Ontology-Driven eMobility Booking Management in the Energy Data Space

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Abstract

The Energy Data Space provides a collaborative framework for data sharing and management, offering a promising foundation for advancing electromobility services. This paper examines the role of semantic interoperability within the Energy Data Space to enhance eMobility booking management. We propose a domain-specific ontology tailored to standardize knowledge representation, facilitating seamless integration of booking platforms, Electric Vehicle charging infrastructure, tariffs, and user preferences. A structured methodology is presented for the design and construction of semantic data models, encompassing requirements analysis, ontology engineering, iterative validation with competency questions, and data-driven testing with real-world scenarios. The resulting ontology forms the backbone of a knowledge graph, supported by a scalable data ingestion workflow designed to harmonize and integrate heterogeneous datasets, enabling functionalities such as real-time reservations, tariff optimization, and personalized services. Practical use cases are explored to demonstrate the applicability of the ontology and knowledge graph, including multi-provider booking harmonization and charging station optimization. In addition, the paper reviews relevant standards and best practices to address implementation challenges and opportunities in leveraging semantic technologies within the Energy Data Space. Our findings highlight the transformative impact of semantic interoperability, structured methodologies, and knowledge graph technologies on the efficiency, accessibility, and sustainability of eMobility services. By adopting collaborative frameworks and semantic solutions, stakeholders can unlock the innovation and integration potential in the evolving electromobility ecosystem.

Keywords

Ontology, Semantic Interoperability, eMobility, Booking Management, Energy Data Space, Electric Vehicle Charging, Semantic Data Ingestion

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1. Introduction

The transition towards electromobility represents a fundamental shift in transportation paradigms, driven by imperatives for sustainability, energy efficiency, and environmental stewardship. Electric vehicles (EVs) and their associated infrastructure promise to revolutionize urban mobility, offering cleaner, quieter, and more cost-effective alternatives to traditional combustion engine vehicles [1]. However, the realization of this vision hinges not only on technological advancements but also on the effective management of the vast amounts of data generated and exchanged within the electromobility ecosystem [2].

A critical aspect of this transformation is *semantic interoperability*, which enables diverse systems, platforms, and stakeholders to exchange, interpret, and utilize data seamlessly. In the context of electromobility, semantic interoperability ensures smooth communication and collaboration among vehicle manufacturers, charging infrastructure providers, energy utilities, policymakers, and end users [3]. This facilitates essential real-time services such as electric vehicle charging reservations, tariff optimization, personalized user experiences, and the seamless integration of charging networks between providers.

Semantic interoperability relies on standardized vocabularies, ontologies, and data models. By utilizing semantic technologies such as RDF (Resource Description Framework) and OWL (Web Ontology Language), stakeholders can overcome interoperability barriers, enabling efficient data exchange across

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heterogeneous platforms [4]. These technologies promote data reuse and integration, aligning with the FAIR principles — Findable, Accessible, Interoperable, and Reusable [5]. However, while semantic technologies significantly contribute to the interoperability and reusability aspects, they are not sufficient on their own to guarantee that data is truly findable and accessible, which also requires appropriate data governance policies, persistent identifiers, and data publication infrastructures [6]. Furthermore, knowledge management plays a pivotal role in this context. It involves the processes, tools, and methodologies used to capture, organize, and leverage knowledge from diverse data sources. In the energy data space, this includes the development of domain-specific ontologies, knowledge graphs, and semantic annotations to provide valuable insights and support informed decision-making [7]. Through semantic technologies, stakeholders can extract actionable intelligence from complex, fragmented data landscapes, paving the way for improved planning, optimization, and policy-making.

At the core of electromobility's evolution is the rise of EVs, which promises significant environmental and economic benefits, such as reducing greenhouse gas emissions and decreasing reliance on fossil fuels. However, for electromobility to succeed, robust and interoperable charging infrastructure is required to meet the growing global demand for EVs [8]. The widespread adoption of electromobility will depend on overcoming various challenges, including range anxiety, infrastructure limitations, and interoperability constraints.

The Energy Data Space provides a collaborative framework for addressing these challenges. It facilitates standardized data management and exchange, offering a foundation for advancing electromobility services. By leveraging semantic technologies, stakeholders can harmonize diverse datasets across the electromobility ecosystem, enabling more efficient and reliable services.

This paper explores the integration of semantic interoperability principles within the Energy Data Space to address the unique challenges of electromobility. Specifically, we propose an electromobility ontology designed to support electric vehicle charging booking services. This ontology is complemented by a scalable knowledge graph and an agile methodology to design and build semantic data models. This methodology, an extension of prior research, incorporates iterative validation with competency questions, real-world scenario testing, and FAIR compliance, ensuring applicability in dynamic, real-world contexts. Practical use cases, such as multi-provider booking harmonization and charging station optimization, are examined to demonstrate the transformative potential of semantic technologies in electromobility. The paper also addresses the broader implications of semantic interoperability, focusing on its role in driving sustainability, accessibility, and innovation in the sector.

The remainder of this paper is structured as follows. Section 2 provides an overview of the foundational concepts and background relevant to semantic interoperability in electromobility. Section 3 introduces a motivating scenario to highlight the pressing need for efficient data exchange and interoperability. Section 4 presents the requirements for interoperable booking services and outlines our proposed methodology for semantic data model design, highlighting its FAIR compliance and agile approach. Section 5 elaborates on the development and implementation of the Electromobility Ontology and its associated knowledge graph. Section 6 details data ingestion workflows, federated query processing, and decision-making applications within the Energy Data Space. Section 7 engages in a critical discussion of the results and addresses the challenges and opportunities for future research. Finally, Section 8 concludes the paper with reflections on the transformative potential of semantic interoperability to advance electromobility and recommendations for future work.

2. Related Work

Previous research has explored various aspects of electromobility and EV charging infrastructure. Although existing studies have made significant contributions to the field, gaps remain in standardizing knowledge representation and ensuring interoperability across diverse electromobility platforms. This paper aims to bridge these gaps by proposing a novel ontology-driven approach to improve the efficiency of EV charging booking services, focusing on improving data integration, decision-making, and user experience.

The intersection of semantic interoperability, knowledge management, and electromobility has garnered significant attention from researchers, practitioners, and policy makers who seek to address the complex challenges of sustainable transportation. This section reviews the existing literature and research initiatives that have contributed to our understanding of these interconnected domains.

Semantic interoperability has become a cornerstone of modern data management systems, enabling seamless communication and collaboration between heterogeneous environments. Smith *et al.* [9] emphasize the importance of semantic technologies, particularly ontologies and semantic web standards, in facilitating data integration and knowledge sharing in smart transportation systems. Using ontologies, linked data, and semantic models, systems can better interpret, exchange, and integrate data from diverse sources, driving more effective decision-making processes and improving system performance.

Further research by Garcia *et al.* [10] has focused on the challenges of semantic interoperability in the context of electromobility, particularly in the integration of EV charging stations into broader smart city ecosystems. They argue that developing a shared vocabulary and a set of standards for data exchange is crucial to ensuring seamless communication between charging stations, vehicle management systems, and user interfaces. They propose a set of semantic models to support these interactions and enhance interoperability between public and private charging infrastructures.

In the context of energy management, some studies have explored how integrating EV-related data into broader energy grids can facilitate demand response and optimize energy usage. The European Union-funded *E-Mobility Observatory* project (European Commission, 2021) aims to establish standards for data exchange and interoperability in electromobility. This initiative, which includes collaboration with industry leaders and government agencies, has worked to create open-source tools for harmonizing data formats and protocols, which could be crucial for improving the interoperability of charging services across different platforms. Garcia *et al.* [11] examine how interoperable booking services can influence user adoption and satisfaction in electric vehicle sharing programs. Their study emphasizes that technical interoperability—ensuring consistent data exchange across systems—is a necessary foundation, but not sufficient on its own. User-centric design plays an equally critical and complementary role in ensuring adoption and usability. Designing intuitive interfaces and ensuring seamless user journeys are crucial for bridging the gap between technical standards and actual user experience. Ontology-driven approaches can support this balance by offering structured, machine-readable representations of data while also enabling flexible, personalized service configurations that meet user needs. In a similar line, the work of Zheng *et al.* [12] focuses on the role of semantic web technologies in enhancing the user experience of electric vehicle charging systems. They argue that by adopting semantic standards, users could benefit from more accurate and personalized booking services that integrate with other transportation modes, further improving the accessibility and convenience of electromobility solutions.

Ontologies have been proposed as a solution to the challenges of standardizing EV charging data. Several studies [13, 14] have explored how ontologies can provide a structured framework to represent complex data on charging stations, connectors, vehicle types, and user preferences. These semantic models can ensure a common understanding of key concepts between different systems and platforms, facilitating data sharing and integration.

Miller *et al.* [15] present an ontology for the electric vehicle charging infrastructure that includes various categories of charging stations, such as public, private, fast and slow chargers, along with detailed specifications on power ratings, connector types, and payment methods. This model is designed to promote standardization in the way charging data is captured, stored, and exchanged, allowing for more efficient and user-friendly booking systems.

In addition to individual research efforts, collaborative initiatives have played an important role in advancing knowledge and best practices for electromobility. The *E-Mobility Observatory*, for example, serves as a key platform for the exchange of research findings and the development of policy recommendations on the future of electromobility. Its focus on data harmonization, interoperability, and open standards aligns with the goals of this paper, which advocates the use of ontologies to streamline and standardize EV charging data exchanges.

Furthermore, the work of the European Commission (2021) highlights the growing importance of cross-sector collaborations in the electromobility ecosystem. Policies aimed at promoting interoperable charging networks, including the standardization of data formats and protocols, are essential to foster a sustainable and scalable transition to electromobility. These policy frameworks provide the regulatory foundation needed for the widespread adoption of interoperability standards, as well as for ensuring privacy, security, and governance in the exchange of energy and vehicle data. Despite the advancements in knowledge management and semantic interoperability, several challenges remain. Privacy and security concerns, particularly in the context of sensitive user data and payment systems, must be addressed through robust encryption and governance mechanisms. Scalability also remains a critical issue, as solutions need to be adaptable to different geographical regions and charging infrastructures, each with varying technical standards and user needs. Additionally, while semantic technologies provide a powerful tool for data integration, their application to real-time decision-making in dynamic environments such as EV charging stations requires further research. Real-world implementations and pilot projects are necessary to validate the effectiveness of ontology-driven solutions in improving EV charging booking systems and ensuring seamless interoperability across platforms.

The literature on semantic interoperability, knowledge management, and electromobility illustrates the importance of developing standardized frameworks and semantic models to address the complexities of the EV ecosystem. While significant strides have been made, there is still a need for comprehensive, ontology-driven approaches that can provide the necessary structure and standardization for data exchange across diverse electromobility platforms. This paper contributes to this ongoing conversation by proposing a novel approach to enhance the efficiency and scalability of EV charging booking services, laying the foundation for future research and development in this area.

3. Methodology for Semantic Data Model Design and Construction

Developing ontologies is a complex and time-consuming task with no universally agreed-upon methodology [16]. Various methodologies have been proposed, including Cyc [17], KACTUS [18], METHONTOLOGY [19], and others [20, 21]. Each has its strengths, but none are universally superior, and the choice often depends on the specific requirements. For the electromobility use case, we adapt the methodologies of [20] and [21] to design a semantic data model. The methodology follows five steps, as shown in Fig. 1:

1. **Ontology Requirements Specification**: Analyze use cases, collaborate with domain experts, develop interaction models, define the ontology's scope, formulate competency questions, and identify relevant terms.
2. **Ontology Analysis**: Identify key concepts/relationships, reuse/extend existing ontologies, and construct the ontology by structuring concepts and relationships.
3. **Ontology Diagrams Design**: Create visual diagrams to represent the ontology and collaborate with stakeholders for validation and refinement.
4. **Ontology Formalization**: Ensure diagram consistency, formalize new modules for integration, and align the ontology with existing models.
5. **Ontology Population/Querying**: Gather and integrate data to populate the ontology, generate semantic data, store it in a triplestore (e.g., GraphDB), and implement SPARQL queries for data retrieval.

4. Motivating Scenario and Data Exchange Requirements

In a bustling urban environment, electromobility is increasingly embraced, requiring efficient data exchange to support services like vehicle charging, route planning, and fleet management. Seamless data flow across heterogeneous systems demands well-defined data exchange requirements and interoperability standards to ensure compatibility, scalability, and reliability.

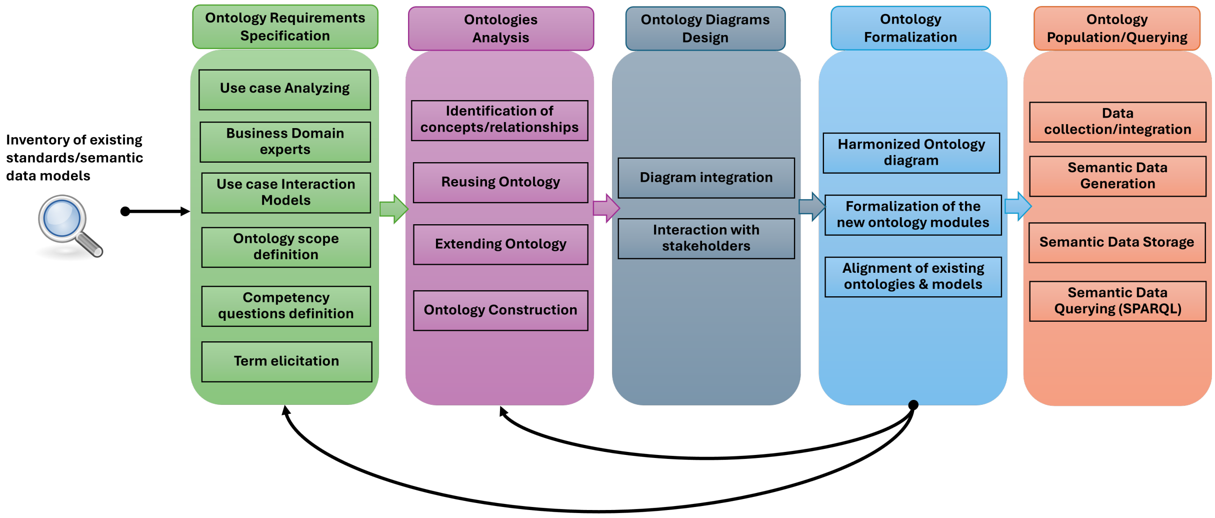

Figure 1: Semantic Data Model Methodology Design's Steps

4.1. Scenario: Interoperable Booking in Electromobility

A common challenge for electric vehicle users is the uncertainty of charging point availability. This use case envisions a booking service where Electric Mobility Service Providers (eMSPs) enable users to locate, reserve, and access charging points across multiple providers and national borders. The scenario emphasizes semantic interoperability for enabling unified access to distributed data sources and heterogeneous systems.

4.2. Functional and Semantic Requirements

To support this scenario, several functional and semantic data exchange requirements have been identified. First, real-time availability synchronization (R1) is essential to ensure that systems can exchange up-to-date status information—such as whether a charging station is occupied, reserved, or available. Second, user identity and authentication exchange (R2) must be supported through cross-provider mechanisms like OAuth2 or eIDAS to enable secure booking across different eMSPs. Third, there is a need for unified service descriptions (R3), whereby charging stations and services are semantically described—covering plug types, power levels, and pricing models—using shared ontologies to facilitate automated discovery and reasoning.

Fourth, cross-border interoperability (R4) must be achieved by ensuring that data exchange complies with regional policies and standards, such as OCPI or ISO 15118, to guarantee service continuity across countries. Fifth, booking lifecycle integration (R5) is required, meaning that systems should support all stages of the booking process—including initiation, confirmation, cancellation, and updates—via interoperable APIs and ontology alignment. Finally, user-centric service adaptation (R6) must be enabled by semantically representing user preferences, such as preferred charging speed or payment method, to ensure personalized service selection.

4.3. Transferring Knowledge Graph

Transferring knowledge graphs within the energy data space offers opportunities for effective knowledge exchange, but challenges such as data quality, consistency, and privacy must be addressed. By adopting standardized ontologies, stakeholders can improve data integration and system compatibility. Privacy concerns arise due to the inclusion of sensitive user data (e.g., identities, locations, usage patterns) in booking services; to mitigate these, the system applies data minimization, anonymization or pseudonymization techniques, role-based access control, and consent management aligned with

GDPR principles. These mechanisms ensure secure data handling and build user trust. The use of standardized, privacy-aware knowledge graphs enhances interoperability and fosters a reliable and seamless electromobility ecosystem.

5. Building a Semantic Data Pipeline for Electromobility

In this paper, we present the Semantic Data Pipeline developed for the booking use case in the Omega-X project[1], focusing on the semantic transformation, storage, and querying of data related to electric vehicle (EV) charging services. The pipeline is designed to integrate real datasets and simulation datasets, using electromobility ontology modules to structure and represent the domain's data effectively. We implemented this pipeline by leveraging the SPARQL-Generate tool[2], an extension of the SPARQL query language, to convert data into RDF graphs in a flexible and expressive manner. The RDF data is stored in a GraphDB triplestore[3] in Turtle format. This semantic data can be queried using SPARQL and shared in JSON-LD format to facilitate smooth data exchange across different systems and services in the broader data space. This semantic data pipeline (see Fig. 2) offers a comprehensive, flexible, and interoperable solution for managing and exchanging electromobility data in a standardized manner, ensuring compatibility with multiple partners and systems in the sector.

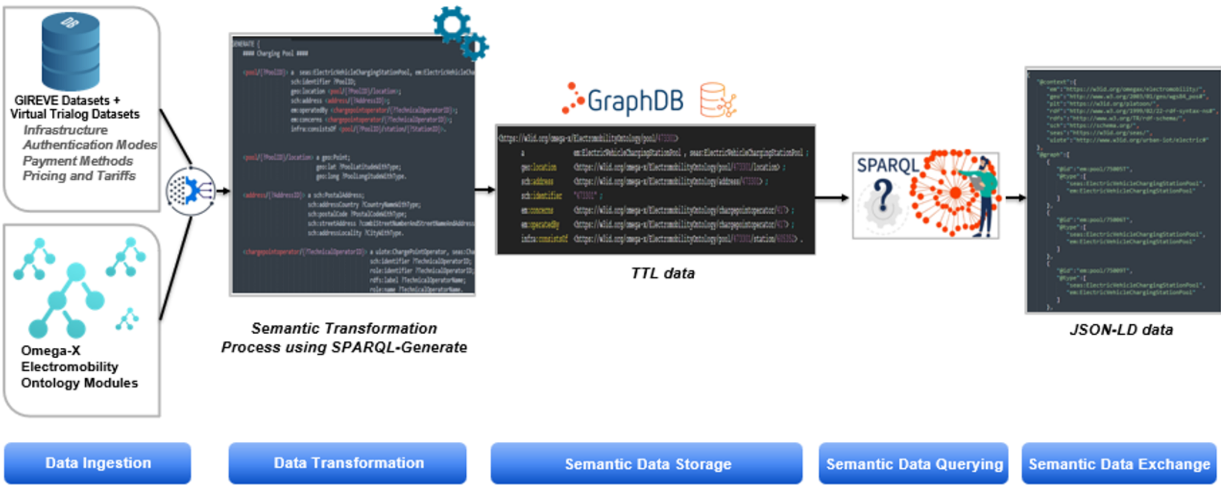

Figure 2: Semantic Data pipeline

5.1. Electromobility Ontology Development

The implementation of the Electromobility Ontology is pivotal to ensuring scalability, interoperability, and extensibility within the electromobility ecosystem. Developed using standardized semantic web technologies such as OWL and Protégé, the ontology facilitates seamless integration by providing a shared, machine-interpretable vocabulary that aligns heterogeneous data formats and terminologies. This standardization allows different EV charging booking systems to interpret and exchange data consistently, regardless of their internal data structures or protocols.

A structured approach was adopted for the ontology design, guided by key questions about its purpose, scope, and application. This approach involves utilizing various resources such as IEC-62559

[1]https://omega-x.eu/
[2]https://ci.mines-stetienne.fr/sparql-generate/
[3]https://www.ontotext.com/telechargez-graphdb/

templates[4], interactions with domain experts, OCPI standard[5], and the eMIP Protocol[6], among others. These include: (1) What are the primary objectives of the ontology?, (2) What is the scope of the ontology?, (3) Who are the end-users, and how will the ontology be applied?, (4) What information should the ontology capture?, and (5) What competency questions should the ontology answer?. The answers to these questions formed the foundation for constructing the semantic data model, ensuring alignment with real-world applications and addressing the critical needs of the electromobility sector.

Ontology Design Principles: The ontology design process adhered to key principles, prioritizing the reuse of existing ontologies where possible. First, existing ontologies were thoroughly analyzed to ensure clarity in concept hierarchies, such as subsumption and part-whole relationships. New concepts were added where existing ontologies proved insufficient, covering only a portion of the use case. In cases where existing ontologies did not address specific requirements, new modules were developed to cater to electromobility-specific use cases while maintaining interoperability within the broader ecosystem.

Ontology Components: The Electromobility Ontology (see Fig. 3) is structured into several key modules, each addressing distinct aspects of the ecosystem. The first module, Physical concepts, represents tangible entities like *Pool*, *Station*, *EVSE (Electric Vehicle Supply Equipment)*, and *Connector*, describing the physical components of EV charging infrastructure. The second module, Abstract concepts, encompasses generic properties such as *Payment*, *Authentication*, *Price*, and *Status*, which are foundational for electromobility applications and extendable to other domains. Finally, the Application-specific concepts module focuses on use-case-specific entities like *Booking* and *Charging session*, enabling efficient scheduling and management of charging operations.

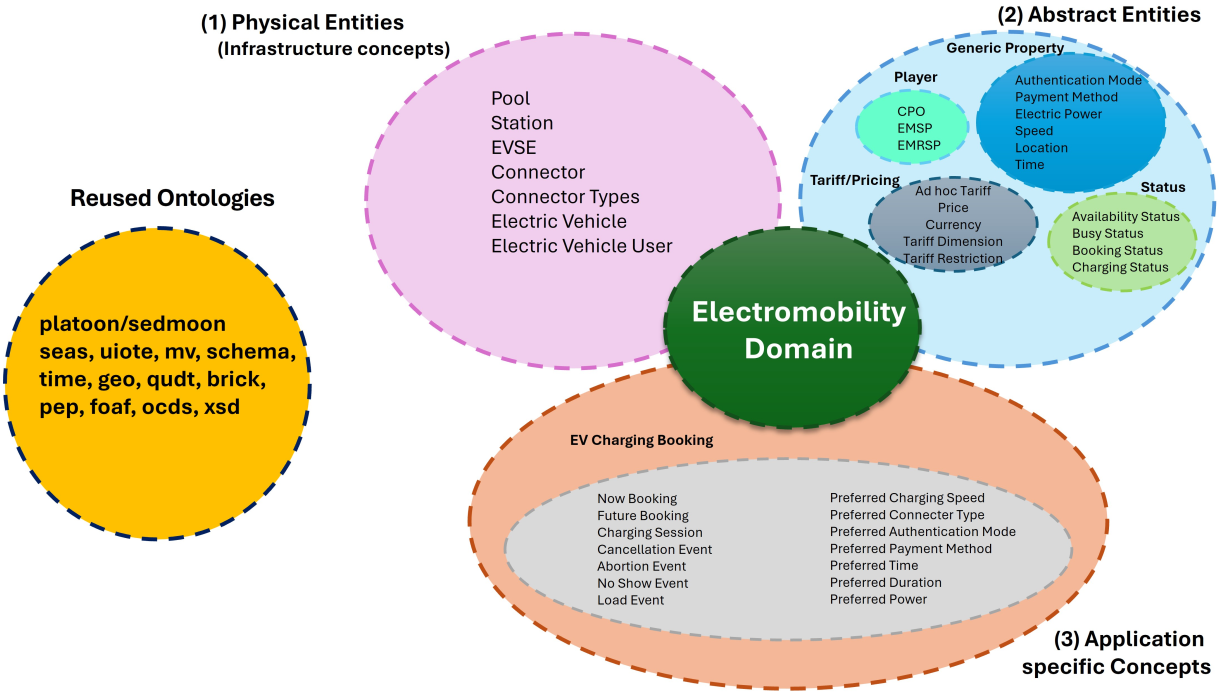

Figure 3: Overview of Electromobility Ontology

[4]https://syc-se.iec.ch/deliveries/iec-62559-use-cases/
[5]https://github.com/ocpi/ocpi
[6]https://www.gireve.com/wp-content/uploads/2022/09/Gireve_Tech_eMIP-V0.7.4_ImplementationGuide_1.0.7_en.pdf

Key Ontology Modules: Different modules are designed to structure and streamline knowledge in the use case of electromobility, addressing specific needs such as managing charging infrastructure, optimizing bookings, facilitating stakeholder coordination, and ensuring interoperability across systems.

- **EV Charge Infrastructure module:** Provides detailed information on charging stations, including location, charger types, capacity, and technical specifications. This module supports accurate decision-making and infrastructure management (see Fig. 4).
- **EV Charging Booking module:** Facilitates slot reservations, availability checks, booking confirmations, and cancellations, optimizing the utilization of charging infrastructure (see Fig. 5).
- **Player module:** Defines stakeholders such as EV users, service providers, and regulatory bodies, enhancing coordination and communication across the ecosystem such as charge point operator (CPO), eMobilityServiceProvider (eMSP).
- **Status module:** Tracks the operational status of charging points, providing real-time updates on availability, usage, and equipment conditions.
- **Tariff Pricing module:** Captures pricing models (e.g., time-based, energy-based, subscription-based) and supports dynamic pricing strategies to ensure transparency and user satisfaction.
- **Generic Property module:** Includes common attributes shared across modules to ensure consistency and reduce redundancy.
- **Alignment module:** Ensures compatibility and alignment with existing ontologies and standards. It incorporates mappings and relationships to other established ontologies, enabling broader interoperability within the electromobility sector and beyond. This module plays a critical role in ensuring that the developed ontology can integrate seamlessly with other systems and data sources, promoting a unified approach to data management in electromobility.

This modular approach to ontology development allows for scalable and flexible enhancements, ensuring that the ontology can evolve with the growing and changing needs of the electromobility sector. By addressing each aspect comprehensively, this ontology not only enhances data exchange and interoperability but also significantly improves the user experience and operational efficiency of electromobility services.

Ontology Evaluation: The ontology was evaluated based on three key criteria: Completeness, which ensured the coverage of all relevant domains and concepts; Consistency, confirming the absence of contradictory relationships; and Alignment with Domain Requirements, ensuring the reflection of real-world needs in electromobility. Feedback from business experts and performance benchmarks validated the ontology's practical utility in enhancing EV charging services.

Competency Questions and SPARQL Queries: A set of competency questions was developed to ensure the ontology captures essential electromobility aspects and supports practical applications. SPARQL queries were created to retrieve information about charging stations, check slot availability and manage bookings, monitor EVSE status and operational conditions, and analyze pricing models and user preferences. These queries enable seamless data integration, enhancing interoperability and supporting efficient decision-making. The ontology optimizes infrastructure management and improves the user experience in electromobility services.

6. Evaluation and Validation

This section evaluates the semantic ontology and data pipeline for modeling and querying EVSE data from the Gireve database, ensuring logical soundness, completeness, and competency question support.

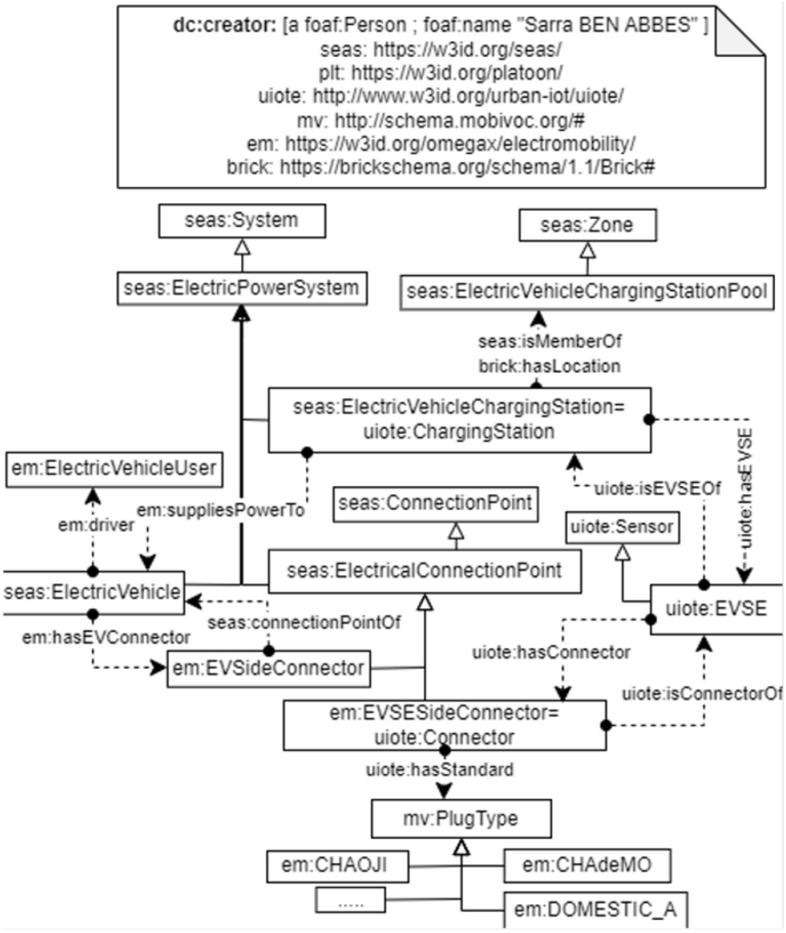

Figure 4: Extract of EV Charging Infrastructure Ontology Diagram

6.1. Dataset Description

The Gireve dataset includes data from 17,986 pools across France and Belgium, covering 18,064 charging stations, 53,105 EVSEs, and 54,169 connectors. It contains key attributes such as pool locations, EVSE configurations, authentication modes, payment methods, and tariffs. While the dataset was partially harmonised according to Gireve's internal data standards, it required further semantic alignment and transformation within our pipeline to ensure full interoperability with the Omega-X Electromobility Ontology and support seamless integration with other heterogeneous data sources.

6.2. Ontology Design and Development

The ontology represents the charging infrastructure with key classes such as *:ElectricVehicleChargingStationPool*, *:ElectricVehicleChargingStation*, *:EVSE*, *:EVSEConnector*, *:AuthenticationMode*, *:PaymentMethod*, and *:TariffProperty*, defining relationships like *:hasEVSE* and *:appliesTariff*, as well as properties such as *connectorFormat* and *powerRating*. It was implemented using Protégé, OWL 2, and SPARQL, with reasoning engines Pellet and HermiT ensuring logical consistency.

6.3. Ontology Validation and Evaluation

The ontology was validated through competency questions (CQs), such as the total EVSEs per CPO, supported authentication methods, and connector availability. Logical consistency was ensured using Pellet, which confirmed there were no contradictory relationships or axioms. Additionally, the mapping of Gireve data to ontology classes was validated, as shown in Table 6.3.

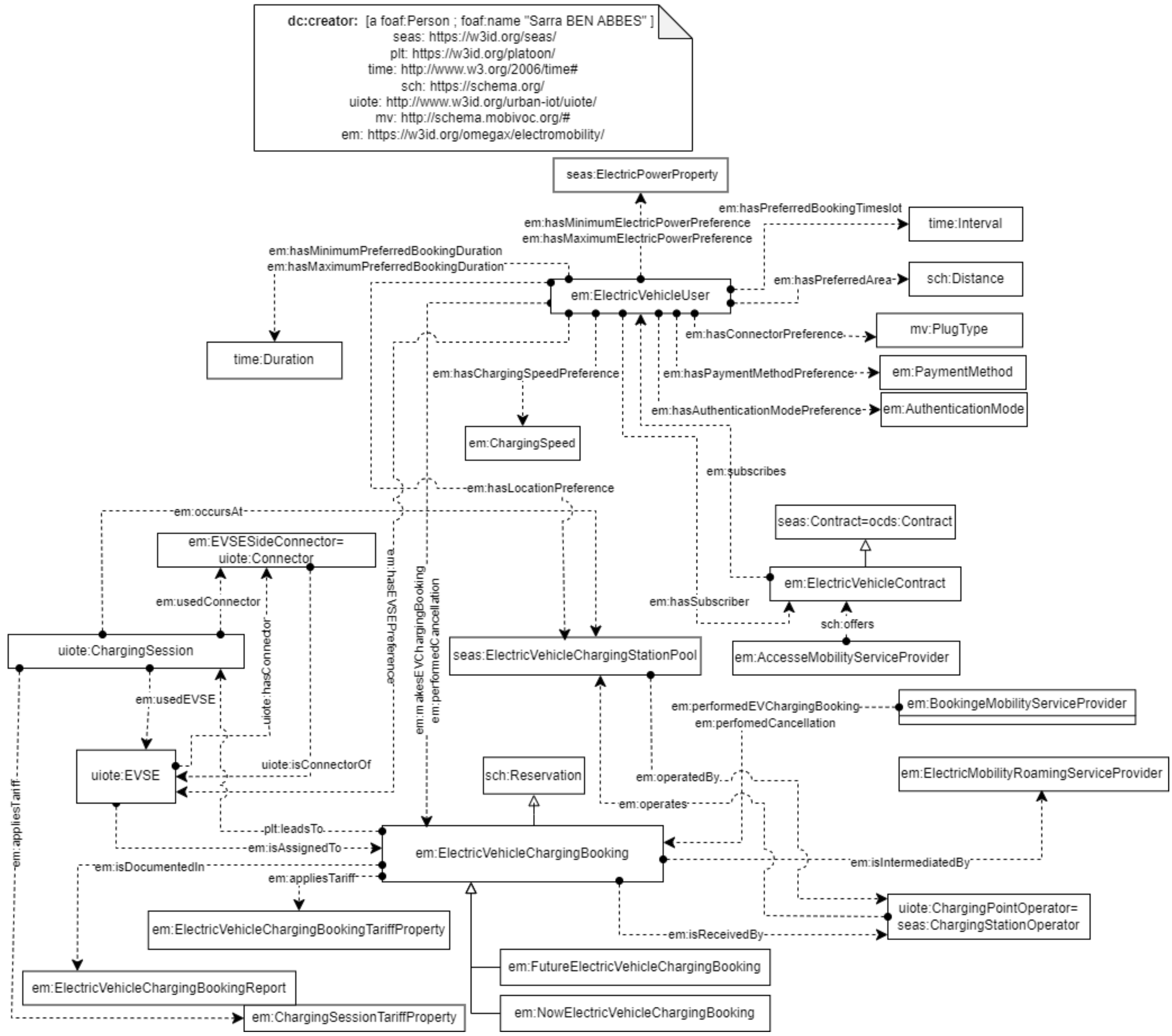

Figure 5: Extract of EV Charging Booking Ontology Diagram

Metric	Value
Total Pools Mapped	17,986
Total Stations Mapped	18,064
Total EVSEs Mapped	53,105
Total Connectors Mapped	54,169
Consistency Errors	0

Table 1

Ontology Validation Metrics

Query Performance SPARQL queries were efficiently executed on GraphDB with response times under 0.2 seconds for datasets with over 50,000 entities.

7. Discussion

Semantic interoperability in electromobility offers significant innovation potential. Common standards and protocols unify data, advancing infrastructure, user services, and regulations. The Electromobility Ontology plays a central role in data integration and insight extraction, though challenges like data silos and technical interoperability remain. Overcoming these requires coordinated efforts, robust technologies, and governance structures.

An additional challenge is the accessibility of semantic technologies for stakeholders who may not have expertise in ontology design or semantic data transformation. Although our pipeline demonstrates successful integration with familiar datasets, applying it to external or unfamiliar data sources requires mapping efforts and domain knowledge. Lowering the entry barrier through tools, templates, and documentation is therefore essential for widespread adoption.

8. Conclusion and Perspectives

The development of the Electromobility Ontology represents a milestone in standardizing knowledge representation within the electromobility sector. By providing a structured framework for organizing and querying data, the ontology improves the efficiency of electric vehicle charging services and supports informed decision-making across the ecosystem. This initiative demonstrates how semantic technologies can address practical challenges and unlock new opportunities in the energy data domain.

To ensure broader applicability, future work will explore the ease of use and adaptability of the pipeline with third-party datasets and by users unfamiliar with semantic tools. This includes evaluating its usability in realistic deployment scenarios and designing intuitive user interfaces to simplify data integration and transformation.

Future research will also expand the ontology's scope to include emerging trends such as smart grid integration and real-time data analytics. Enhancing scalability and performance to accommodate growing datasets will be prioritized. Continued collaboration among industry, academia, and policymakers is essential to maintain the ontology's relevance and adoption.

Leveraging semantic principles and advanced tools, stakeholders can foster collaboration, drive innovation, and pave the way for a sustainable and resilient transportation system. A shared commitment to innovation and inclusivity will be crucial in shaping the future of mobility.

Acknowledgments

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Declaration on Generative AI

The authors did not use any Generative AI tools (as defined in ceur-ws.org/genai-tax.html) during the writing of this paper. Only non-generative tools such as DeepL were used for translation assistance. The authors reviewed all content manually and take full responsibility for the final version.

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