoperability has been addressed through various communication protocols and platforms, including open charge point operators for charger-to-backend communication and roaming-oriented frameworks such as open charge point interface (OCPI), open clearing house protocol (OCHP), open intercharge protocol (OICP), and e-mobility service provider (e-MSP) models [16]. These solutions have been widely implemented in Europe and other regions to enable cross-network roaming, smart charging, and interoperability between charging operators and service providers. However, while such frameworks provide strong technical foundations, their implementation is highly dependent on regulatory structures and market governance models.

In Indonesia, a unified interoperability framework that aligns international standards with national regulations and institutional roles has yet to be fully established. This gap is also reflected in the existing literature, where most studies focus primarily on protocol-level interoperability or commercial roaming mechanisms between operators, with limited attention to regulator-led integration and national data governance. Few works explicitly address how interoperability can be structured to support regulatory verification, aggregated national reporting, and policy-driven analytics within the Indonesian EV ecosystem. Consequently, there remains a research gap in developing an interoperability architecture that bridges technical interoperability standards with regulatory oversight requirements.

To address this gap, this paper proposes a regulatory-centric interoperability framework in which the regulator assumes a dual role as both a verifier of charging infrastructure and a national data aggregator. The proposed solution employs a lightweight representational state transfer (REST) application programming interface (API)–based interoperability layer that enables multi-operator integration while leveraging standardized backend datasets already maintained by charging station management systems (CSMSs), without requiring proprietary protocol alignment. This study adopts a design-oriented research approach focusing on interoperability architecture and regulatory integration rather than payment mechanisms or quantitative performance benchmarking. The main objective of this research is to develop a scalable and standards-compliant interoperability framework tailored to Indonesia's regulatory context. The primary contributions of this work include: i) proposing a regulator-centered interoperability architecture; ii) integrating multi-operator backend data into a unified regulatory reporting structure; and iii) providing a governance-oriented foundation for future integration with smart grid systems, vehicle-to-grid technologies, and data-driven mobility planning.

2. INTEROPERABILITY IN ELECTRIC VEHICLE CHARGING NETWORKS

2.1. Definitions and key concepts

Interoperability is the seamless data exchange between systems, enabling EV charging processes to connect across various equipment models and vehicle types through information exchange and process control

[17]. An EV charging system consists of three main components—EV, charging facility, and connector—requiring effective coordination. OCPP has standardized communication between CSs and central management systems, with open charge alliance (OCA) membership exceeding 220 participants in 43 countries over the past two years [18]. The Netherlands implements open smart charging protocol (OSCP) [19], while OCPI is widely adopted in Europe, including the Netherlands, Belgium, Luxembourg, Germany, Austria, and France [20]. Interoperability also supports demand response via open automated demand response (OpenADR) [21]. Globally, OICP by Hubject connects 767 partners in 52 countries with over 250,000 CSs [22]. OCHP, managed by Smartlab and ElaadNL, operates in Germany and the Netherlands [23]. The e-MSP protocol is also common in Europe, with GreenFlux integrating with Mobi.E in Portugal [24]. In PCS systems, interoperability can occur between CS networks, CS machines and networks, vehicles and electricity networks, or physically between plugs and EVs [25]. This discussion focuses on inter-network interoperability, where independent networks, such as those owned by state-owned companies, can connect to others through cooperation agreements [26]. CSMS is vital for managing multiple PCS units, with PCS communicating via OCPP, which supports simple object access protocol (SOAP) and WebSocket. Customers must register with a CSMS to transact; with multiple CSMS platforms, separate registrations are required for each provider [27].

2.2. Existing solutions for enhancing interoperability and roaming

OCPP is a communication protocol developed by the OCA to standardize interactions between EV CSs and central management systems. It supports two methods: WebSocket and SOAP. WebSocket uses JavaScript object notation (JSON) over a full-duplex connection for simultaneous, low-latency data exchange and real-time monitoring, which is essential for continuous EV charging operations. SOAP uses extensible markup language (XML) over hypertext transfer protocol (HTTP), offering cross-platform compatibility, robust error handling, and reliability in distributed systems. From version 1.6 onward, OCPP exclusively uses WebSocket; version 1.5 supported both. With Smart Charging, JSON WebSocket is expected to handle increasingly complex data. OCPP defines mandatory and optional messages. At the charging point, required messages include authorize, boot notification, data transfer, heartbeat, meter value, start transaction, and stop transaction. On the central system side, mandatory messages include change availability, change configuration, clear cache, data transfer, get configuration, remote start/stop transaction, reset, and unlock connector [28]. In operation, a charging session begins when the CP sends an authorization request to the CSMS (via card tap and QR scan). Once verified, the CS authorizes charging. During the session, messages are exchanged continuously for monitoring. When charging ends, the CP sends a termination request, the CS verifies the user, and sends final authorization to stop. The OCA provides certification and updates to ensure interoperability and compliance with the latest standards.

The OCPI is a protocol designed to enable roaming across different CS operators [29]. Initially developed in 2015, OCPI is now managed by the Netherlands Knowledge Platform for Public Charging Infrastructure (NKL). The protocol is publicly available, and registration is free. OCPI is the only roaming protocol built on a REST architecture, utilizing JSON format and supporting standard HTTP request methods such as GET, POST, PUT, PATCH, and DELETE, similar to a REST API. OCPI defines several key actors in the EV charging ecosystem, including e-MSP, CPO, navigation service provider (NSP), and national access points (NAP). It facilitates seamless data exchange between these entities to support various functions, such as roaming via hubs, peer-to-peer roaming, authorization, reservation, billing, session management, and remote start/stop of charging sessions [30]. OCPI also enables communication between roaming hubs, which serve as intermediaries for exchanging information between market participants. Additionally, it supports direct data exchange between e-MSPs and CPOs. However, not all platforms rely exclusively on hubs for communication. Some may prefer to maintain peer-to-peer connections, especially when a hub lacks support for new functionalities. The eMobility inter-operation protocol (eMIP) is a communication protocol developed by Groupement pour l'Itinérance des Recharges Électriques de Véhicules (GIREVE) to facilitate data exchange between operators, such as CPO and e-MSP. It enables these entities to communicate through their respective partners via GIREVE's inter-operations platform (IoP). This platform serves as a data aggregator, storing and managing information about EV charging infrastructure, which can be accessed through the IoP. Designed and maintained by GIREVE, eMIP aims to provide open access to CS. The protocol enables roaming through a data clearing house, access to a comprehensive charging point database, and smart charging capabilities. eMIP is based on SOAP and is primarily designed for real-time communication, though it also supports asynchronous messaging when needed. While eMIP is available for free, registration is required to access and use the platform [31].

2.3. Policy and regulatory frameworks

In terms of policy and regulatory frameworks, the implementation of interoperability technology varies across countries such as Britain, the Republic of Ireland, and the Netherlands. In Britain, the charging market operates under an independent model, meaning it is primarily managed by the private sector. There are approximately 14 charging networks or CS operators. The ownership of CSs is largely controlled or tendered by local, city, or central governments. CS service providers operate under contractual agreements with energy suppliers, while the responsibility for improving network quality falls on electrical utilities or electricity network operators. From a policy perspective, Britain does not have a national policy mandating interoperability between operators. However, in some regions, CS providers collaborate with other operators, allowing for limited data exchange and service integration despite the absence of a standardized nationwide framework.

In Ireland, the charging market follows an integrated model, meaning it is government-initiated and managed in collaboration with electricity network operators. There are approximately 0–5 charging networks or operators. CSs are primarily owned or tendered by electricity network operators or their subsidiaries. CS service providers operate under contracts with electricity operators, while network quality upgrades are the responsibility of the Irish electricity grid operator. From a policy perspective, Ireland does not have a national interoperability policy between operators. However, service providers offer subscription-based services that allow EV owners to charge across multiple networks through platforms like ZapMap, PlugShare, and OpenChargeMap. This helps streamline the user experience by reducing the need for multiple apps from Ireland's approximately six major operators: ESB eCars, EasyGo, Circle K, Ionity, Tesla, and Applegreen.

In contrast, the Netherlands follows a decentralized charging market model, where the private sector plays a leading role. There are approximately 15–20 charging networks or operators [32]. CS ownership is divided among local authorities, private companies, and government entities. Most CS stations are either directly owned or tendered by central or local governments. CS service providers include private operators specializing in charging infrastructure, energy companies, and other CS service providers. The responsibility for network quality falls on the PCS owner. From a policy perspective, the Netherlands has a national framework for interoperability, with industry associations such as CharIN and the OCA playing key roles in defining interoperability guidelines.

3. METHOD

The proposed interoperability model for PCS operators in Indonesia is based on a hub system that connects various PCS operators to a central hub entity, which will be overseen by a relevant government ministry. This approach is designed to streamline communication and data exchange among operators while ensuring compliance with national policies and international standards. The rationale behind this proposal will be detailed, including government regulations related to PCS, communication protocols, and international communication standards. The system should cover the architecture and data in terms of exchanging the data between operators and regulators safely and securely. The method could be modified to an existing system that has been installed on each CPO. The data from CP is encapsulated in a message between protocols, which have roles when the charging is processing. The packaging will be modified in our design due to regulations, protocols, and standards. In this case, we were separating the system into a regulator account and an operator account. The regulator receives the proposed data as input data for applying the new CP from the operator's account. To exchange data, the proposed system was tested by transmitting data via a REST API between the regulator and operator accounts. The authentication for transferring the data will be obtained by the token identification (ID) that should be encrypted by the system. The proposed system retrieves and processes data according to the function of each charging state. The state will cover the charging process until the end or until the plug is in place. On the other side, measured data passes the message in the charging process to inform the value of energy. The process will be explained in our proposed system, along with the architecture and data approach.

Implementing interoperability within the proposed design architecture requires seamless and standardized data exchange between charging operators, as illustrated in Figure 1. Real-time data sharing is essential to maintain system efficiency, ensure accurate operational visibility, and enhance user accessibility. On the operator side, critical datasets include connector type, connector status, error codes with diagnostic information, and vendor details with vendor-specific codes. These parameters, retrieved via the adopted communication protocol—commonly the OCPP—enable the CSMS to process and relay operational commands to the CS. Connector status is particularly important, as it determines whether a connector is available, occupied, or in a fault condition, and this information is dynamically updated in operator applications to inform customers of real-time charging availability. In OCPP v1.6, the charging process is categorized into nine distinct states of charge, providing granular insights into session progress and enabling precise operational analytics. When a fault occurs, the OCPP server updates the connector status message, facilitating accurate fault identification and rapid resolution. An example API request for retrieving connector status messages is shown in Figure 1, illustrating the mechanism for real-time monitoring and troubleshooting.

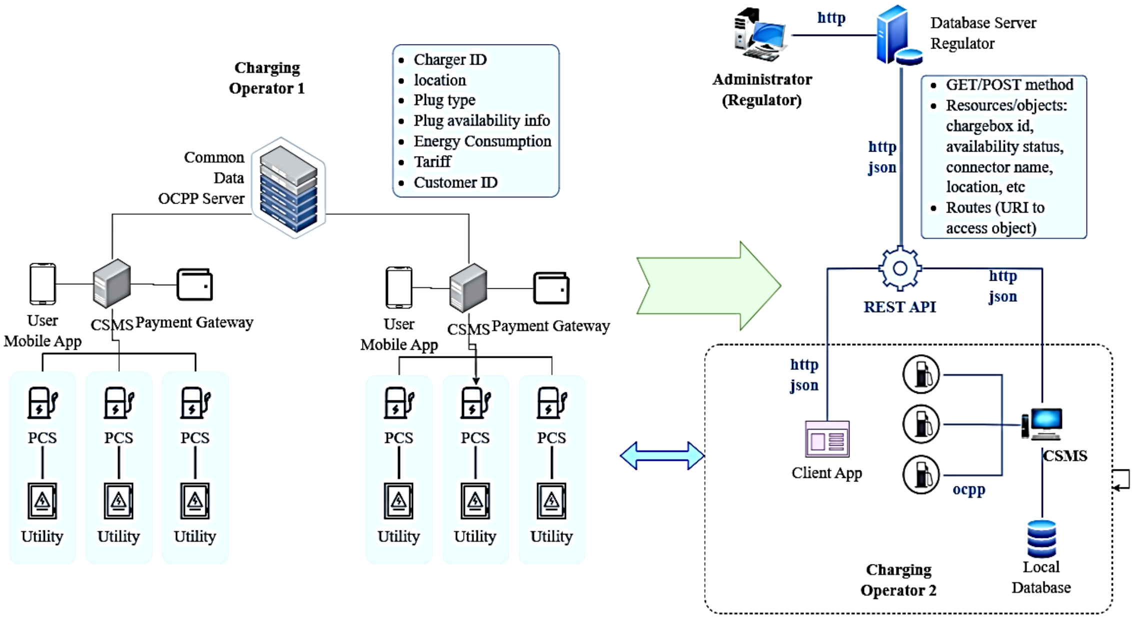

Figure 1. Conceptual design of a CS monitoring system for the regulator

The proposed system architecture integrates multiple source datasets into a unified charging infrastructure management platform. CS operational data from multiple operators includes location, plug type, availability status, and daily or monthly energy consumption in kilowatt-hours. The dataset also supports the calculation of carbon emission reductions, estimating the environmental benefits of transitioning from ICEVs to EVs. Data from CS operators is collected via secure APIs that provide periodic updates on station location, plug availability, and energy usage, while battery swapping station data is incorporated to ensure interoperability between plug-in charging and battery-swapping infrastructure, thereby enhancing network flexibility and user convenience. From a regulatory perspective, the Ministry of Energy and Mineral Resources (MEMR) mandates a centralized application platform for monitoring and managing all PCS in Indonesia. All PCS operators are required to register their stations through the platform to obtain a unique CS identity number issued by the government. Each active PCS must periodically transmit operational status to the platform using its assigned identity number, and operators must submit general operational datasets to the regulator to inform policy development, infrastructure planning, and performance benchmarking. This integrated system approach improves operational efficiency, enhances user experience, ensures compliance with interoperability standards, and supports Indonesia's EV roadmap by enabling data-driven decision-making and tracking measurable sustainability outcomes. In our proposed data, we combined the data selection from the regulation, standard, and protocol. From our perspective, we analyzed the functionality of the data and mapped the significant parameters. First, standardized data overlaps with communication protocol data, including transaction process, electricity parameters, and identification of chargers. Then, the key data exchanged in communication protocols primarily focus on chargers and customer management, such as authorization ID, backend central system uniform resource locators (URLs), and the roles of each party within the protocol.

To ensure effective data exchange and interoperability among various stakeholders, the essential data categories that should be communicated include location, connector type, charging duration, charging session start and end times, energy consumed, total transaction fee, user identification, heartbeat signals (for system monitoring), and connection status. By standardizing this information exchange from International Electrotechnical Commission (IEC) 61851-1 [33], IEC 63119-2, and IEC 61851-24 [34], all parties involved can leverage the data for efficient operations, seamless interoperability, and improved user experience. Figure 2 illustrates the intersection data among operators, structured based on standards, protocols, and government regulations. The summarized data effectively addresses the needs of various stakeholders by aligning with three key elements: communication protocols, industry standards, and regulatory requirements. For customers, data such as location, connector type, heartbeat signals, and connection status provide real-time availability information, enabling easier access to CSs. For operators, critical data, including charging duration, charging session time, energy consumption, and transaction fees, help monitor charging activities, ensuring transparency in billing and usage. By integrating these datasets, the system enhances charging infrastructure efficiency, improves customer experience, and supports regulatory compliance.

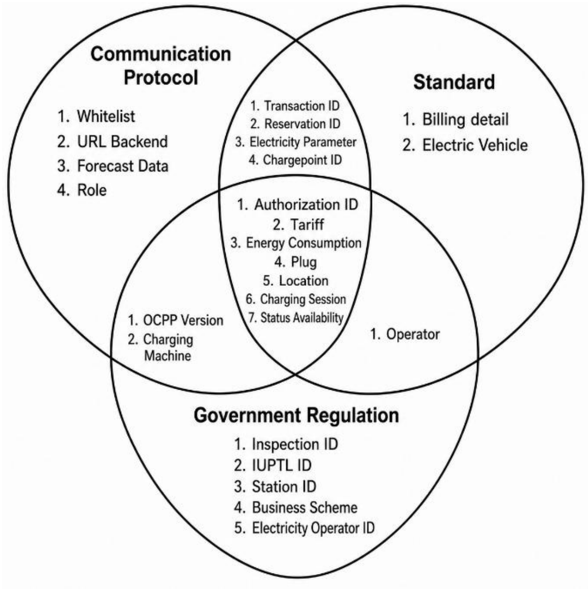

Figure 2. Proposed data interoperability model

The proposed interoperability framework employs a lightweight RESTful API to enable standardized data exchange between CS operators and a regulatory platform. Each operator deploys a secure API client that periodically submits operational and transaction data—such as station identifiers, connector types, charging duration, energy consumption, tariff information, availability status, and anonymized user identifiers—to a centralized interoperability hub in JSON format. Representative API functions include station registration, charging session reporting, and connector status updates, allowing heterogeneous CSMSs to integrate without modification to existing OCPP-based backend logic. All communications are conducted over encrypted HTTPS channels and protected using token-based authentication issued by the regulatory platform, with scoped access control, timestamps, and digital signatures applied to ensure data integrity and prevent unauthorized access. The architecture was validated through a prototype deployment consisting of simulated OCPP-compliant PCS backends and a centralized regulatory interoperability server. The test environment emulated charging sessions, connector status changes, and periodic heartbeat signals, which were transmitted to the regulator via the defined REST API to verify data consistency and architectural feasibility rather than system performance. To enhance reproducibility, Figure 3 illustrates the end-to-end interoperability workflow from operator systems to regulatory aggregation.

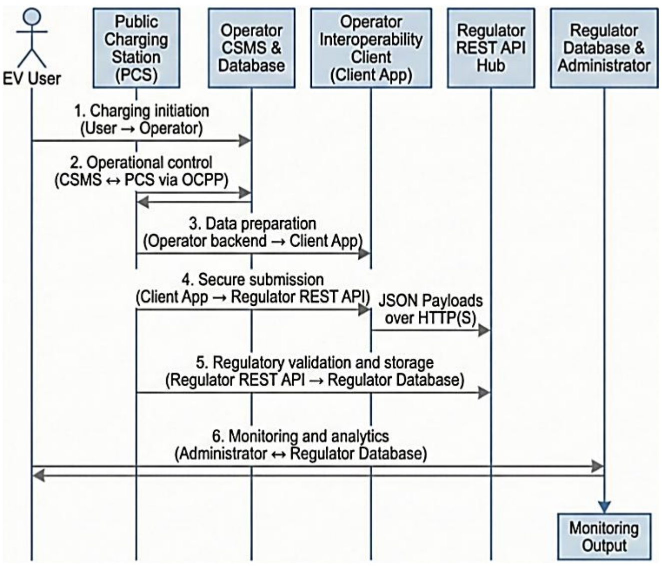

Figure 3. Consolidated regulatory dataset for cross-operator monitoring

Furthermore, Figure 3 illustrates the core workflow for authentication, data validation, secure transmission, and regulatory storage. Together, these elements demonstrate how standardized datasets can be exchanged across heterogeneous systems while remaining compliant with technical standards and regulatory oversight requirements.

4. RESULTS AND DISCUSSION

Interoperability between PCS operators is achieved through the deployment of a REST API implemented on both the regulatory aggregator server and the PCS operator systems. In this architecture, the aggregator functions as a client application with controlled access to selected datasets stored in the operator's backend, including CS operational status and performance-related metrics. The REST-based interface enables standardized and secure bidirectional data exchange using JSON over HTTP/HTTPS, ensuring compliance with interoperability requirements and cybersecurity considerations. Data retrieval is initiated through HTTP GET requests, with exchanged payloads containing parameters such as PCS identification code, registration number, connector type and operational status, CS geolocation, transaction timestamps, and per-session energy consumption measured in kilowatt-hours [35]. Functional validation of inter-operator communication is performed using connector status messages, wherein the CS is prompted to report the real-time availability of its connectors.

The system architecture defines two primary roles: charging operators and regulators. Operators are required to submit administrative and technical documentation in accordance with ministerial regulations, which undergo verification prior to the issuance of a unique CS identity number. Regulators are responsible for reviewing submissions, approving registrations, assigning identifiers, and enforcing periodic reporting obligations based on the prescribed interoperability data schema. Charger registration is conducted through a regulator-managed application, after which approved chargers become visible within the operator interface for continuous monitoring. Charging transaction data are not transmitted in real time but are aggregated and forwarded at predefined intervals, as stipulated in inter-operator and regulatory agreements, as depicted in Figure 4. This periodic reporting mechanism enables the regulator to systematically consolidate operational datasets across multiple operators, improving oversight while avoiding continuous data streaming. The results indicate that the proposed framework can integrate heterogeneous charging assets into a unified regulatory ecosystem, allowing the regulator to function simultaneously as a verification authority and a central data aggregator. This consolidated visibility supports evidence-based policy refinement and strategic planning for infrastructure expansion.

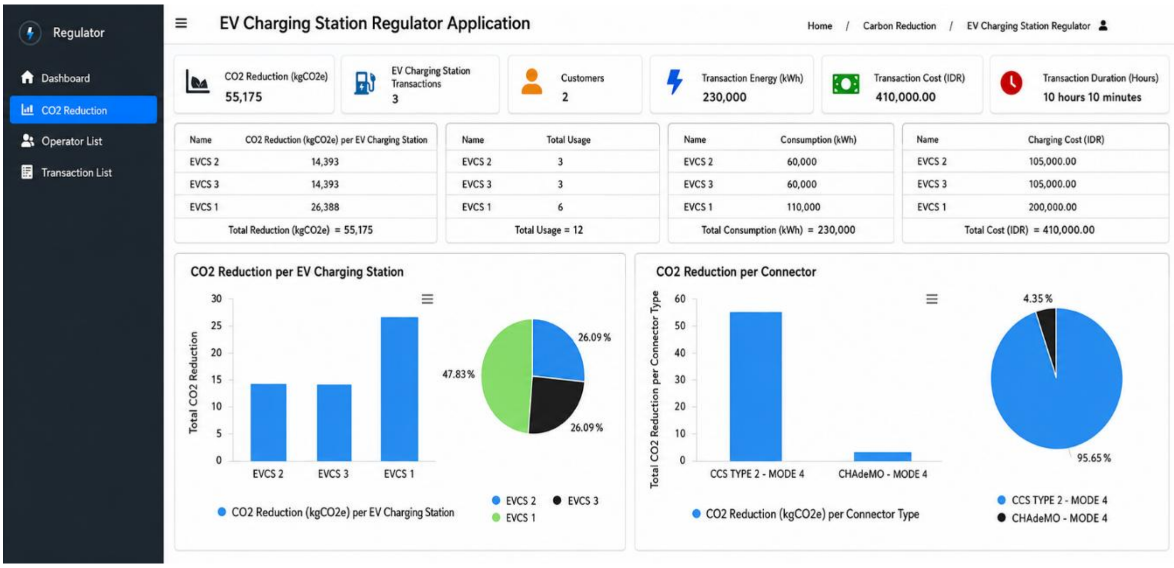

Figure 4. Periodic transaction report to the regulator

From a governance perspective, the regulatory authority mandates the collection of specific datasets related to the EV industry and public charging infrastructure to support policymaking, compliance monitoring, and long-term ecosystem development. In accordance with ministerial regulations, each CPO must submit EV user data, including vehicle brand and model, CS vendor information, and connector type data, which together enable assessment of connector standardization trends and technology adoption. Additional administrative datasets—such as PCS business permit numbers, PCS identification numbers, utility customer IDs, operator schemes, and inspection numbers—ensure that all CSs are formally registered and compliant with safety and operational requirements. Beyond energy delivery, each charging station is integrated with a backend CSMS that exchanges operational messages with charging points through OCPP, enabling standardized communication and vendor-independent interoperability [36]. To support interoperability between operators and integration with the national electricity grid, the framework also requires protocol-related datasets, including protocol version information, geospatial attributes, charger and plug types, and location metadata. Given the critical role of cybersecurity in interconnected EV charging infrastructure, communication interfaces and exchanged datasets should undergo protocol conformance, authentication, and vulnerability testing before deployment to ensure secure and reliable interoperability across heterogeneous charging networks [37].

When compared with interoperability approaches widely implemented in Europe, such as OCPI-based roaming frameworks and hub-oriented clearinghouse models, the proposed solution exhibits a distinct integration focus. Existing European frameworks primarily emphasize customer roaming, billing settlement, and operator-to-operator interaction within mature market structures. In contrast, the proposed model prioritizes regulatory oversight, standardized reporting, and policy-driven analytics, reflecting the needs of emerging EV markets such as Indonesia. By introducing a REST API-based interoperability layer above existing OCPP-based control planes, the framework avoids intrusive modifications to operator systems while enabling cross-network data harmonization. This architectural separation distinguishes the proposed approach from single-network management systems and roaming-centric models, positioning interoperability as a regulatory and planning enabler rather than solely a commercial feature.

In addition to periodic reporting, real-time operational awareness is supported through WebSocket-based interoperability. WebSocket enables full-duplex, bidirectional data exchange over a persistent transmission control protocol (TCP) connection, reducing latency compared to polling mechanisms and supporting timely monitoring of CS status and fault conditions [38]. These capabilities facilitate rapid detection of system failures and efficient coordination between charging infrastructure components. However, continuous WebSocket communication introduces challenges, including increased memory consumption, higher coordination requirements, dependency on predefined confidentiality agreements, and potential security risks if unencrypted channels are used. These findings suggest that WebSocket-based communication is best applied selectively for event-driven monitoring, while REST-based periodic reporting remains more suitable for large-scale regulatory aggregation. Radio frequency identification (RFID)-based interoperability is also discussed to contextualize alternative mechanisms for user identification and transaction processing. RFID technology enables efficient authentication and payment integration when combined with compatible readers and payment gateways, offering advantages such as rapid data acquisition and flexible deployment [39]. Nevertheless, limitations related to data collision, frequency interference, and privacy exposure constrain its applicability as a primary interoperability mechanism at the regulatory level. Consequently, RFID is more appropriately positioned as a complementary technology within operator ecosystems rather than a core component of national interoperability architecture.

Overall, the results confirm that the proposed REST API and regulator-centric interoperability framework provide a scalable and standards-compliant solution for integrating heterogeneous EV charging networks. By enabling secure data exchange, supporting periodic regulatory reporting, and selectively incorporating real-time monitoring, the framework addresses key limitations of single-network management systems and roaming-focused interoperability models. These findings reinforce the role of interoperability as a foundational enabler for regulatory visibility, service transparency, and future integration with smart-grid and vehicle-to-grid systems. Recent studies on EV charging interoperability published between 2019 and 2025 predominantly focus on protocol-level compatibility, roaming enablement, or single-network optimization, often assuming mature market structures and commercial interoperability objectives. Several European-oriented works emphasize OCPI-based roaming and clearinghouse models to support cross-operator billing and user mobility, while others investigate centralized charging management systems aimed at operational efficiency within individual networks. In contrast, the proposed framework addresses a different interoperability dimension by prioritizing regulator-led data aggregation, compliance-oriented reporting, and policy-driven analytics. Unlike prior approaches that treat the regulator as an external stakeholder or passive data consumer, this study explicitly integrates regulatory functions into the interoperability architecture, enabling standardized national-scale monitoring without disrupting existing operator control systems. This distinction positions the proposed REST API-based model as complementary to roaming frameworks while filling a critical gap in regulatory governance for emerging EV markets.

5. CONCLUSION

The continued growth of EV adoption will lead to an increasingly heterogeneous charging ecosystem, requiring structured interoperability between multiple operators and regulatory institutions. This study aimed to develop a regulatory-centric interoperability framework that enables coordinated data exchange between charging operators and governmental stakeholders.

The proposed architecture introduces a lightweight REST API–based interoperability layer that leverages existing OCPP-based backend systems without requiring proprietary protocol modification. The framework supports cross-operator data harmonization, compliance-oriented reporting, and improved regulatory visibility, thereby strengthening governance-based EV infrastructure management.

These findings highlight the importance of aligning technical interoperability standards with regulatory oversight to ensure scalable and transparent charging infrastructure development. Future research should focus on empirical validation through real-world implementation, quantitative performance assessment, and the integration of complementary aspects such as cybersecurity, payment interoperability, and smart-grid functionalities.

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AUTHOR CONTRIBUTIONS STATEMENT

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

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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