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E-maintenance innovations in electric vehicle supply equipment: Enhancing reliability and efficiency through industry 4.0

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Abstract

This paper explores the transformation of Electric Vehicle Supply Equipment (EVSE) maintenance practices, shifting from reactive approaches to e-maintenance strategies powered by Industry 4.0. Using a design thinking framework and the Double Diamond method, this study investigates key challenges faced by stakeholders such as Charge Point Operators (CPOs), eMobility Service Providers (eMSPs), installers, and manufacturers. Based on interviews and surveys with industry professionals, the paper identifies major causes of EVSE downtime, including software failures, electrical issues, and physical damage. Emphasis is placed on the need for standardized maintenance protocols and broader access to Level 3 tasks for certified installers. The integration of technologies like IoT, cloud computing, predictive analytics, and remote diagnostics is highlighted as a critical pathway to improving availability, reducing maintenance costs, and enhancing user trust. The study supports adopting intelligent tools and collaborative ecosystems to ensure a scalable and reliable charging infrastructure for electric vehicles.

Keywords: EVSE, Industry 4.0, Maintenance, Predictive maintenance, Smart charging.

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1. Introduction: EVSE State-of-the-Art

1.1. EVSE Eco-System

The Electric Vehicle Supply Equipment (EVSE) ecosystem includes several key stakeholders: the Charge Point Operator (CPO), the eMobility Service Provider (eMSP), the Charge Point Management System Provider (CPMSP), the Installer, the Charger Manufacturer, and the Interoperability Platform. These stakeholders work together to support the operation and development of EV charging infrastructure.

1.1.1. The Charge Point Operator (CPO)

Charge Point Operators (CPOs) are critical players in the electric vehicle (EV) charging infrastructure. They are responsible for managing, maintaining, and ensuring the availability of charging stations. For charging station owners, CPOs offer different business models, such as the direct sale of infrastructure, where the owner purchases the station and assumes responsibility, or a third-party investor model, where an external investor funds the installation, and the CPO manages it while sharing the profits. Some CPOs also use a leasing model, where they own the charging infrastructure and lease it to station owners [1].

From the perspective of EV drivers, CPOs ensure a seamless charging experience by maintaining the chargers, managing payments, and providing customer support. CPOs often use digital platforms that enable users to locate charging stations, check availability, and monitor charging progress. The charging stations operate using the Open Charge Point Protocol (OCPP), which facilitates communication between the stations and the CPO's backend system. The OCPP has evolved over time, from version 1.5 to 1.6 and 2.0.1, introducing features such as enhanced remote diagnostics, smart charging, and improved energy management capabilities, ensuring flexibility across different hardware [1].

In terms of expanding the charging network, CPOs often collaborate with municipalities, governments, and businesses to strategically deploy new charging stations, addressing both urban and rural charging needs. As the market matures, CPOs are adapting to new challenges, such as integrating renewable energy into charging operations and improving grid stability through smart charging and load management [2].

1.1.2. eMobility Service Provider (eMSP)

An eMobility Service Provider (eMSP) is a crucial entity within the electric vehicle (EV) ecosystem, enabling drivers to access charging stations across multiple networks through roaming agreements, typically via a unified mobile application or platform. This role facilitates seamless charging, payment processing, and customer support, thereby improving convenience for EV users. eMSPs often establish bilateral agreements with Charge Point Operators (CPOs) to expand network coverage and develop flexible pricing models based on time, location, or energy consumption patterns [3]. By supporting diverse business models and partnerships with fleet operators, automotive manufacturers, and original equipment manufacturers (OEMs), eMSPs help optimize and scale the charging infrastructure.

EMSPs monetize their services by increasing their user base and establishing roaming agreements through protocols like the Open Charge Point Interface (OCPI), which enables interoperability between networks. They also leverage partnerships with OEMs and offer promotional packages, such as free charging for new EV buyers, and support fleet operators by managing billing and usage through the EMSP platform. EMSPs collect and analyze data on driver behavior and charging patterns to refine their services and enhance user experience [3].

A Charge Point Management System Provider (CPMSP) offers essential software solutions for managing electric vehicle (EV) charging infrastructure. CPMS platforms enable operators, such as Charge Point Operators (CPOs) and eMobility Service Providers (eMSPs), to monitor, control, and optimize their charging stations remotely. These systems facilitate key functions such as real-time monitoring, dynamic pricing, automated billing, and user management. For instance, with real-time monitoring, operators can detect issues with chargers, remotely troubleshoot, and ensure maximum uptime, thereby improving user experience.

Additionally, CPMS enables flexible pricing models, allowing operators to adjust rates based on electricity demand or time of day, which helps manage load and maximize profits. Automated billing reduces administrative tasks, ensuring seamless payment processing for both users and operators. Another critical feature is energy management, where the CPMS helps integrate smart charging protocols like OCPP (Open Charge Point Protocol), optimizing energy usage and balancing grid demand during peak times.

CPMSPs also provide tools for user access management, allowing operators to set permissions for private or public use of charging stations, catering to different types of customers. This flexibility helps businesses such as fleet operators or residential complexes manage their charging infrastructure more effectively, enhancing both operational efficiency and customer satisfaction [4].

1.1.3. EVSE Installer

An Electric Vehicle Supply Equipment (EVSE) installer is responsible for the safe installation, maintenance, and operation of EV charging infrastructure. The installer typically undergoes rigorous training programs that include both technical and safety aspects. These programs equip the installer with knowledge of electrical systems, local and national electrical codes, and hands-on skills related to wiring, load calculations, and grounding for EVSE systems [5, 6].

Certification programs such as the Electric Vehicle Infrastructure Training Program (EVITP) in North America provide in-depth training for electricians. These programs cover the installation of residential and commercial charging systems, understanding safety protocols, grounding, and adherence to local electrical standards such as the NEC in the United States. Similarly, in Europe, standards such as IEC 61851 and IEC 62196 outline the requirements for both AC and DC charging setups [5]

Safety standards that installers must follow include protocols for preventing electrical hazards, such as the use of Ground Fault Circuit Interrupters (GFCI) and compliance with OSHA and NFPA safety regulations. Proper grounding, ventilation, and ensuring the system is safe for use in public and private settings are also part of the requirements [7]. In France, for instance, installers must comply with the NF C 15-100 standard, which regulates electrical installations, ensuring both safety and reliability [5].

1.1.4. EVSE Manufacturer and Technologies

Electric Vehicle Supply Equipment (EVSE) manufacturers play a crucial role in developing charging infrastructure that supports the growing demand for electric vehicles (EVs).

They are responsible for creating chargers that meet global standards and cater to various types of charging methods, including wired, wireless, and bidirectional charging technologies.

Ensuring interoperability, safety, and efficiency across different regions is essential for manufacturers, who adhere to international standards such as SAE J1772, CHAdeMO, and the Combined Charging System (CCS).

Charging technologies

Wired charging

- AC Charging (Level 1 and 2): Level 1 charging uses standard 120V outlets, primarily for residential use, offering slower charging (approximately 5 miles of range per hour).
- Level 2 chargers, operating at 240V, are faster and are commonly installed in homes, workplaces, and public stations, providing up to 25-30 miles of range per hour.
- DC Fast Charging (DCFC): This method uses high-voltage direct current (typically 480V), allowing for much faster charging. DCFC can provide up to 100 miles of range in as little as 20-30 minutes, bypassing the onboard AC charger and directly charging the vehicle's battery.

Wireless Charging:

Wireless, or inductive, charging is an emerging technology that allows electric vehicles (EVs) to charge without a physical connection. This system operates through electromagnetic fields between a charging pad and a receiver in the vehicle. The SAE J2954 standard governs wireless charging, ensuring safety, interoperability, and performance across different manufacturers.

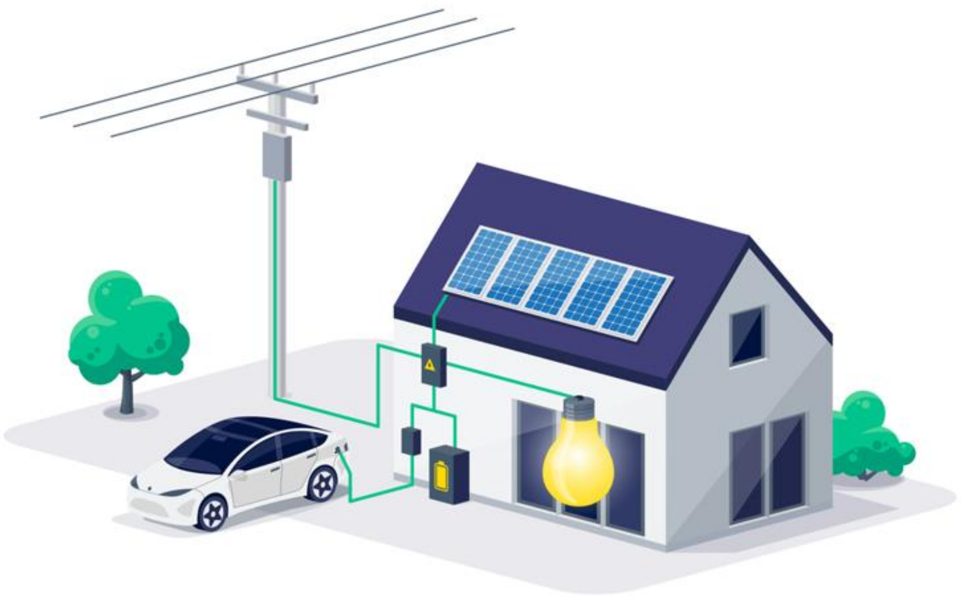

Figure 1.
Wireless charging.

Charging Gun Standards:

Different global regions use specific connector types or 'charging guns' for EV charging:

- SAE J1772 (Type 1): This standard, widely used in North America, supports both AC and DC charging and is designed for compatibility with most EVs in the region.
- Type 2 (IEC 62196): Primarily used in Europe, Type 2 supports both AC and DC charging, and it is integrated into the Combined Charging System (CCS) for high-speed charging.
- CHAdeMO: This Japanese-developed DC fast-charging standard is known for supporting bidirectional charging, allowing vehicles to not only charge but also send power back to the grid (Vehicle-to-Grid or V2G).
- Type E and Type F: These connectors are used primarily for AC charging in regions such as France and Germany. They support medium-range voltage charging and are compatible with domestic electrical systems.

Bidirectional Charging:

Bidirectional charging, enabled by technologies such as CHAdeMO and evolving versions of CCS, allows energy to flow in two directions: from the grid to the vehicle (charging) and from the vehicle back to the grid (discharging). This capability is particularly significant for Vehicle-to-Grid (V2G) applications, where electric vehicles (EVs) can serve as mobile energy storage units, helping to stabilize the grid during peak demand periods or even powering homes and buildings during outages.

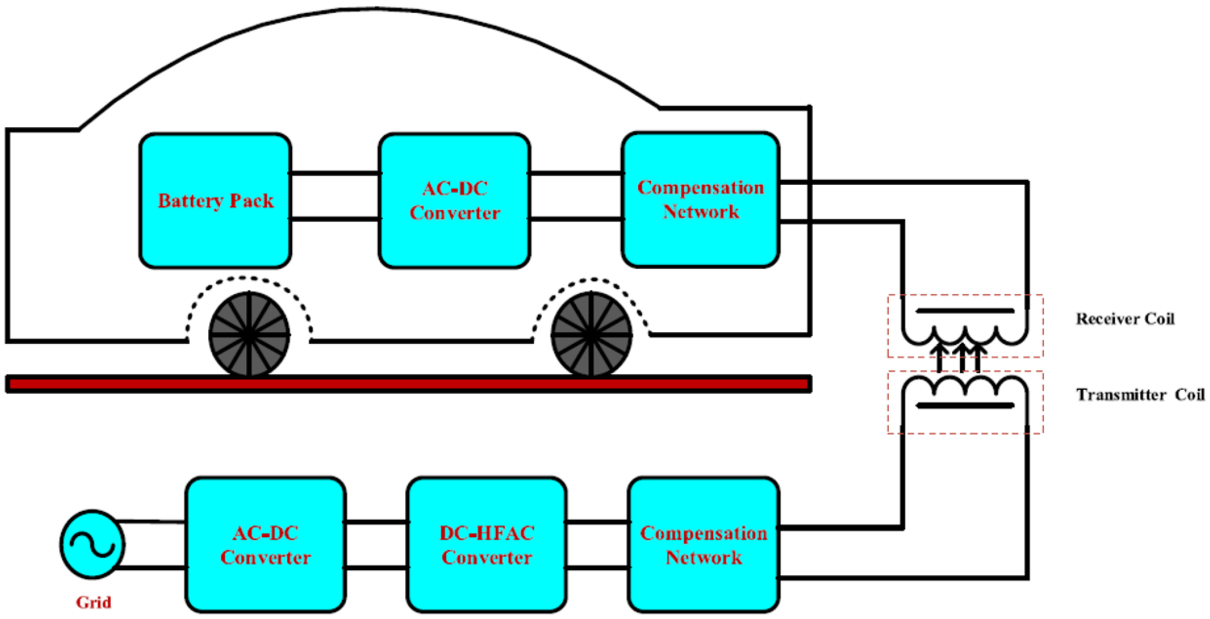

Figure 2.
Bidirectional charging illustration.

V2G technology is regarded as a significant advancement, as it facilitates renewable energy integration and improves grid resilience. For example, an electric vehicle (EV) can store excess energy generated by solar panels during the day and feed it back to the grid or supply power to a home at night. Currently, CHAdeMO is the most widely adopted standard supporting bidirectional charging, while CCS is progressing with bidirectional capabilities through ongoing developments.

Norms and Safety Standards:

Global safety standards ensure that EVSE manufacturers meet rigorous requirements for performance, durability, and interoperability. The IEC 61851/62196 standards define the technical requirements for AC and DC charging systems, including safety measures, connector designs, and communication protocols between the charger and the vehicle. SAE J2954 ensures wireless charging safety and efficiency, while SAE J1772 covers conductive charging standards.

1.1.5. Roaming Platforms

EVSE roaming platforms are essential in supporting the widespread adoption of electric vehicles (EVs) by addressing interoperability challenges between different charging networks and regions. Traditionally, EV drivers needed separate accounts, RFID cards, or apps for each Charge Point Operator (CPO), making long-distance or cross-border travel cumbersome. Roaming platforms simplify this process by enabling seamless access to charging stations across multiple networks through a single subscription. These platforms rely on protocols such as the Open Charge Point Interface (OCPI) and Open Charge Point Protocol (OCPP), which ensure standardized communication between CPOs and eMobility Service Providers (eMSPs) [8].

Through these platforms, drivers can locate, charge, and pay for sessions at various stations without worrying about different payment systems or subscription requirements [8]. The backend system manages session management, billing, and real-time status updates, ensuring a user-friendly experience. The integration of blockchain technologies is being explored to enhance security, privacy, and transparency in transaction management. For example, blockchain can securely store user credentials and charging session data, enabling a decentralized yet secure energy transaction process.

One of the primary benefits of these platforms is their contribution to overcoming the fragmentation of charging networks, particularly in Europe, where each country or region may have different operators with proprietary systems. Roaming platforms ensure that drivers can easily move across borders and access charging infrastructure regardless of which operator manages the charging stations.

Additionally, roaming platforms facilitate a more competitive marketplace by allowing operators to collaborate without monopolizing access to charging infrastructure. This openness fosters innovation and better pricing models, ultimately benefiting consumers. Moreover, these platforms enhance scalability by allowing new operators to join existing networks, accelerating the deployment of charging infrastructure [9].

Figure 3.
Roaming platform comprehensive interaction schematic.
Source: Gireve
Note: BOP*: BackOffice Provider : Is also known as CPMS Provider as explained above.

Despite these advantages, challenges remain, such as achieving complete cross-border compatibility and ensuring that all operators adopt common standards [10]. The continued evolution of roaming platforms, along with emerging technologies like blockchain and cloud-based solutions, holds promise for solving these issues and further promoting EV adoption worldwide [8-10].

1.2. Charging Modes

1.2.1. Workplace Charging

The growing necessity for effective electric vehicle supply equipment (EVSE) deployment in workplace environments continues as the adoption of plug-in electric vehicles (PEVs) increases. Nuh et al. propose a multi-objective optimization (MOO) model designed to establish the most effective charging infrastructure that balances various cost factors associated with workplace charging.

Context and Importance of the Study

The transition to electric vehicles is not merely a technological shift but a crucial aspect of achieving national decarbonization targets. Workplaces represent a significant opportunity for PEV charging due to their extensive operating hours, which allow for the installation of charging stations that can be utilized by employees and fleet vehicles alike. As the number of PEVs on the road increases, there is an urgent need to optimize workplace charging facilities to ensure they are both cost-effective and capable of meeting demand without straining the local power grid [11-13].

Model Overview:

The authors introduce a multi-objective optimization (MOO) model that aims to find the optimal configuration for EVSE in workplace environments. This model accounts for various cost components:

- Daily levelized infrastructure costs for EVSE.
- Energy charges incurred by PEVs.
- Demand charges based on peak usage.

The model aggregates these factors to identify Pareto optimal solutions, which assist stakeholders in balancing conflicting objectives, such as minimizing costs while maximizing charging efficiency and service availability. By utilizing real-world charging data, the authors develop a comprehensive charging behavior model that reflects the usage patterns typical of workplace charging stations.

Key Findings and Analysis:

The results from the implementation of the MOO model indicate significant cost savings up to 14.6% compared to existing practices and 7.8% relative to traditional single-objective optimization approaches. A noteworthy aspect of the findings is the performance of the flexibility ratio policy, which emerged as the most effective scheduling strategy. This policy facilitates optimal PEV scheduling, ensuring the lowest possible unit costs while maximizing the efficient use of grid assets [13-15].

The analysis reveals that unit costs are more sensitive to scheduling policies than to the specific charging strategies employed. This suggests that effectively managing how and when vehicles are charged can yield substantial savings and operational efficiencies. For instance, during peak demand periods, employing smart charging strategies can significantly reduce demand charges, which are a crucial component of overall costs [16, 17].

Technological Implications:

Various charging technologies explored within the framework of the MOO model, including:

- DC fast chargers (DCFC).
- Level 2 AC charging options.
- Smart charging algorithms that allow for interrupted and uninterrupted charging profiles.

These technologies are evaluated in terms of their operational costs and impacts on the electrical grid, demonstrating how different charging strategies can be implemented to enhance overall system performance. The model also incorporates a sensitivity analysis that examines how variations in battery sizes and onboard charger ratings influence cost behavior, providing insights into the practicalities of implementing charging solutions across different workplace settings [18, 19].

The articles analysed underscore the critical need for strategic planning in the deployment of EVSE at workplaces [18]. The MOO model serves as a valuable tool for stakeholders, enabling them to design charging infrastructures that are not only cost-effective but also responsive to the demands of the power grid. By balancing multiple objectives, this model can guide the development of charging networks that support the broader adoption of electric vehicles while contributing to sustainability efforts.

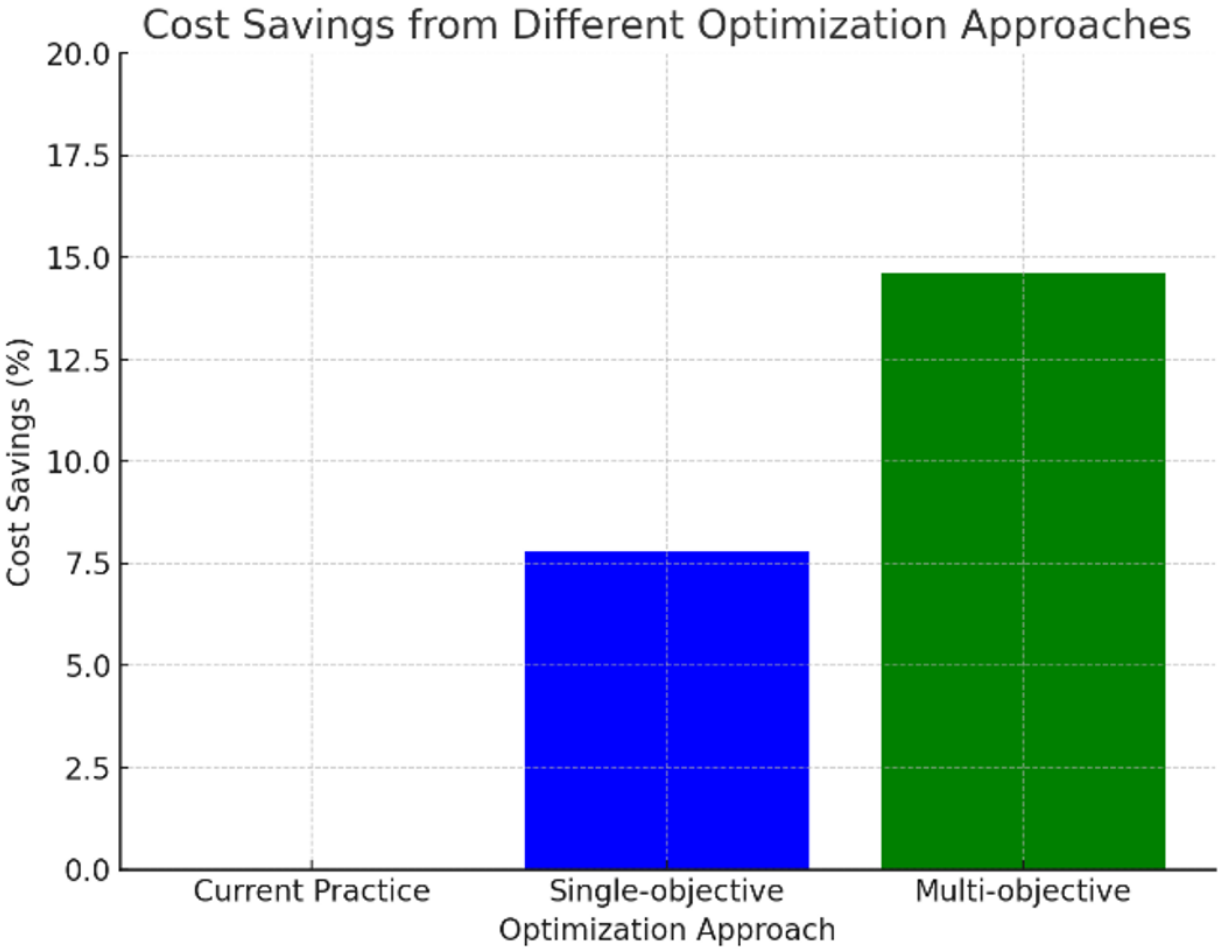

Figure 4.
Cost savings from different approaches.

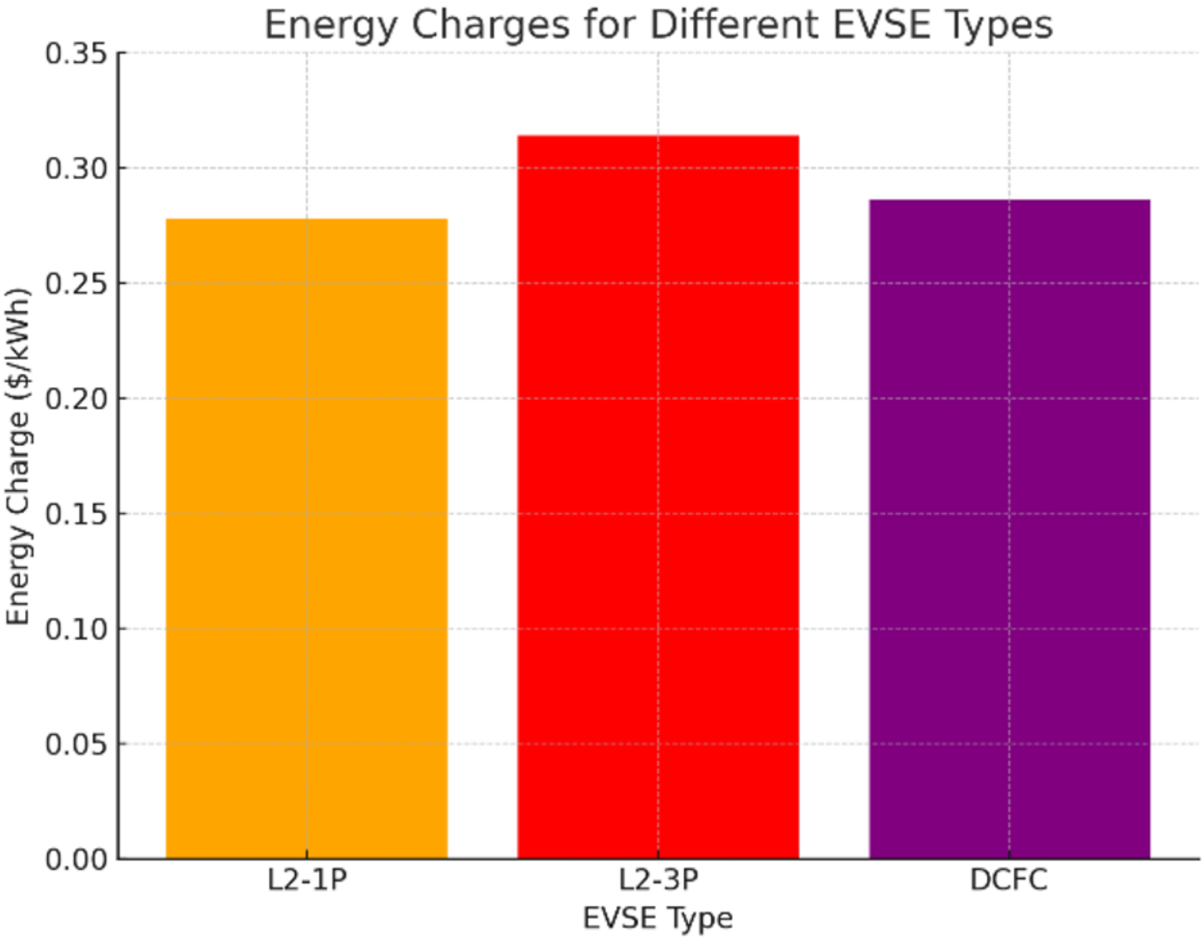

Figure 5.
Energy Charges for Different EVSE Types.

1.2.2. Itinerary Charging

Itinerary charging refers to strategically placed charging stations along travel routes and highways, providing long-distance electric vehicle (EV) drivers with the necessary infrastructure for recharging during extended trips. These stations are typically equipped with fast or ultra-fast chargers, reducing the time needed to charge an EV and minimizing disruption to travel plans. Itinerary charging plays a crucial role in reducing range anxiety, which remains a significant barrier to EV adoption. The success of these stations relies on effective planning, ensuring coverage along major routes while minimizing strain on local electrical grids. Frequent use of fast chargers may lead to accelerated battery degradation, as indicated by studies that show increased wear on batteries with repeated high-speed charging [20, 21].

Another aspect of itinerary charging is the integration of smart grid technologies to optimize energy distribution, such as demand-response strategies, which help manage the load during peak travel times. Strategic placement of these stations near renewable energy sources can also reduce the environmental impact of long-distance EV travel. The deployment of itinerary charging infrastructure is particularly important for promoting electric mobility in regions where long distances between urban centres require reliable access to fast chargers. However, challenges such as grid limitations and the impact of frequent fast charging on battery health remain critical factors for consideration [21, 22].

1.2.3. Home Charging

Home charging for electric vehicles (EVs) has become the most convenient and widely used method for charging, especially for drivers with access to private parking. Home chargers typically operate using AC Level 1 or Level 2 charging systems, with Level 1 being slower, drawing power from a single-phase outlet, while Level 2 uses bi-phase or three-phase outlets, depending on the country, providing significantly faster charging times. Home charging accounts for the majority of EV charging events due to its convenience, allowing vehicles to charge overnight during off-peak electricity hours, benefiting both users and the grid.

However, there are challenges related to grid impacts and energy demand management. Studies show that uncoordinated home charging can lead to increased strain on local transformers, especially during peak demand periods, which accelerates the aging of grid infrastructure [10, 11]. Integrating smart charging systems at home, which schedule charging during off-peak hours, helps mitigate these impacts by spreading demand more evenly and reducing the likelihood of grid overload.

Additionally, advancements in vehicle-to-grid (V2G) technology offer a solution where EVs can not only draw energy but also discharge excess stored energy back to the grid, acting as a distributed energy resource. This contributes to grid stability, especially when paired with renewable energy sources like solar [3].

1.3. Charging Technologies

1.3.1. Smart Charging

Smart charging refers to an advanced system for charging electric vehicles (EVs) that adjusts the timing, speed, and intensity of charging based on various factors such as electricity prices, grid demand, and the availability of renewable energy. Unlike conventional charging methods, smart charging helps to balance the load on the electrical grid, making the system more sustainable and cost-effective while still meeting the energy needs of EV users [23, 24].

Smart charging allows EVs to charge when electricity costs are lower (e.g., during off-peak hours) or when renewable energy is abundant, reducing reliance on fossil fuel-powered generation. Dynamic pricing models, such as time-of-use (TOU) tariffs, real-time pricing, and critical peak pricing, incentivize consumers to charge their vehicles at optimal times, thereby lowering costs for both consumers and grid operators. Moreover, smart charging technology can be integrated with vehicle-to-grid (V2G) systems, enabling EVs to send electricity back to the grid during high-demand periods, enhancing grid stability [3-5].

The Charger Reservation Web Application is designed to enhance the management of Electric Vehicle Supply Equipment (EVSE) through a user-friendly reservation system. This system allows electric vehicle (EV) operators to monitor, control, and reduce operational costs while ensuring the availability of charging units, and it is a part of smart charging [8].

The Charger Reservation Web Application is a mobile-friendly web application that integrates with the Open Charge Point Protocol (OCPP), facilitating interaction with EVSE systems accessible on both mobile and desktop platforms. It interfaces with an Energy Management System (EMS) to forecast power demands and modulate charging rates, helping to alleviate peak energy demands at charging facilities [5, 6, 8].

EV operators can easily identify and reserve available charging stations through the app, which provides insights into optimal charging times, customizable rates, and cost-effective options, thus improving the overall user experience [25]. The backend architecture employs Express and SQLite to manage reservations dynamically, enabling the system to forecast and respond to energy demands efficiently, particularly during peak usage times [5, 6].

Figure 6 illustrates the infrastructure of the reservation application, showcasing components such as the SQLite database, which acts as the primary data storage, managing reservation commands and enabling charge forecasting [10].

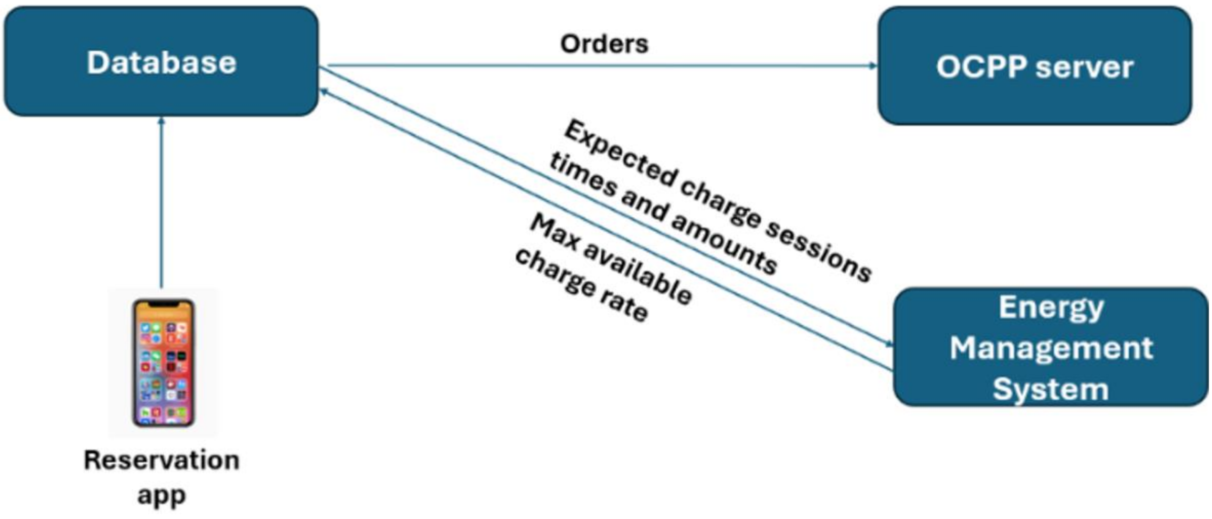

Figure 6.
EVSE reservation application.

The development of the Charger Reservation Web Application aligns closely with the concept of smart charging. By intelligently managing when and how much power is allocated to EVSE, the application helps balance the grid and reduces stress during peak demand hours [9]. Smart charging involves dynamic load management, allowing the adjustment of charging rates based on real-time energy availability and demand, thus mitigating issues like the duck curve, where energy demand fluctuates throughout the day. By enabling users to schedule charging during off-peak hours or when renewable energy is abundant, both facilities and consumers can benefit from lower electricity costs. Additionally, the app supports the transition to electric vehicles by enhancing the accessibility and efficiency of charging infrastructure, promoting a more sustainable transportation model [5, 6, 8-11].

1.3.2. Vehicle-to-Grid (V2G)

Vehicle-to-Grid (V2G) technology allows electric vehicles (EVs) to not only draw power from the grid but also to send energy back to it, functioning as mobile energy storage units. This bidirectional energy flow enhances grid stability, particularly during peak demand periods, by balancing supply and demand more effectively. V2G is considered a critical innovation in supporting the integration of renewable energy sources (RES), such as wind and solar, which are intermittent by nature. By enabling EVs to store excess energy during low demand and discharge it back to the grid when needed, V2G can reduce reliance on fossil fuel-based power generation and improve the efficiency of energy use [8-10].

V2G technology provides several benefits to both the power grid and EV owners. For the grid, it helps in managing peak loads, frequency regulation, and voltage stabilization. By participating in energy markets, EV owners can potentially earn income by selling stored energy back to the grid during times of high demand or through services like frequency regulation and demand-response programs [10].

However, the widespread adoption of V2G faces challenges, such as the need for advanced infrastructure, regulatory frameworks, and incentivized business models that make it economically viable for both consumers and utilities. Moreover, concerns about battery degradation from frequent cycling of charge and discharge remain a technical issue that needs addressing for long-term viability [11, 12].

1.3.3. Plug and Charge

Plug & Charge is a streamlined method for electric vehicle (EV) charging that allows drivers to simply plug in their vehicle, and the system automatically handles user authentication and billing. This technology, standardized by the ISO 15118 protocol, eliminates the need for RFID cards or apps, enhancing user convenience and security. Plug & Charge integrates directly with the vehicle’s onboard system, enabling automatic communication between the EV, charging station, and back-end payment systems [16-19].

By using Public Key Infrastructure (PKI) for encrypted communication, Plug & Charge ensures secure transactions, which are crucial for expanding EV charging networks globally. This technology also supports smart charging by enabling utilities to manage energy loads dynamically and by providing a seamless way to interact with other smart grid technologies [18].

2. EVSE Maintenance

The maintenance of Electric Vehicle Supply Equipment (EVSE) is essential for ensuring reliable charging infrastructure and long-term system efficiency. EVSE systems are exposed to environmental factors and usage patterns that necessitate regular upkeep. This includes monitoring the charging hardware, applying software updates, and conducting periodic inspections to ensure optimal functioning. Effective EVSE maintenance helps prevent system failures, which could otherwise disrupt the charging network and negatively impact electric vehicle (EV) users.

One of the emerging trends in EVSE maintenance is the use of predictive maintenance systems. These systems employ sensors and IoT (Internet of Things) technologies to continuously monitor the performance of charging stations. Data from these sensors is analyzed to predict potential issues before they result in system failures, thus reducing downtime and maintenance costs. Predictive maintenance is part of a broader shift towards smart charging and smart grid integration, where real-time data and analytics play a significant role in enhancing the resilience and efficiency of EVSE systems [14, 15].

Moreover, as EV adoption rises, the need for standardized maintenance protocols** becomes more apparent. Standardization allows for consistent practices across various networks and manufacturers, reducing complexity in maintaining diverse EVSE systems. Regular software updates are essential to ensure compatibility with evolving vehicle technologies and charging standards like ISO 15118, which governs Plug & Charge functionalities [13].

Upon interviewing key EVSE players:

The availability and reliability of Electric Vehicle Supply Equipment (EVSE) in Europe are crucial factors influencing the adoption of electric vehicles (EVs) and the overall user experience. Through interviews with key industry players, such as Gireve, Hubject, and Avere, as well as reviews of existing data, it becomes clear that while EVSE networks aim for high availability, the actual rates often fall short of expectations. For slow chargers, the availability rate averages around 72%, while fast and ultra-fast chargers show slightly lower rates at 67% and 71%, respectively.

One major issue is the discrepancy between reported uptime and actual uptime. Reported uptime, typically communicated by operators via software, often overestimates the functional availability of chargers. In reality, many EV drivers encounter non-functional chargers, with actual uptime dropping as low as 72.5% in some regions. This gap is exacerbated by issues such as aging infrastructure and inconsistent maintenance practices [17].

A significant contributor to downtime is the increasing demand placed on charging networks, coupled with aging infrastructure and unreliable payment systems. Predictive maintenance technologies, which leverage real-time data collected through Internet of Things (IoT) sensors, are proving to be critical in addressing these challenges. Predictive systems can forecast potential equipment failures, enabling operators to perform proactive repairs before a breakdown occurs. This approach not only improves EVSE availability but also reduces long-term operational costs.

Moreover, the variability in network performance is stark, with some networks maintaining uptime levels of over 90%, while others experience frequent outages, particularly in the ultra-fast charging category, which is essential for long-distance EV travel. Proactive solutions, such as predictive maintenance and improved technician training, are recommended to ensure high reliability, particularly as the number of EVs on the road continues to grow rapidly. By adopting these measures, EVSE operators can provide a more seamless and reliable charging experience for users across Europe.

3. Conclusion

EVSE maintenance is critical for a reliable and consistent charging infrastructure, yet availability rates in Europe are often lower than expected, with averages around 72% for slow chargers, 67% for fast chargers, and 71% for ultra-fast chargers. This gap between reported and actual uptime indicates persistent challenges due to aging infrastructure, inconsistent maintenance, and rising demand from increasing EV adoption. According to interviews with key EVSE players in Europe, including Gireve, Hubject, and Avere, we identified the need for a deeper understanding of maintenance practices and challenges. To explore this further, we are conducting an empirical study using questionnaires and interviews with EVSE ecosystem stakeholders.

4. Empirical Study: Design Thinking

4.1. Design Thinking

Design Thinking (DT) is a human-centered, iterative approach to problem-solving that has gained traction across sectors, including business, healthcare, and education. Emphasizing empathy and creativity, DT focuses on understanding users' needs and developing solutions that are feasible and desirable through stages such as empathizing, defining, ideating, prototyping, testing, and implementing. We plan to leverage this approach to investigate challenges in EVSE maintenance further [15, 16].

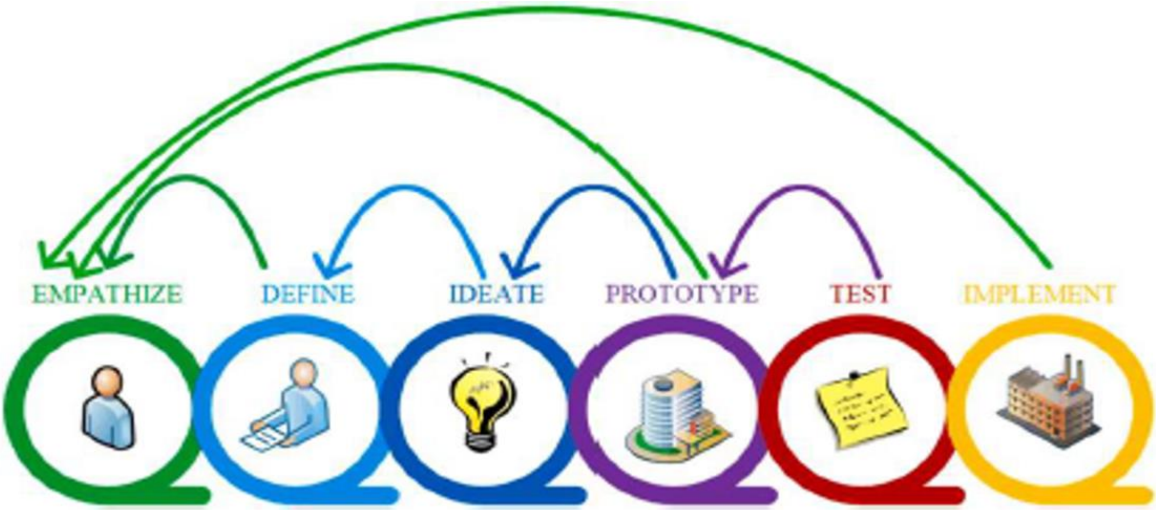

Figure 7.
Design thinking process.

4.2. Double Diamond Method

The Double Diamond (DD) model, as outlined by the Design Council (2019) [20], consists of two key phases represented by diamonds. The first diamond focuses on thoroughly exploring a problem by incorporating insights from individuals with relevant experiences. This stage aims to define the problem clearly and identify potential solutions [26, 27]. The second diamond involves the development of these solutions, enhancing viable ideas while discarding those that do not address the problem effectively [20, 21]. This model emphasizes a shift from divergent to convergent thinking, illustrating a non-linear, iterative process where new ideas can prompt revisiting earlier stages. This flexibility allows for continuous feedback and ongoing improvement throughout the design process [28].

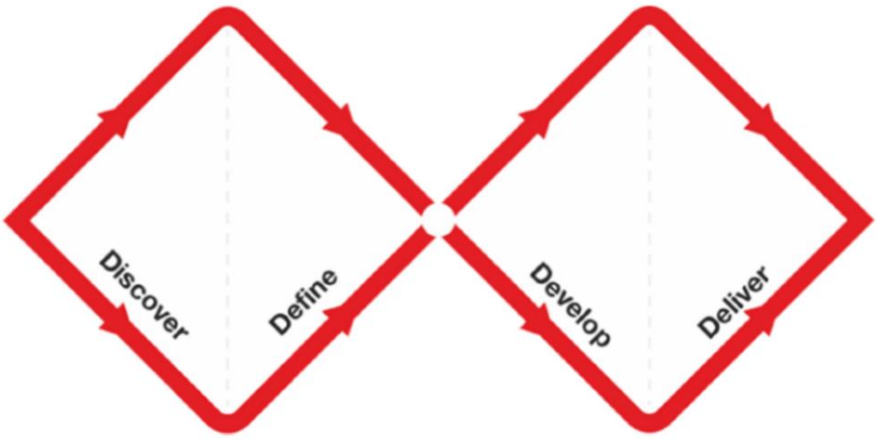

Figure 8.
Double diamond process.

The goal is to utilize the Double Diamond process to initiate the first two steps of design thinking: empathizing and defining the problem. By exploring insights from individuals with firsthand experience, we can gain a deeper understanding of the issues at hand. This foundational exploration ensures that the problem is accurately defined, setting the stage for relevant and effective solutions in the design thinking process.

4.3. Empathize Phase

In the empathize phase of our design thinking process, we undertook an empirical study aimed at gaining a comprehensive understanding of the problem at hand. This involved conducting a combination of interviews and questionnaire-based surveys, targeting a total of 200 participants. We successfully gathered 127 responses, comprising 35 interviews and 92 completed questionnaires. The survey was conducted over the months of July, August, and September 2024, allowing us to capture insights during a critical period. Our targeted interviewees included Charge Point Operators (CPOs), EVSE installers, charger manufacturers, and electric vehicle (EV) drivers, who represent our key personas. By engaging with these stakeholders, we aimed to delve into their unique experiences, needs, and challenges associated with electric vehicle charging. This approach enabled us to gather diverse perspectives, ensuring our understanding is both rich and relevant for informing the subsequent phases of the design thinking process. The insights obtained will not only help us define the problem more accurately but also guide the development of solutions that truly resonate with the target audience.

Personas:

Charge Point Operators (CPO).

EVSE Installer, maintainer (Technician).

Charger Manufacturer (Manufacturer).

EV Driver (Driver).

Questionnaire blocs:

Demographic information.

Maintenance strategy.

Availability rate.

Maintenance expenses.

Customer satisfaction.

Interviewees' feedback by persona:

4.3.1. Charge Point Operator

As mentioned earlier, Charge Point Operators (CPOs) are key players in the electric vehicle (EV) ecosystem, responsible for managing and operating charging infrastructure for electric vehicles. They oversee the installation, maintenance, and operation of charging stations, ensuring that EV drivers have reliable access to charging facilities. CPOs often collaborate with various stakeholders, including manufacturers, local governments, and businesses, to expand charging networks and improve user experience. Their role is crucial in facilitating the transition to electric mobility, as they work to ensure that charging solutions are efficient, accessible, and aligned with the growing demand for sustainable transportation.

Pain:

- Higher failure rate of around 35% on average
- Corrective maintenance is carried out upon failure, 1 week later on average
- Preventive maintenance is carried out according to the manufacturer’s schedule, which is once a year, starting from the second year, with no maintenance in the first year of deployment
- Most of the failures occur in the first 12 months upon deployment
- EV drivers are not satisfied
- Maintenance expenses are too high, as most of the time technicians go to the field to fix small issues (for AC chargers, almost half of the EVSE deployment cost every year and 30% for DC chargers)
- 65% of breakdowns are hardware and 35% are software-related

Gain:

- More EV drivers
- More manufacturers
- More technicians

It would be a game-changer:

- To cut down the EVSE failure rate
- To diagnose remotely
- To carry out some 1-level maintenance remotely
- To share the problem quickly with technicians

How Might We statement: This statement is used to reframe the problem.

How might we provide a maintenance technology and process to reduce failure rates and cut down maintenance expenses?

4.3.2. EVSE Installer Maintainer (Technician)

EVSE maintenance installers are essential professionals in the electric vehicle (EV) infrastructure sector, tasked with the installation, upkeep, and repair of electric vehicle supply equipment (EVSE). They ensure that charging stations are properly installed, operational, and safe for use by EV drivers. Their responsibilities include routine maintenance, troubleshooting issues, and performing necessary repairs to minimize downtime and enhance user satisfaction. EVSE maintenance installers collaborate closely with Charge Point Operators (CPOs), manufacturers, and other stakeholders to provide effective solutions that support the growing demand for reliable charging infrastructure. Their expertise is critical in ensuring that charging stations function optimally, contributing to the overall efficiency and reliability of the EV ecosystem.

Pain

- High failure rate.
- Called by CPO on average a couple of days after the breakdown.
- Often asked to intervene quickly.
- 80% of operations are level 1 maintenance that could be carried out if technologies like IoT (Internet of Things) are available.
- In the remaining 20%, almost 83% are physical damages caused by vandalism or collisions with cars and do not require intervention by an electricity technician. These cases are handled directly by the manufacturer.
- 85% of EVSE are 100km away.
- Level 3 EVSE (Ultrafast charging) requires a specific manufacturer qualification to each manufacturer to carry out a maintenance task.

Gain

- Most of the repairs are easy.
- Maintenance above level 2 is done by the manufacturer.
- EVSE maintenance generates important revenue for simple actions. Only travel that takes a lot of time justifies the technician’s invoices.

It would be a game-changer:

- To inform the technician immediately after the failure occurs.
- To diagnose remotely.
- To carry out some 1-level maintenance remotely.
- To have one standardized qualification for all manufacturers.

How Might We statement:

“How might we make it easier and intuitive for technicians to carry out maintenance tasks properly?”

4.3.3. Charger Manufacturer

EVSE charger manufacturers play a pivotal role in the electric vehicle (EV) ecosystem by designing and producing the equipment necessary for charging electric vehicles. These manufacturers develop a range of charging solutions, including home chargers, public charging stations, and fast chargers, tailored to meet the diverse needs of EV users and operators. They are responsible for ensuring that their products are not only efficient and reliable but also compliant with safety standards and regulations.

Pain:

- Often asked to intervene for electricity-related issues and not charge itself.
- Often, chargers need only a simple reboot to be up-to-date and available.
- Chargers are damaged by a car collision or vandalism.

Gain:

- Increasing demand for products.
- Technicity progresses constantly.

It would be a game-changer:

- To reach out manufacturer when it’s necessary.
- To physically protect chargers from collision.
- To protect chargers from vandalism.
- To carry out most of the tasks remotely.

How Might We statement:

“How might we optimize manufacturers' intervention and outsource the utmost maintenance tasks?”

4.3.4. Electrical Vehicle Driver

The EV driver is a crucial participant in the charging ecosystem, serving as its primary customer. As the individual most affected by maintenance issues, the driver not only bears the cost of charging but also has a significant influence on the overall experience. Their feedback is invaluable and should be treated with the utmost seriousness. Furthermore, the satisfaction level of EV drivers is an essential factor that must be prioritized in the development and improvement of charging services.

Pain:

- Charging stations unavailability
- Drivers acknowledge that some chargers are not available once they arrive to charge as the equipment is not connected
- Once faced with an unavailable charger, the back office had no remote solutions available, except for unlocking the gun locker if it was stuck.
- The driver either can't do any action to make it work
- Chargers are sometimes damaged physically by car collisions or vandalism acts

Gain:

- More chargers than before
- More protected in terms of cybersecurity
- Many choices of payment methods

It would be a game-changer:

- To allow the driver to contribute to charger availability
- To give the back office more room for maintenance tasks
- To repair physical damage as quickly as possible
- To have available data about all chargers on the app

How Might We statement:

"How might we enhance the customer experience to enable drivers to charge their cars with ease and peace of mind?"

4.4. Define Phase

By gathering all "How Might We" statements, one statement emerges: "How might we create a seamless and efficient ecosystem that enhances the customer experience for EV charging, optimizes manufacturer interventions, simplifies maintenance tasks for technicians, and integrates technology to reduce failure rates and maintenance costs?"

4.5. Ideate Phase

The ideate phase of design thinking is a crucial step where teams generate a wide array of creative solutions based on insights from earlier phases. It fosters open-mindedness and divergent thinking through techniques like brainstorming and mind mapping. Following this, the second diamond of the Double Diamond process emphasizes convergent thinking, where teams assess and refine these ideas through prototyping and testing. This iterative approach, grounded in user feedback, helps ensure that the final solutions are effective, innovative, and aligned with user needs.

4.5.1. EVSE Breakdowns Root Causes

Five "why" questions were incorporated into the interview questions and the survey questionnaire to uncover the root causes of recurring problems. The results indicate that three primary reasons account for most breakdowns, as reported by key stakeholders. These causes include software failures, electrical hardware failures related to either the infrastructure or the charger, and physical damage resulting from collisions or vandalism.

Table 1.
Maintenance tasks comparison.

Main root causes	Explanation	Traditional solution steps	Sophistical solution (Failure rate > 95%)	Industry 4.0 tools
Software-related causes	Software bug Firmware bug	1 CPO informs the technician 2 Field visit 3 Diagnosis 4 Manual charger reboot	1 CPO carries out a remote reboot	Connectivity 4G IoT
Infrastructure electrical failure	Ground problem Differential problem Undervoltage Shortcircuits	1 CPO informs the technician 2 Field visit 3 Diagnosis 4 Problem identification If maintenance level 1 or 2 5 Parts preparation 6 Intervention If maintenance level 3, 4 or 5 8 CPO informs the manufacturer 9 Manufacturer intervention	1 CPO extract primary data (ground, voltages, current) 2 CPO sends primary data to the technician 3 Technicians carry out a differential voltage test remotely 3 Technician has clearer data over the problem and carries out a precise intervention, in case of maintenance level 1 or 2, with all needed material and estimated intervention time upfront. Or inform the manufacturer directly if the maintenance level is 3 or higher	Connectivity 4G IoT Connected circuit breaker Connected ground controller Cloud computing
Charger or infrastructure physical damage	Charger chassis damaged Cable damaged	1 CPO cannot see the damage	1 CPO notices damage through high high-definition camera installed in the EVSE 2 CPO informs insurance 3 Insurance asks the manufacturer to proceed to repair or replacement	High definition connected cameras 4G IoT Cloud computing

4.5.2. Comparison

To define a solution, we acknowledged that experience is invaluable and subsequently questioned interviewees regarding their insights. Approximately 7% of our target audience reported an availability rate of between 95% and 100%. The questions posed were technical and specifically focused on how they address the three main root causes of failures. Table 1 shows a comparison of maintenance tasks carried out.

On top of that, CPOs with higher availability rates stated that they have put in place all the ways for EV drivers to reach out to the back office in the breakdown case (QR codes, hotline, email address, messaging, WhatsApp). As a result, most failures are noticed and are claimed by the EV driver themselves. This approach also involves the user in the maintenance process, which concretely reflects the TPM (Total Productive Maintenance) mindset [29].

4.5.3. Statistics

Based on the comparison, CPO could save the following:

Table 2.
Maintenance tasks comparison.

Breakdown nature	Saved time
Software/firmware	7 to 10 working days
Infrastructure electrical failure	7 to 20 working days
Charge physical damage	25 to 60 working days

5. Conclusion

In conclusion, addressing environmental challenges necessitates a swift acceleration toward transportation electrification, with electric vehicles (EVs) playing a crucial role in reducing greenhouse gas emissions and promoting cleaner urban environments. However, significant barriers to user adoption persist, particularly concerning the deployment and availability of Electric Vehicle Supply Equipment (EVSE). Many charging installations in regions like Europe and

China are beginning to show signs of aging, leading to declining availability rates that hinder user satisfaction and undermine the broader goal of encouraging electric vehicle adoption.

To overcome these challenges, effective maintenance strategies are essential to ensure that EVSE facilities remain operational and capable of meeting the growing demand for charging. The integration of Industry 4.0 tools, such as the Internet of Things (IoT), cloud computing, and high-definition cameras, presents a transformative opportunity for Charge Point Operators (CPOs) and manufacturers. These technologies enable real-time monitoring of charging station performance, allowing stakeholders to identify potential issues before they escalate into major failures. For instance, IoT devices can track usage patterns and alert operators to maintenance needs, optimizing charging station operations and enhancing reliability.

Additionally, manufacturers must expand maintenance access beyond Level 2 for installers without restrictions, facilitating quicker and more efficient repairs. Establishing standardized maintenance protocols is crucial for ensuring consistent upkeep across networks, which will help maintain the infrastructure's reliability and user confidence. Moreover, integrating evolving technologies such as ISO 15118 for Plug & Charge compatibility will further streamline the user experience, making electric vehicle charging more convenient.

By prioritizing effective maintenance strategies, embracing advanced technological innovations, and fostering collaborative practices between manufacturers and installers, we can significantly enhance the availability of EVSE. This comprehensive approach will not only encourage greater consumer confidence in electric vehicles but also contribute to the sustainable growth of the electric mobility ecosystem, paving the way for a cleaner, greener future for all.

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