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Lessons learned, impact and replicability potential assessment for the Danish demo

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Disclaimer

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[1] https://ev4eu.eu/

Executive Summary

This report presents the results of the Danish demonstrator, which evaluates a distributed electric vehicle (EV) charging system deployed at two sites: Risø (at DTU) and Campus Bornholm. The objective of the demonstrator was to assess the technical performance, user interaction, and operational feasibility of a smart, user-driven charging solution in both controlled and semi-public environments.

The deployed system integrates modular alternating current (AC) charging hardware, a cloud-based backend architecture, and a mobile application (Circle Grid) to enable real-time monitoring, distributed load management, and user-controlled charging sessions. The infrastructure at both sites consists of six dual-outlet chargers, supporting up to 12 simultaneous charging sessions, connected to the grid with a shared capacity and managed through distributed control mechanisms.

Operational results from the analysis period (November 2024 to December 2025) show that the system successfully enabled EV charging in real-world conditions while providing valuable insights into user behaviour and system flexibility. User engagement varied between the two sites, reflecting their different contexts: Risø, primarily used by office employees, exhibited more consistent weekday usage with peak activity on Mondays, whereas Campus Bornholm, serving educational staff, showed higher variability and peak usage on Thursdays.

From a system perspective, the solution demonstrated a strong capacity for flexibility in terms of power, energy, and time. Both sites were able to operate below their maximum grid capacity during peak periods, indicating effective load distribution. Flexibility indicators confirmed that the system can contribute to grid balancing, although limitations in charging power influenced charging duration and time-based flexibility.

During early operation, several technical challenges were identified, particularly related to hardware reliability, app usability, and system integration. Issues such as cable locking failures, charging initiation errors, and inconsistencies between frontend and backend systems reflected the immaturity of the initial solution. However, continuous monitoring, structured issue tracking, and iterative software updates led to significant improvements and overall system stabilization.

The results highlight the importance of robust integration between hardware, software, and user interfaces in ensuring reliable operation. At the same time, the demonstrator confirms the feasibility of distributed EV charging control in semi-public environments and its potential to support flexible energy management.

In terms of product development, the charger design emphasizes modularity, durability, and scalability. The use of extruded aluminium structures, flexible mounting configurations, and modular electronics supports cost-efficient manufacturing, simplified installation, and long-term maintainability. These characteristics, combined with a scalable cloud-based backend, position the solution well for replication and broader deployment.

In conclusion, the Danish demonstrator validates both the technical concept and practical applicability of the proposed EV charging system. While further improvements are needed, particularly in software stability, user experience, and hardware robustness, the overall results demonstrate a strong foundation for scaling the solution and contributing to the wider adoption of smart EV charging infrastructure.

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Acronyms

AC	Alternating Current
ADMS	Advanced Distribution Management System
AWS	Amazon Web Services
BEOF	Bornholms Energi & Forsyning
BOM	Bill of Materials
CAN	Controller Area Network
CP	Control Pilot
DTU	Technical University of Denmark
EFI	Energy Flexibility Index
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
I2C	Inter-Integrated Circuit
IAM	Identity and Access Management
IoT	Internet of Things
IP	Ingress Protection
KPI	Key Performance Indicator
MPFI	Minimum Power Flexibility Index
APFI	Average Power Flexibility Index
MQTT	Message Queuing Telemetry Transport
PCB	Printed Circuit Board
PCC	Point of Common Coupling
PP	Proximity Pilot
PV	Photovoltaic
RCM	Residual Current Monitor
RCD	Residual Current Device
TFI	Time Flexibility Index
TRL	Technology Readiness Level

1 Introduction

This document presents an overview of the Danish demonstrator within the project, focusing on the deployment, operation, and evaluation of a distributed electric vehicle (EV) charging system in real-world environments. The demonstrator includes two primary sites, Risø (DTU) and Campus Bornholm, representing both controlled and semi-public use cases.

The purpose of this report is to analyse the lessons learned from the Danish demonstration, covering technical performance, system integration, user interaction, and operational challenges. Particular emphasis is placed on understanding how the combination of hardware, software, and user-facing applications performed under real conditions, and how iterative improvements contributed to system stabilization over time.

The Danish demonstrator has shown that distributed control of EV charging is technically feasible and can operate effectively in semi-public environments. At the same time, the deployment revealed important challenges, especially related to early-stage software maturity, hardware reliability, and user experience. Issues such as app usability, charging initiation, and communication between system components highlighted the importance of robust integration and continuous development.

Overall, the demonstration provided valuable insights into both the strengths and limitations of the solution. These findings form the basis for further optimization and support the scaling and replication of the system in future deployments.

1.1 Scope and Objectives

The scope of this chapter is to document and evaluate the Danish demonstrator from both a technical and operational perspective. It covers the design, deployment, and performance of the EV charging system, including hardware components, backend infrastructure, mobile application, and user interaction.

The main objectives are to:

- Assess the functionality and reliability of the deployed system in real-world conditions
- Identify key technical and operational challenges encountered during the demonstration
- Analyse user interaction and system usability in both controlled and semi-public environments
- Evaluate the effectiveness of the distributed control approach for EV charging
- Extract lessons learned to support future development, optimization, and large-scale deployment

1.2 Structure

This report is structured to provide a comprehensive overview of the Danish demonstrator and its outcomes.

It begins with a description of the tested solutions and deployment environments, outlining the technical setup and characteristics of the demonstration sites. This is followed by an evaluation of system performance and operational experiences, including identified issues and their resolution.

Subsequent sections present an analysis of the lessons learned, focusing on key aspects such as hardware design, software integration, user experience, and system scalability. The chapter concludes with an assessment of the replicability and future potential of the solution.

1.3 Relationship with other deliverables

This deliverable D9.5 Lessons learned, impact and replicability potential assessment for the Danish demo builds directly on the results and data generated throughout WP9 and uses these as concrete input for the analysis presented.

The methodological foundation for the Danish demonstrator is defined in D9.1 [1], which specifies the use cases, system architecture, and evaluation framework. The assumptions, and evaluation criteria established in D9.1 are used in D9.5 as the reference baseline for assessing system performance, identifying deviations, and framing the extracted lessons.

D9.2 [2] provides detailed documentation of the commissioning and start-up phase, including installation procedures.
System integration challenges, and early operational issues, is detailed in D9.3 [3]. The technical and organizational challenges identified during this phase, such as hardware reliability, communication stability, and system integration are directly reflected in the lessons learned presented in this deliverable.

The operational data recorded in the context of D9.3 [3] is a one of many inputs to D9.5. The operation log includes system events, charger availability, error cases, and user interaction patterns over time. This dataset is used to identify recurring issues, evaluate system robustness, and support the qualitative and quantitative assessment of system behaviour under real-world conditions.

D9.4 [4] provides the formal analysis of the Danish demonstration results, including evaluation, flexibility metrics, user engagement patterns, and energy performance. These results are explicitly used in D9.5 as the analytical basis for interpreting system performance.

D9.5 builds on these findings to assess their implications, explain observed behaviours, and ideally translate them into actionable lessons.

In this context, D9.5 acts as a consolidation and interpretation layer across WP9, Planning (D9.1, [1]), commissioning (D9.2, [2]), operational data (D9.3, [3]), and performance results (D9.4, [4]) into insights on system performance and improvement potential.

2 Technical assessment

The technical assessment evaluates the deployment and operation of a distributed electric vehicle (EV) charging system tested at two demonstration sites: Risø (DTU) and Campus Bornholm. The project integrates modular charging hardware, a cloud-based backend infrastructure, and a user-facing mobile application (CircleGrid) to enable intelligent, user-driven charging in semi-public environments.

Initial operation revealed several technical challenges, particularly related to hardware reliability, app usability, and system integration. Issues such as cable locking failures, charging initiation errors, and inconsistencies between frontend and backend systems highlighted the immaturity of early-stage development. However, continuous monitoring, structured issue logging, and iterative software updates led to progressive system stabilization.

The backend architecture, built on scalable AWS services, successfully supports real-time data processing, secure user management, and IoT connectivity. Combined with a Flutter-based mobile application and the Nordic mobile app integrated payment solution (MobilePay), the system demonstrates a robust and flexible platform for EV charging management.

Overall, the demonstration confirms the feasibility of distributed control for EV charging in semi-public contexts. At the same time, it underscores the importance of further improvements in app stability, user interaction, and hardware reliability to ensure a fully mature and scalable solution.

2.1 Overview of tested solutions and deployment environments

The tested solution consists of an integrated EV charging ecosystem combining hardware, software, and cloud-based services, deployed and evaluated at two demonstration sites: Campus Bornholm (Figure 1) and Risø (DTU) (Figure 2).

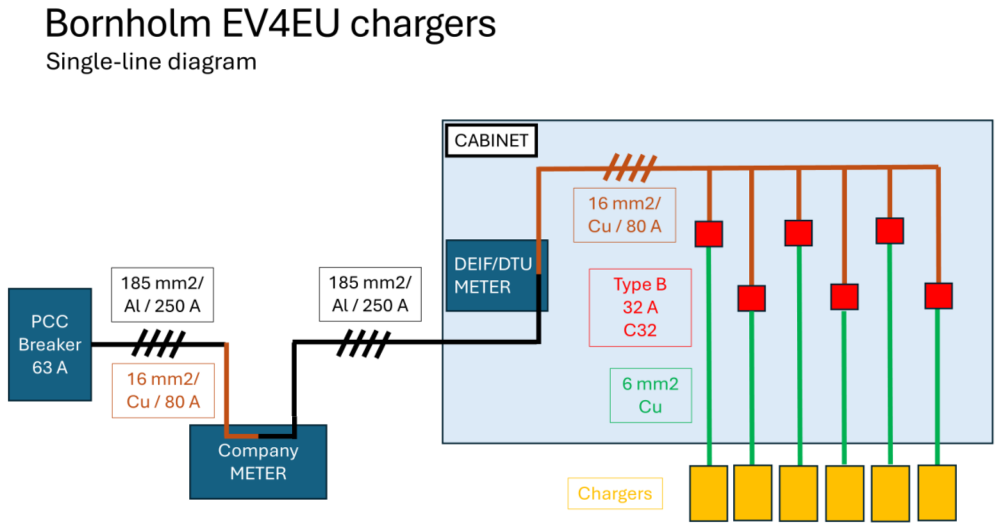


Figure 1: Diagram of the electrical infrastructure at Bornholm Campus

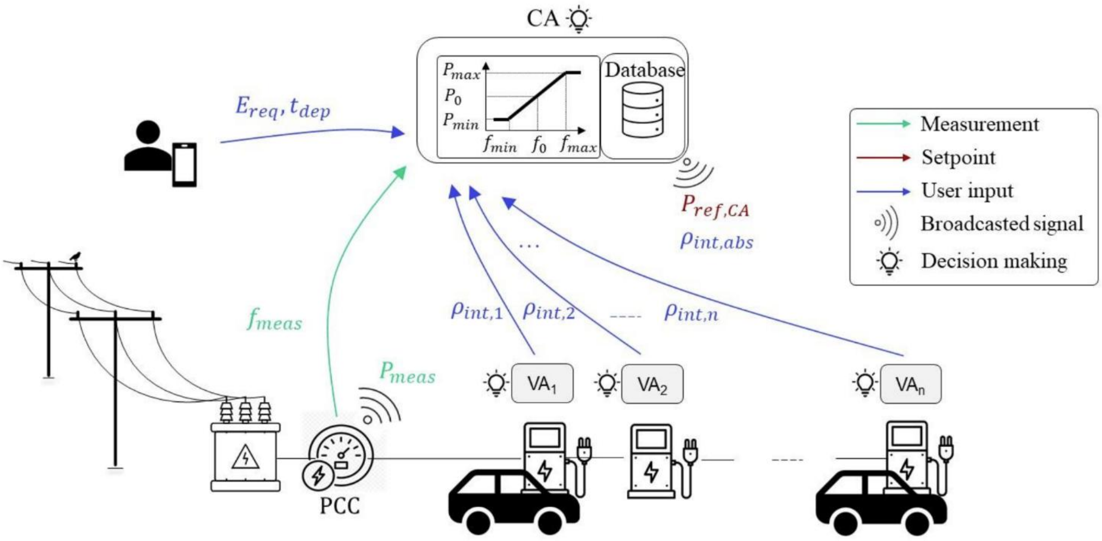


Figure 2: Simplified diagram of Risø

The two deployment environments offered complementary testing conditions. The Risø site, managed primarily by DTU, enabled controlled internal testing and rapid iteration during early development phases. In contrast, Campus Bornholm provided a semi-public, real-world environment with active user participation, offering valuable insights into user behavior, system usability, and operational robustness.

Both sites were equipped with identical charging infrastructure, consisting of six dual-outlet AC chargers rated at 22 kW each, enabling up to 12 simultaneous charging sessions per location. The installations are connected to the electrical grid via a 43 kW connection and incorporate a distributed load management system. This system enables autonomous control of individual chargers, optimizing energy distribution in real time based on grid capacity and user demand. Communication and control between the chargers and connected vehicles are implemented in accordance with the IEC 61851-1 standard.

From a hardware perspective, the chargers are designed using a modular architecture that integrates key electrical components, including CEE grid connections, AC charging outlets, and multiple printed circuit boards (PCBs). These include relay boards for power control, energy metering boards for phase-level measurement, and communication boards for sensor data acquisition. Safety is ensured using residual current monitoring (RCM) and residual current devices (RCD). Below is a table of the PCB specifications.

Table 1 - PCB specifications

General Configuration
Each charger is equipped with 2 independent charging outlets. Each outlet operates as a self-contained system with dedicated power, control, measurement, communication, and safety functionalities.
Hardware sub systems

PSU PCB	Converts 230 VAC (RMS) input into regulated +12 V, −12 V, and +3.3 V DC outputs. These voltage rails supply all electronic subsystems within the outlet, ensuring stable and reliable operation.
Relay PCB	Responsible for power switching and control. Includes 32 A relays for each phase, enabling safe connection and disconnection of the load. Additionally, it manages control pilot (CP), proximity pilot (PP), and actuator signals required for proper operation of the charging interface.
Metering PCB	Provides real-time measurement of voltage and current on each phase. Utilizes shunt resistors and current transformers to ensure accurate monitoring, supporting system control, diagnostics, and energy tracking.
Communication PCB	Handles sensor data acquisition and coordination between system boards. Enables external communication with backend servers and mobile devices via Bluetooth, Wi-Fi, and 4G, supporting monitoring, control, and user interaction.
Safety System	Incorporates an HPFI relay (RCD Type A) and residual current monitoring to detect leakage currents. Ensures immediate protective action to maintain user safety and comply with electrical protection requirements.

The software solution is built on a serverless cloud architecture using Amazon Web Services (AWS). Core components include Amazon Cognito for authentication, DynamoDB for scalable data storage, AWS Lambda for event-driven processing, AWS AppSync for real-time API communication, and AWS IoT Core for secure device connectivity via MQTT. This architecture enables seamless communication between users, backend services, and physical charging devices, ensuring scalability, reliability, and secure data handling.

User interaction is facilitated through the Circle Grid mobile application, developed in Flutter for cross-platform compatibility. The app allows users to locate chargers, initiate sessions via QR code or manual input, and monitor charging in real time. Payment integration is handled through MobilePay, enabling secure and streamlined transaction processing.

Additionally, a web-based Master interface provides administrative oversight, allowing operators to monitor charger status, manage configurations, and track usage and payment data.

Together, these environments enabled comprehensive evaluation of the system under both controlled and real-world conditions, supporting iterative improvements and validation of the overall solution.

2.2 Evaluation of demonstration sites

Conclusion of operation:

At the Risø site, where DTU managed most testing internally, issues were primarily related to app usability, session management, and inconsistencies between the user interface and system backend. Despite these problems, iterative debugging and software updates helped stabilize the system over time.

At Campus Bornholm, several problems, particularly cable lock failures, unresponsive charging initiation, and repeated app-to-payment communication errors were likewise connected to immaturity in the app development and integration phase. In addition, periods of signal instability prevented reliable communication between the backend system and the chargers. This highlighted the dependency of stable user operation on both robust communication infrastructure and continuous improvements of the Circle Grid app. However, this site also provided valuable insights into real-world usage scenarios and user engagement, especially in a semi-public educational environment.

To address the signal quality issues the chargers were retrofitted with non-metallic lids, and the RF design and antenna orientation was changed.

During operation of the EV chargers on the Bornholm installation, two units experienced vandalism affecting the cable locking mechanism. The internal gearing of the lock was forcibly damaged, rendering the chargers inoperable (see D9.3). The equipment used is based on industry-standard components from Mennekes, which are widely deployed and considered high quality. The incidents therefore do not indicate a deviation from expected component performance under normal use, but rather highlight exposure to non-standard user behaviour in the deployment environment.

The observed failures demonstrate that even widely adopted, high-quality charging components have inherent limitations when deployed in public or unsupervised environments. The issue is not related to component selection, but to the mismatch between standard design assumptions and real-world usage conditions, including vandalism. Future deployments should therefore address this at a system level through site selection, risk acceptance, and appropriate mitigation measures, rather than through significant redesign of the core hardware, which would negatively impact cost and scalability.

2.3 Site preparation and infrastructure

The Danish demonstration sites at DTU Risø and Campus Bornholm were prepared to support the deployment of intelligent EV charging infrastructure in semi-public parking environments. Both sites implemented identical charging systems consisting of six dual-outlet AC chargers rated at 22 kW, enabling up to twelve vehicles to charge simultaneously through a shared 43 kW grid connection.

At DTU Risø, the charging infrastructure was installed within a semi-public research and office environment integrated into the SYSLAB - Energy System Integration Lab. Site preparation included electrical cabling, installation of charging poles, protective equipment, and an electrical cabinet acting as the point of common coupling (PCC). Additional commissioning activities focused on integrating the chargers with SYSLAB’s distributed energy resources, monitoring systems, and distributed control architecture.

At Campus Bornholm, the charging cluster was deployed in a publicly accessible parking area intended for students, staff, residents, and tourists. Preparation work included underground cabling, charger installation, and smart meter integration. Although the site was not physically connected to the SYSLAB grid, the same distributed control architecture was implemented to allow coordinated operation and monitoring.

Several common challenges were identified during installation and commissioning at both locations. These included coordination between hardware installation and software integration, limited grid capacity requiring advanced load management, and ensuring stable communication between chargers and backend systems. Periods of signal instability occasionally disrupted communication and affected charger coordination and monitoring. The preparation phase therefore required extensive testing and validation to ensure reliable interoperability between chargers, control systems, and user applications.

The photos below show the charging site at DTU Risø campus in front of building 330 (Figure 3) and the BEOF parking lot (Figure 4).

Figure 3: Risø parking lot

Figure 4: BEOF parking lot

2.4 Hardware integration

The electrical sub-components of the charger system consist of a CEE power plug to connect to the grid, and two AC outlets to connect an EV, and several other PCBs inside the charger that facilitate and monitor the charging process. The electrical hardware is setup in a modular fashion to achieve a compact charger while also meeting clearance and creepage distance requirements to the electrical isolation. Furthermore, RCMs (Residual Current Monitors) and RCD (Residual Current Device) complement electrical safety.

Four different PCBs were designed for this project. Each with a specific purpose and they are referred to as:

- Relay board, to connect the AC mains and EV via relays

- Energy metering board, to measure the energy delivered for each phase
- Communication board, to gather sensor data and establish IoT connectivity
- Power Supply board, to provide power to the communication and energy metering board

One charger consists of two relay boards and two energy metering boards for each outlet (primary and secondary). The relay boards are distinguished by a different variant of the Bill-of-Materials (BOM). Depending on the variant, a primary or secondary relay board may be composed. As a result, only one PCB had to be designed to produce the primary secondary side relay boards, that make up the charger. In a similar way, though only one variant exists, a metering board was designed to be installed on either side of the charger. It differs in the manner it is mounted inside the enclosure. Using this approach, designs could be reused for modularity.

For connectivity, a broadband PCB antenna was used on the communication board. Although a connection can be established, two aspects were initially not considered that diminished the signal strength. One was that the directivity of the antenna was not examined properly. This issue was solved by fitting the communication board to a bracket that would rotate the antenna by 90° from its original position. Secondly, the whole enclosure was initially composed of aluminum, which greatly reduced the signal strength. Here, replacing the top-lid of the enclosure with a plastic lid constitutes a window for the antenna signals enter and escape.

A large factor that compromised the reliability of the charger was the inter-board communication. It was established via an Inter-Integrated Circuit (I2C) bus, connecting all the boards via connectors and cables. Due to the physical length of the bus and the noisy environment, this solution required several hardware modifications on the boards to work reliably. An alternative solution is to use Controller Area Network (CAN) bus protocol. Despite its larger overhead CAN would improve the reliability, especially in prospect of larger production volumes.

Another source hampering the reliability of the charger was the signal processing of the Control Pilot (CP) and Proximity Pilot (PP) of the AC outlets. The circuitry for this function was implemented via analog circuitry, which is prone to component variations and need sufficient tolerances. More integrated circuitry for EVSE (electric-vehicle supply equipment) can increase reliability and are advised. Additionally, the chosen AC outlet is also prone to mechanical failure due to wear and tear. A substitute would need to be sought out.

2.5 Software Backend

This system is built on a scalable, serverless backend using several AWS services to support user management, application logic, real-time data synchronization, and IoT device connectivity.

Authentication:

User authentication and identity management are handled through Amazon Cognito. It provides secure user sign-up, sign-in, and token-based authentication, enabling the application to manage users without maintaining custom authentication logic.

Access control across the system is enforced using AWS IAM. IAM roles and policies define what authenticated users, services, and components are allowed to do, ensuring secure and fine-grained permissions throughout the architecture.

Data Storage:

Data storage and retrieval in the backend are managed using Amazon DynamoDB. DynamoDB provides a fully managed, highly scalable NoSQL database that stores charger information, user data, and charging session records. Its low-latency performance ensures that both the app and the Master interface can access and update data in real time, supporting operations such as session tracking, charger status updates, and payment verification. The combination of DynamoDB with AppSync and Lambda enables a fully serverless, event-driven architecture that scales automatically with demand.

Frontend (App and Master Interface):

The frontend application, the app is integrated with AWS Amplify, which simplifies interaction with backend services. Amplify provides built-in support for authentication, API communication, and state management, accelerating development and deployment.

For application data and real-time synchronization, AWS AppSync is used. It enables GraphQL-based APIs that allow clients to efficiently query and update data. AppSync also supports real-time subscriptions, ensuring that clients receive live updates when data changes.

A Master interface is provided as a web-based administrative dashboard, enabling authorized users to monitor and manage the system. The interface interacts directly with Amazon DynamoDB to retrieve and update operational data, including charger status, configuration, and user activity. Administrators are given a comprehensive overview of all connected chargers, including real-time state, historical performance, and individual charge sessions. The dashboard also provides visibility into transaction data and payment flows, integrating with the MobilePay API to track, validate, and manage payments. Through this interface, admins can ensure system health, audit usage, and handle operational tasks efficiently from a centralized platform.

Data processing:

Business logic and backend processing are implemented using AWS Lambda. Lambda functions are triggered by events such as API calls, authentication events, or IoT messages, allowing the system to scale automatically without managing servers.

Charger connection:

IoT device connectivity, with chargers, is handled via AWS IoT Core. Chargers securely connect to the cloud using MQTT protocol, enabling bi-directional communication between the backend and the physical charger.

IoT Core also integrates with rules that can trigger Lambda functions, store data, or forward messages to other services, enabling real-time processing of device telemetry and commands.

Payment Solution:

Payments are integrated using MobilePay as the primary payment solution. The backend handles payment requests by securely communicating with the MobilePay API, managing transaction states, and ensuring that payments are verified before granting access to services such as charger usage.

Lambda functions can be used to orchestrate payment flows, including initiating transactions, handling callbacks or webhooks from MobilePay, and updating application data through AppSync once payments are completed.

Generally:

The architecture supports secure communication between users, backend services, and devices, ensuring that only authorized users can interact with specific resources or devices.

Data flows from chargers through IoT Core, where it can be processed by Lambda and then stored or exposed through AppSync APIs to the App and Master Interface.

Similarly, user actions in the App trigger AppSync operations, which may invoke Lambda functions for validation or processing before updating the data layer.

This event-driven design ensures high scalability, as each component operates independently and scales based on demand.

Overall, the system leverages managed AWS services to reduce operational overhead, improve reliability, and enable rapid development of a secure, real-time, and connected application ecosystem.

2.6 APP Design

The mobile application is developed using Flutter, enabling a consistent and high-performance user experience across both iOS and Android platforms. The design focuses on simplicity and efficiency, guiding users seamlessly through the process of initiating and monitoring a charging session.

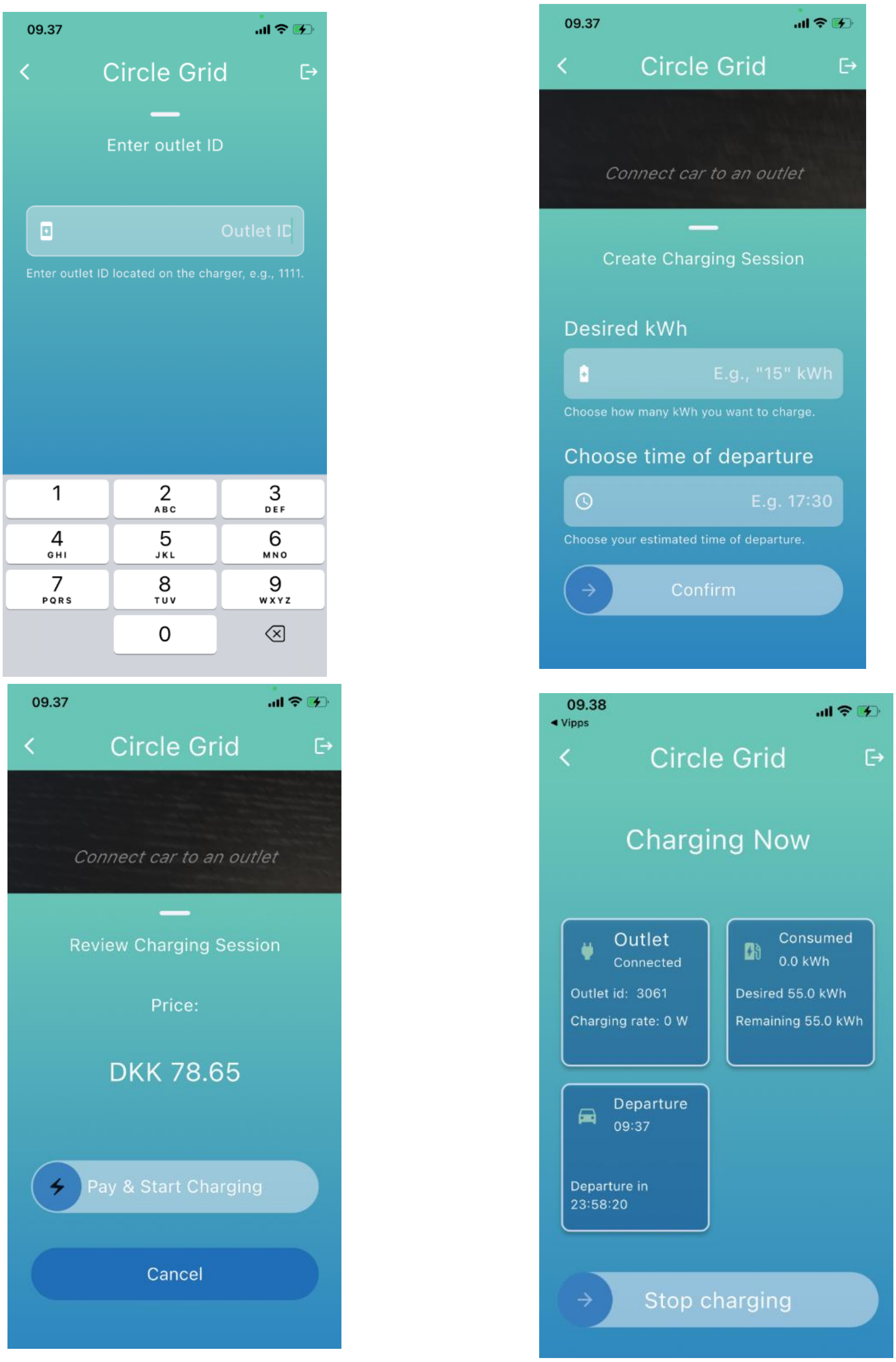
Users can start a charging session either by scanning a QR code located on the charger or by manually entering a charger ID. The QR scanning functionality ensures quick and error-free identification of devices, while manual input provides flexibility in cases where scanning is not possible.

Once a charger is selected, the app initiates the charging flow by communicating with backend services through APIs powered by AWS AppSync. This ensures that charger availability, status, and session validation are handled in real time.

Payment is integrated using MobilePay, where the user is redirected via deep linking to the MobilePay app to approve the transaction. After payment confirmation, the user is seamlessly redirected back to the application, maintaining a smooth and uninterrupted experience.

Following successful payment, the charging session is started and continuously monitored. The app subscribes to real-time updates via AppSync, allowing users to track session progress, charging status, and relevant metrics such as duration and energy usage.

The overall user flow is designed to minimize friction, combining intuitive navigation, real-time feedback, and secure payment handling. This ensures a reliable and user-friendly experience from charger selection to session completion.



Enter outlet ID

Outlet ID

Enter outlet ID located on the charger, e.g., 1111.

Connect car to an outlet

Create Charging Session

Desired kWh

E.g., "15" kWh

Choose how many kWh you want to charge.

Choose time of departure

E.g. 17:30

Choose your estimated time of departure.

Connect car to an outlet

Review Charging Session

Price:

DKK 78.65

Charging Now

Outlet
Connected
Outlet id: 3061
Charging rate: 0 W

Consumed
0.0 kWh
Desired 55.0 kWh
Remaining 55.0 kWh

Departure
09:37
Departure in
23:58:20

Figure 5: Screens from the CircleGrid App.

3 Operational assessment

This chapter demonstrates the operational results of both Risø and Bornholm parking lot in practice, with the analysed period from 01-11-2024 to 31-12-2025. The analysis depicts the charging performance from the perspectives of both the users and system.

3.1 User engagement

Figure 6 describes the charger utilization during the testing period. From the graph it is possible to see when the chargers have been dismounted for maintenance and therefore went offline, as well as the charging capability provided for the users. This figure provides a background of how users engage with the chargers in both sites.

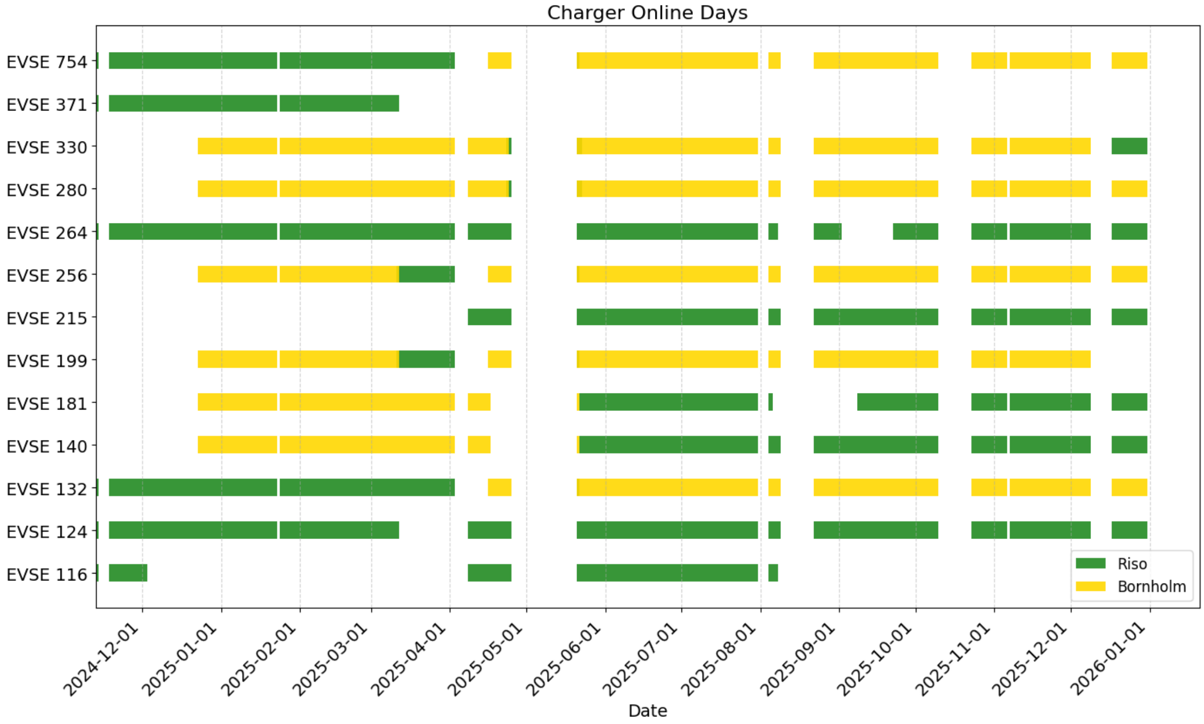


Figure 6: Online period of the chargers in Risø and Bornholm parking lots

Subsequently, Figure 7 shows the average number of EVs connected and charging during the work week in Risø and Bornholm parking lots. For Risø parking lot, the average number of connected cars during the day spans from 2 on Monday and Friday, to 1.5 on Thursday, while the average amount of charging cars reaches 1.5 on Monday and is the lowest on Thursday as well, with a value below 1.0. Thursday, of all weekdays seems to be the day with the highest difference between the number of cars connected and charging.

On the contrary, Bornholm parking lot has the highest number of EVs connected on Thursday, this is caused by the different user behaviours in both parking lots. Risø parking lot serve the office employees, while Bornholm parking lot handle school faculty members.

Meanwhile, the figure also shows the total number charging sessions on each workday of the week during the analysed period. The total number of charging session is 785 in Risø parking lot and 207 in Bornholm parking lot. For Risø parking lot, the days with the highest amount of charging session is Monday, followed by Tuesday and Friday. On Wednesday and Thursday there is generally a smaller number of charging sessions. Bornholm parking lot demonstrates the highest number of sessoins on Thursday and the lowest on Tuesday.

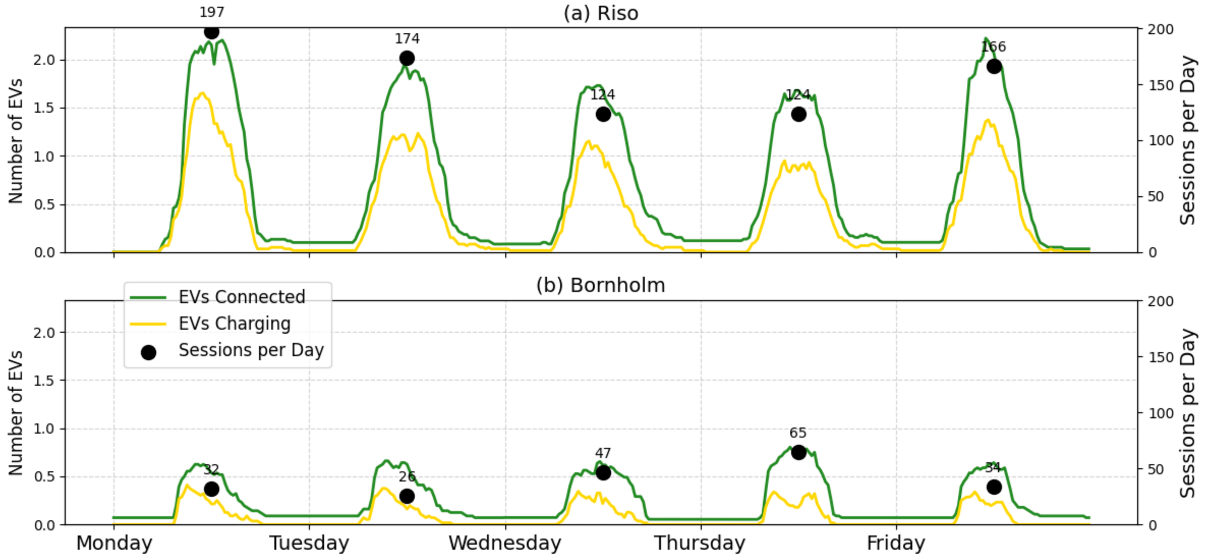


Figure 7: Average number of EVs connected and charging during the work week, as well as the total charging sessions of each workday in Risø and Bornholm parking lot

3.2 System flexibility

The flexibility of a parking lot is also evaluated in three different domains: namely power, time and energy. The method provides the following flexibility indexes: Minimum Power Flexibility Index (*MPFI*), Average Power Flexibility Index (*APFI*), Energy Flexibility Index (*EFI*), and Time Flexibility Index (*TFI*). The higher the index, the more flexibility the parking lot can provide. The definition of the indexes are shown below:

Minimum Power Flexibility Index (*MPFI*):

$$MPFI = 1 - \frac{P_{max,avg}}{CC}$$

Measures the remaining power flexibility during peak demand by comparing the average maximum charging power $P_{max,avg}$ to the grid connection capacity CC. A higher MPFI indicates more available power flexibility when the system is most loaded.

Average Power Flexibility Index (APFI):

$$APFI = 1 - \frac{P_{mean,ch}}{CC}$$

Assesses the average power flexibility during charging periods by comparing the average charging power dispatched $P_{mean,ch}$ to the connection capacity CC. It reflects how much the charging cluster can adjust power under typical conditions.

Energy Flexibility Index (*EFI*):

$$EFI = 1 - \frac{E_{ch}}{E_{pot}}$$

Indicates the cluster's ability to delay energy delivery by comparing the actual energy delivered $E_{ch}$to the potential energy demand E_{pot} ,where a higher *EFI* means more flexibility in shifting energy consumption over time.

Time Flexibility Index (*TFI*):

$$TFI = \frac{t_{tidle,avg}}{t_{tot,avg}}$$

Quantifies how much charging sessions can be shifted without affecting total energy delivery, by measuring the ratio of average idle time when fully charged $t_{tidle,avg}$ to the average total connection time $t_{tot,avg}$.

For more details on the methodology the reader is referred to the reference paper [5].

Figure 8 demonstrates the indexes over the analyzed period for the Risø and Bornholm parking lots. It can be observed that both parking lots can provide great flexibility, especially Bornholm parking lot. For example, the *MPFI* of Risø is 0.49, showing that on average the power consumption during peak utilization is 49% of the connection capacity. The TFI is relatively low, showing that the EVs on average spend only 26% of the connection time in idle mode. One of the possible reasons why such *TFI* value is that the power capacity of the plugs is limited to 11 kW, extending the charging time.

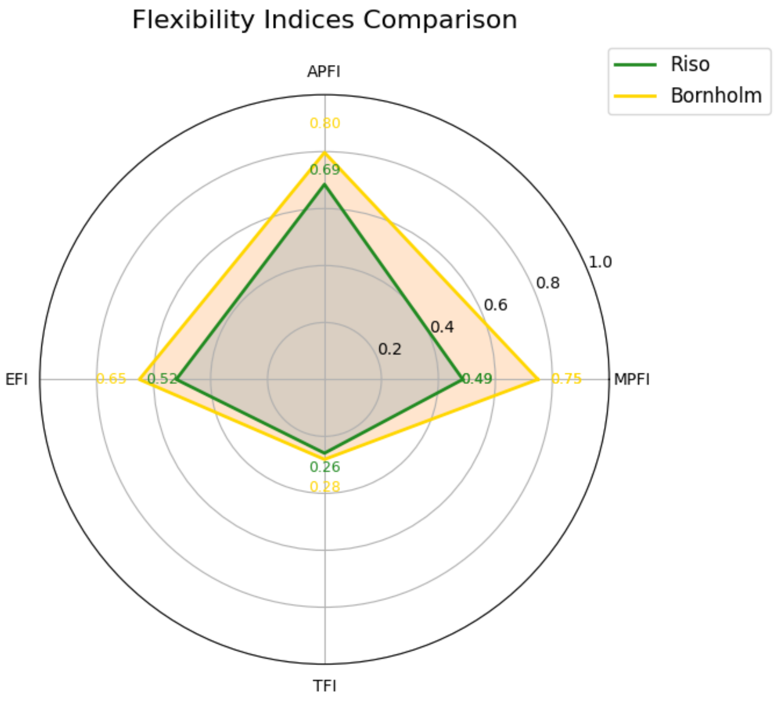


Figure 8: Flexibility indices of Risø and Bornholm parking lot

More specific performance can be found in Figure 9 regarding the monthly flexibility indices of Risø parking lot in 2025, especially the second half of the year, since Risø parking lots is observed to have significantly more charging sessions and participants throughout the analyzed period. The month of May has the highest flexibility in terms of *EFI*, *APFI* and *MPFI*, which is attributed to users' preferences of cycling over driving to work when the weather allows. The summer months also have high flexibility indices. On the other hand, the winter months deliver much lower indices, with November as the lowest. Although December is supposed to have the lowest indices, its charging performance is affected by the Christmas vacation period that the employees started their vacation from the second half of the month, hence nobody came requesting charging sessions.

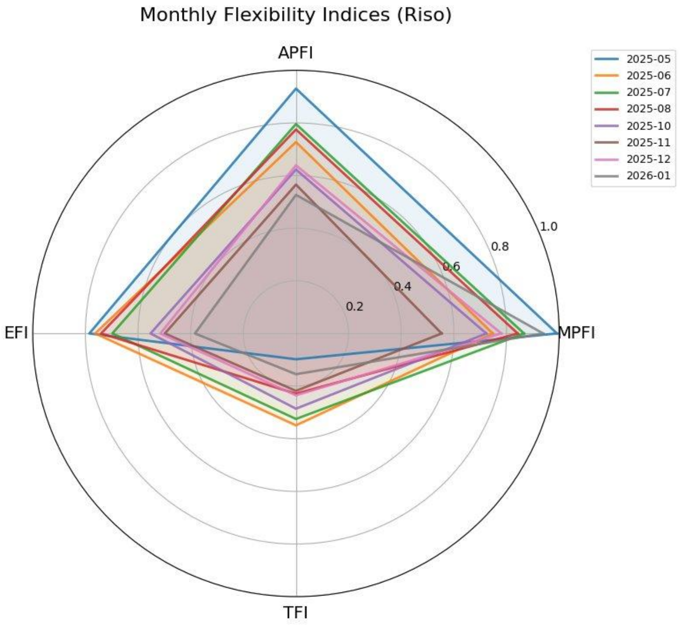
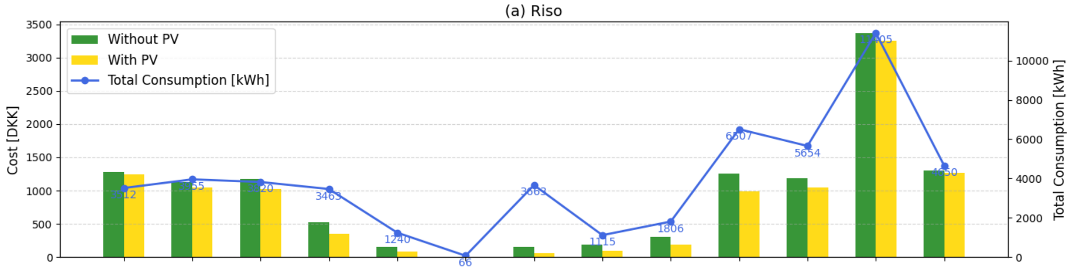


Figure 9: Monthly flexibility indices in Risø parking lot

3.3 Local renewable integration

The testing sites also incorporate the generation of local PV into the charging sessions to evaluate the feasibility and benefits of charging with renewable integration. Figure 10 shows a bar graph with two bars for each month: in green the cost of charging energy without accounting for the self-consumption from the local renewable energy sources available for the workplace building, while in yellow the reduced price after taking into account the self-consumption and therefore the reduced energy import from the grid.


(a) Riso

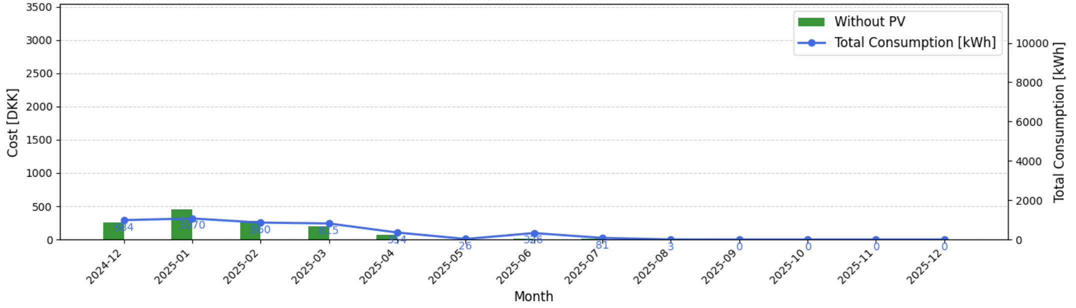

(b) Bornholm

Figure 10: Cost of energy with and without accounting for the self-consumption from PV in Risø and Bornholm parking lots.

An overall reduction in the price paid going from December 2024 to December 2025 in both cases is observed. In May there is no price at all, and in July it is increasing again. This trend, overall cannot be generalized to other workplace parking lots, because there are factors that were affecting it:

1. During the period under analysis, the development of the hardware and the user application for Android and IOS phones is still ongoing, and therefore the chargers were undergoing frequent updates, which increased the downtime of the parking lot in general.
2. The downtime of the system and the coming of the warmer weather might have driven down the number of users coming to the parking lot, especially in May, during which the Danish Cyclists' Federation runs an annual campaign called "Bike to Work" (Vi Cykler Til Arbejde). This campaign is a competition going on during the whole month of May, where different workplaces create a team and compete on the number of days and kilometers are cycled to work.

On the other hand, the contribution from local renewable energy sources can also be observed in warmer season that the gap of the cost between with and without PV scenarios in Risø parking lot is greater than the counterpart in colder weather due to the increase of solar energy. Therefore, it is worth noting that the local renewable energy sources do provide positive support for EV users from an economic perspective, however, specific scheme that considers the user charging behaviors and the weather conditions is required to achieve the best outcome.

4 Replicability and potential of product

The developed EV charging station demonstrates strong potential for replicability and scalable deployment, driven by a design that prioritizes modularity, manufacturability, and adaptability to different installation environments. The combination of a robust mechanical structure, flexible mounting options, and a modular electronics architecture enables the product to be efficiently produced, deployed, and maintained across a wide range of use cases, including public and semi-public charging scenarios.

Key design choices, such as the use of extruded aluminium for the enclosure, support cost efficiency in medium to large production volumes while ensuring durability and long-term reliability in outdoor conditions. At the same time, the modular electronics system allows for iterative upgrades and component replacement without requiring redesign of the mechanical structure, significantly reducing lifecycle costs and supporting continuous product improvement.

The charger’s flexible installation configurations, including wall, pole, and back-to-back mounting, further enhance its applicability across diverse deployment contexts while simplifying logistics and inventory management. Additionally, features such as integrated user interface elements, reliable sealing for environmental protection, and built-in electrical safety components contribute to a high-quality, user-friendly, and compliant solution.

Overall, the product is well-suited for scaling beyond pilot deployments. Its design enables efficient manufacturing, streamlined installation, and cost-effective maintenance, making it a viable candidate for broader market adoption. While some trade-offs exist, particularly in service accessibility and upfront tooling costs, these are balanced by long-term benefits in durability, flexibility, and total cost of ownership.

The overall enclosure concept, including the extruded aluminium structure, mounting flexibility, and general system architecture, has proven robust and suitable for replication. The modular design approach has also demonstrated value during development and can be partially retained to support scalability and future updates.

Before commercial deployment, however, further refinement is required. The electronics architecture should be more highly integrated to reduce the number of PCBs and cable interconnections, improving assembly efficiency and reliability. Additionally, the enclosure design should incorporate the revised plastic top cover and an optimized sealing strategy to ensure consistent environmental protection and reliable communication performance in real-world conditions.

4.1 Charger design and cost

The EV charging station has been developed with a strong focus on modularity, durability, manufacturability, and user interaction. The following sections outline the key design decisions and their associated impact on cost.

<u>Mechanical Design and Material Selection</u>

The enclosure is primarily constructed from extruded aluminium profiles, providing a robust and corrosion-resistant structure suitable for outdoor applications. Aluminium extrusion enables high repeatability and dimensional accuracy, while also allowing integration of functional features such as mounting tracks and sealing interfaces.

Extrusion tooling represents a relatively high upfront investment; however, it significantly reduces per-unit manufacturing cost in medium to high production volumes. Additionally, aluminium offers a favourable balance between weight and strength, reducing transportation and installation costs compared to heavier materials such as steel.

Compared to plastic alternatives, aluminium offers significantly higher mechanical strength and stiffness. This makes the structure more resistant to impacts, deformation, and long-term mechanical stress, which is particularly important for public and semi-public installations. While plastic solutions may offer lower material and tooling costs, they typically require increased wall thickness or internal reinforcement to achieve similar structural performance, which can offset some of the cost advantages.

The top cover is manufactured from plastic to ensure good wireless communication performance. This is particularly important for embedded communication modules, as metallic enclosures would otherwise attenuate signal strength. While introducing an additional material and manufacturing process, this design improves connectivity reliability and reduces the need for external antennas or signal amplification solutions.

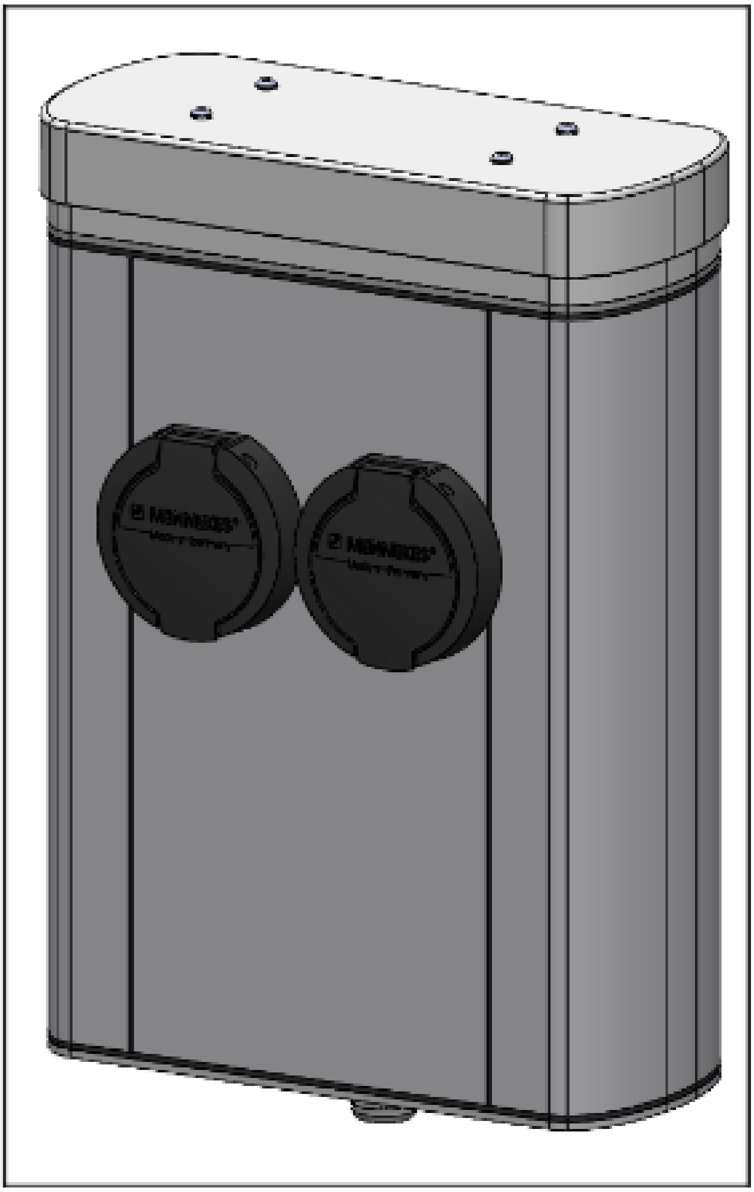


Figure 11: Overall design of EV-charger.

User Interface and Visual Communication

A transparent acrylic plate is integrated at the top of the enclosure, allowing light emission from an internal LED strip. This feature enables intuitive communication of charger status (e.g., idle, charging, fault) to the user.

While the inclusion of acrylic and LED components adds material and assembly cost, it enhances user experience and perceived product quality. This can reduce user errors and support costs.

Mounting and Installation Flexibility

The enclosure includes mounting holes on the rear side, enabling attachment of a bracket system designed for both wall mounting and pole mounting (e.g., installation on a streetlight pole).

Additionally, the design allows two units to be mounted back-to-back. This configuration is particularly beneficial in installations where dual-sided access is required, such as parking areas or public charging stations with vehicles positioned on opposite sides.

This dual-use and back-to-back mounting capability increases installation flexibility and reduces the need for multiple product variants. Although it introduces slight additional design complexity and hardware cost, it simplifies logistics and inventory management while broadening the range of deployment scenarios.

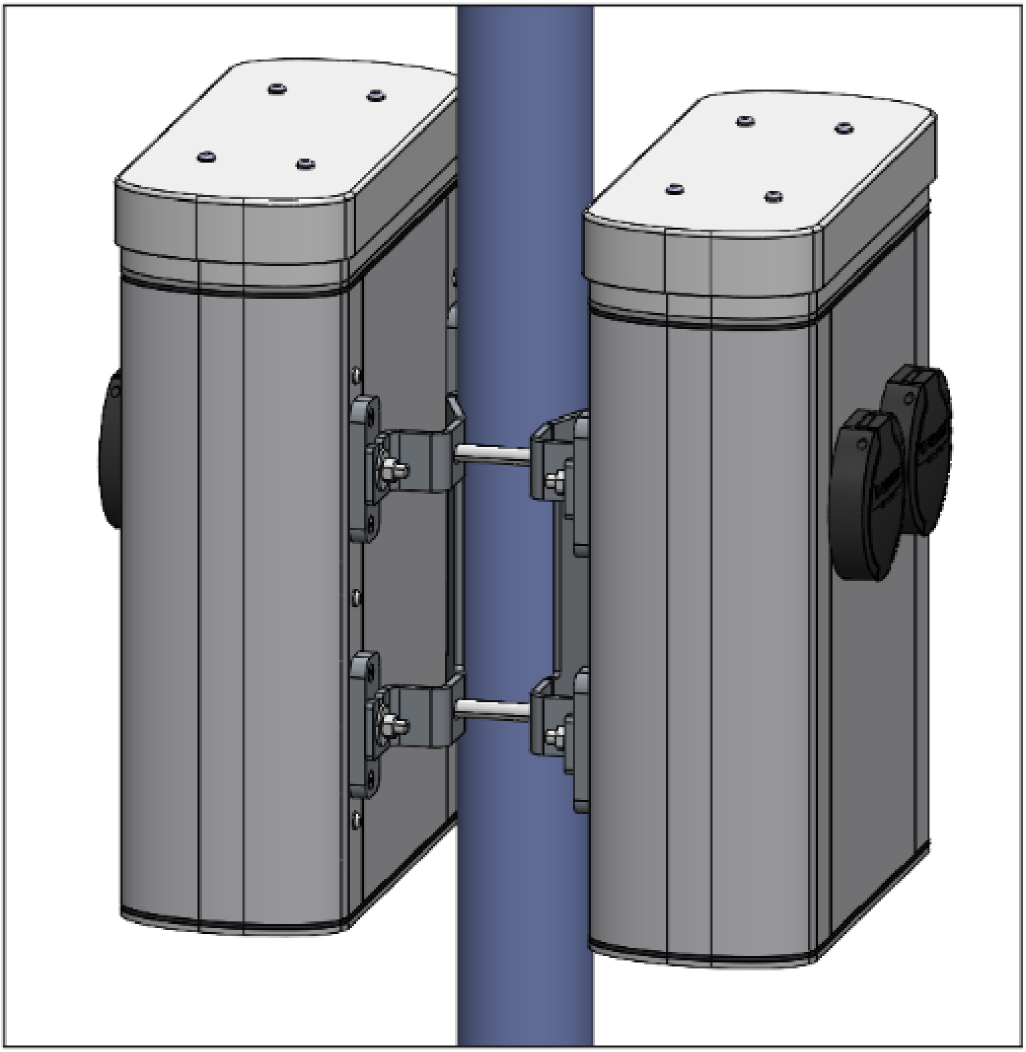


Figure 12: Back-to-back installation of 2 EV-chargers.

Modular Electronics Architecture

The charger is designed with a modular electronics system consisting of a two-part electronics frame. The primary structural part is installed from the bottom, while a secondary module is inserted from the top during assembly.

The system contains multiple custom-designed PCBs, including:

- Two energy metering boards
- Two relay boards (connected via board-to-board connector)
- Communication board
- Power supply

This modular approach enables clear separation of functions and supports scalable development. In case of design updates or component changes, the electronics can be replaced without modifying the extruded aluminium profiles, which are associated with high redesign and tooling costs.

To service or replace components, the full electronics assembly must be removed. While this increases service effort compared to fully accessible submodules, it simplifies the internal architecture and ensures mechanical robustness. The trade-off favours long-term cost savings by preserving the mechanical platform while allowing iterative improvements of the electronics.

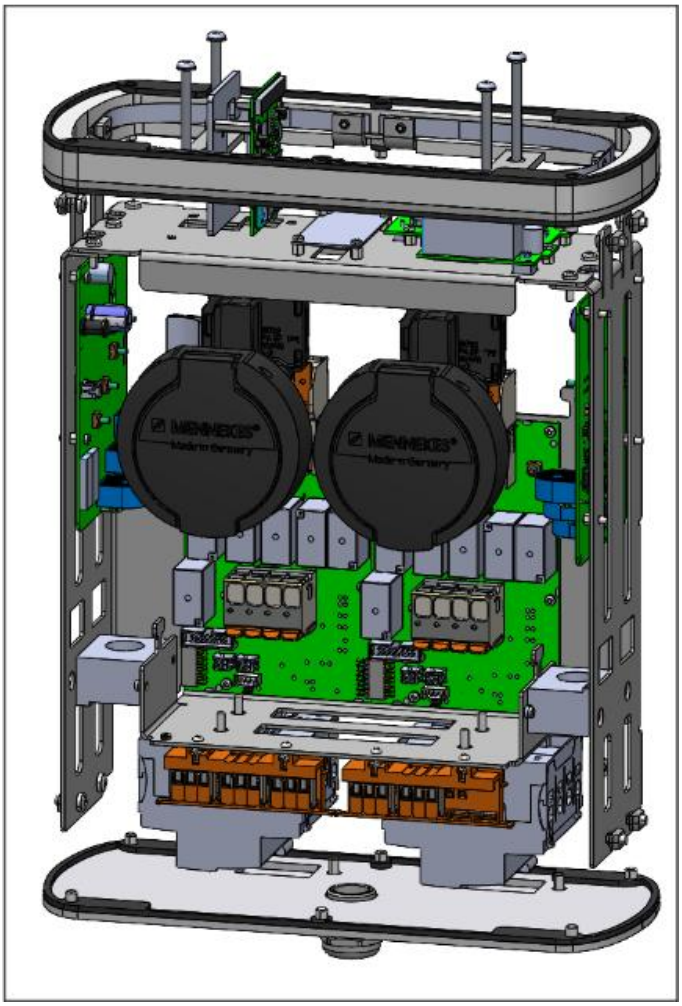


Figure 13: EV-charger without extruded aluminium profiles.

Electrical Safety and Accessibility

Each outlet is equipped with both Residual Current Monitoring (RCM) and Residual Current Device (RCD) protection, ensuring compliance with safety standards and redundancy in fault detection.

Removable covers are integrated at the bottom of the enclosure, allowing access to switch the RCD on and off. This improves serviceability and operational control without requiring full disassembly.

The inclusion of RCM and RCD components increases the bill of materials (BOM) cost, but significantly enhances safety, reduces liability risks, and minimizes potential warranty costs.

Figure 14: Outer design of EV-charger including the removable covers for access to the RCD switch.

Interconnection Strategy

The relay boards are interconnected via a board-to-board connector, while other components are connected using cables. This hybrid approach balances reliability, assembly efficiency, and flexibility.

Board-to-board connectors reduce assembly time and wiring complexity, lowering labour cost and minimizing potential assembly errors. Cable connections provide flexibility in routing and tolerance to mechanical variations, though they introduce slightly higher assembly effort.

Sealing and Environmental Protection

The enclosure is designed to meet IP44 protection requirements. Horizontal joints are sealed with gaskets, including sealing around screws. Vertical joints are geometrically designed to prevent water ingress, and additional gaskets are implemented around the outlet interfaces.

This comprehensive sealing strategy ensures protection against splashing water and ingress of solid objects, which is critical for outdoor installations. The use of gaskets and sealing features increases both material and assembly cost but is necessary to ensure product longevity and reduce field failure rates.

Assembly and Serviceability

The bottom-insertion design of the main electronics frame, combined with the secondary top-mounted module, improves assembly flow and modular integration. Components can be pre-assembled and tested before final enclosure integration.

Although servicing requires removal of the full electronics assembly, the modular architecture allows for replacement or upgrading of the entire electronics system without impacting the mechanical enclosure. This reduces lifecycle costs by avoiding expensive redesigns of the extruded aluminium components.

Lessons Learned and Design Improvements

The development process has highlighted several important trade-offs between modularity, assembly efficiency, and environmental robustness.

The strong focus on modular electronics has resulted in a design with multiple PCBs and a high number of cable interconnections. While this has provided flexibility during development, it has also led to increased assembly time and complexity. The number of components and interfaces has proven to be a significant cost driver, both in terms of labour and potential assembly errors.

A key lesson learned is the need to reduce system complexity in future iterations. This can be achieved by consolidating functionality into fewer, more integrated PCBs, thereby reducing wiring, assembly time, and potential failure points. While this reduces some flexibility, it is expected to improve manufacturability and overall system robustness.

In addition, the initial use of a metallic top cover revealed challenges in achieving reliable water sealing, particularly around fasteners and joints. Real-world testing indicated that the design was vulnerable to water ingress under certain environmental conditions.

This led to a transition to a plastic top cover, which enables improved geometric design for water management. The updated design more effectively directs rainwater away from critical interfaces such as seals and screw connections, thereby improving overall enclosure sealing performance.

The change to plastic has also significantly improved wireless communication performance, as it allows signals from internal antennas to pass with minimal attenuation. This reduces the need for additional antenna solutions and improves connectivity reliability.

Overall, these lessons support a shift towards a more integrated electronics architecture and a more robust enclosure design, balancing performance, cost, and manufacturability in future product iterations.

5 Conclusions and future recommendations

5.1 Overall Assessment of Solution Viability

The Danish demonstrator confirmed the technical feasibility of deploying a distributed EV charging system in both controlled and semi-public environments. The integration of modular charging hardware, cloud-based backend infrastructure, and a mobile user application enabled intelligent charging management and flexibility-oriented operation.

The demonstration showed that distributed control strategies can successfully manage charging demand under limited grid capacity while supporting user-oriented charging services and integration with renewable energy sources. Although the system experienced challenges related to software maturity, communication stability, and hardware robustness during early deployment phases, iterative updates and continuous monitoring improved overall operational stability throughout the project period.

5.2 Strategic Implications

The results of the Danish demonstrator underline the importance of integrated system design in smart EV charging solutions. Reliable operation depends not only on individual components but on seamless interaction between hardware, backend infrastructure, and user interfaces.

From a strategic perspective, the demonstrated flexibility potential positions distributed EV charging as a relevant asset for future energy systems, particularly in supporting grid stability and enabling demand-side management. However, achieving this potential requires robust communication, standardized interfaces, and user-centric design.

Furthermore, the variation in user behaviour between sites highlights the need for context-aware deployment strategies. Charging solutions must be adaptable to different environments, such as workplaces, educational institutions, and public spaces, to maximize utilization and effectiveness.

5.3 Key Results and KPI Assessment

The operational evaluation demonstrated that both charging sites could support real-world EV charging demand while providing flexibility services to the local energy system.

The analysed KPIs showed:

- High flexibility potential at both demonstration sites, particularly in terms of power flexibility (MPFI and APFI), demonstrating the capability to adapt charging demand according to grid limitations.
- Successful implementation of distributed load management under a constrained 43 kW grid connection shared between twelve charging outlets.
- Real-time coordination between backend systems, chargers, and users through the distributed control architecture.
- Integration of local renewable energy sources at the Risø site, reducing imported grid energy during periods of high photovoltaic production.

- Different charging behaviours between Risø and Bornholm, reflecting how workplace and educational environments influence charging demand and flexibility potential.

The operational data further showed that the solution remained functional under real-world conditions despite periods of downtime caused by maintenance activities, communication instability, and ongoing software development.

5.4 Lessons Learned

Several important lessons were identified during the deployment and operation of the Danish demonstrator.

5.4.1 Hardware and Charger Design

- Modular hardware architecture simplified development and troubleshooting but introduced increased wiring complexity and multiple inter-board communication points.
- I2C-based internal communication proved sensitive to electrical noise and cable length, reducing reliability in practical operation.
- Metallic enclosure components negatively affected wireless communication performance and required redesign using a plastic top cover and optimized antenna positioning.
- Public and semi-public deployments expose charging hardware to vandalism and non-standard user behaviour, requiring consideration of robustness and protection strategies.

5.4.2 Software and System Integration

- Early-stage integration between backend services, chargers, payment systems, and mobile application introduced significant operational instability.
- Stable communication infrastructure is critical for distributed charging control and real-time monitoring.
- Continuous software updates, structured debugging, and operational logging were essential for progressive stabilization of the system.
- The AWS-based serverless backend architecture demonstrated strong scalability and flexibility for IoT-based charging management.

5.4.3 User Experience

- User acceptance depends heavily on reliable charging initiation, stable payment flows, and intuitive app interaction.
- QR-based charger identification and MobilePay integration simplified the charging process but required robust synchronization between frontend and backend systems.
- Different deployment environments resulted in different charging patterns and user expectations, highlighting the need for context-specific deployment strategies.

5.4.4 Smart Charging and Flexibility

- Distributed charging control successfully managed limited grid capacity while supporting simultaneous charging sessions.
- Smart charging demonstrated clear potential for supporting renewable energy integration and demand side flexibility services.
- User charging behaviour significantly influences achievable flexibility and should be considered in future optimization strategies.

5.5 Innovation Outputs per Demonstrator (TRLs)

The Danish demonstrator has advanced the maturity of several key components of the EV charging solution:

- **Charging hardware:** Developed and validated in operational environments, reaching approximately TRL 6–7 (technology demonstrated in relevant environment), with identified areas for improvement in reliability and component durability.
- **Backend architecture:** A scalable, serverless cloud infrastructure successfully deployed and operated, reaching TRL 7–8, demonstrating robustness in real-time data handling and IoT integration.
- **Mobile application (Circle Grid):** Functional and deployed to end users, reaching TRL 6–7, with ongoing improvements required in usability, stability, and integration with payment systems.
- **Distributed control and flexibility management:** Concept validated through real-world operation, reaching TRL 6–7, demonstrating the capability to optimize load distribution and provide flexibility services.

Overall, the demonstrator has moved the integrated system from prototype stage toward pre-commercial readiness, while identifying key areas requiring further development.

5.6 Next Steps for Research, Pilot Expansion, and Market Adoption, Policy and Regulatory

To support further development and large-scale deployment, the following actions are recommended:

Technical development and research

- Improve hardware reliability, particularly in charging outlets, locking mechanisms, and internal communication systems.
- Enhance system integration, focusing on stable communication between frontend, backend, and physical devices.
- Optimize charging performance and flexibility by addressing power limitations and improving control strategies.
- Further develop the mobile application to improve usability, robustness, and user trust.

Pilot expansion and validation

- Deploy the solution in a wider range of environments (e.g., public parking, residential areas, commercial sites) to validate scalability and adaptability.
- Increase the number of users and charging points to assess performance under higher demand and more complex usage patterns.
- Continue systematic data collection and KPI evaluation to refine system performance and quantify benefits.

Market adoption

- Refine the product design for manufacturability and cost efficiency to support commercialization.
- Develop standardized installation and maintenance procedures to reduce operational costs.
- Strengthen interoperability with existing charging infrastructure and energy management systems.

Policy and regulatory considerations

- Support the development of standards for communication protocols, interoperability, and smart charging functionalities.
- Encourage regulatory frameworks that incentivize flexible EV charging and integration with renewable energy sources.
- Address requirements related to payment systems, data privacy, and user authentication to ensure compliance and user confidence.

Overall, the Danish demonstrator provides a solid foundation for advancing distributed EV charging solutions toward commercial deployment. Continued development, combined with supportive regulatory frameworks and expanded real-world validation, will be essential to unlock the full potential of smart and flexible EV charging systems.

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