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Evaluation and lessons learn of the Azores demo

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Prepared by	Samuel Matias (NEW), Marta Brandão (NEW), Cindy Lascano (INESC ID), João Taveira (INESC ID), Hugo Morais (INESC ID), Catarina Rocha (SEL), Catarina Nogueira (SEL), Carlos Caetano Martins (EDA), Mário Mendes (EDA), Miguel Quinto (DREn)
Reviewed by	Ilias Manitaris (HEDNO), Haris Ziras (DTU)
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[1] https://ev4eu.eu/

Executive Summary

The Portuguese demonstrator focused on validating Vehicle-to-Everything (V2X) technologies across three distinct environments: households, buildings (LREC) and companies (EDA campus). The pilots involved a diverse electrical ecosystem, including residential PV inverters, battery energy storage systems, and a fleet of over 40 electric vehicles at the company campus.

The technical assessment validated the interoperability of heterogeneous hardware from different OEMs and mixed connectivity solutions (Wi-Fi, PLC, and TCP/IP) coordinated through the EV4EU control architecture. Operationally, the demonstrator highlighted that participant trust is built through face-to-face engagement and transparent communication. While digital tools like messaging apps provided rapid troubleshooting, managing complex communications across multiple partners occasionally caused user frustration, leading to the recommendation of maintaining single points of contact for each use case.

The pilot successfully demonstrated that coordinated smart charging delivers immediate economic and environmental value. Households achieved an average cost reduction of 8.6% (with some saving up to 14%) after controlling the charging sessions, even though most of the users already optimized their charging schedules to minimize cost. Although few examples, the smart charging algorithm increased RES integration in households by 10.4% to 21.9%. When it comes to bidirectional charging, EDA campus recorded over 160 kWh of energy discharged to support fleet management and peak shaving.

The findings from D6.4 indicate that while the solutions are technically viable (reaching high TRLs), their full potential is currently capped by regulatory and economic frameworks:

- Prioritizing early in-person engagement to build long-term participant commitment and boost pilot support.
- The transition to an ever-growing intermittent generation power system amplifies the need of a more robust compensation scheme for flexibility services.
- Enforcing strict compliance with open standards (e.g.: OCPP 2.0.1) and promoting EU-level standardization of EVSE, OEM and IT technologies to reduce integration complexity.

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Acronyms

BESS	Battery Energy Storage Systems
CCS2	Combined Charging System 2
CHAdeMO	CHArge de MOve
CS	Charging Station
DSO	Distribution System Operator
EDA	*Eletricidade dos Açores*
EMU	Energy Management Unit
EU	European Union
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
IP	Internet Protocol
KPI	Key Performance Indicator
LREC	*Laboratório Regional Engenharia Civil*
OBD	On-Board Diagnostics
OCPP	Open Charge Point Protocol
OEM	Original Equipment Manufacturer
PLC	Power Line Communication
PV	Photovoltaic
RES	Renewable Energy Sources
SoC	State of Charge
SoH	State of Health
TCP	Transmission Control Protocol
TRL	Technology Readiness Level
UI	User Interface
V2B	Vehicle-to-Building
V2G	Vehicle-to-Grid
V2X	Vehicle-to-Everything
WC	Wind Curtailment

1 Introduction

The Portuguese demonstrator was structured into three specific types of locations to test different Vehicle-to-Everything (V2X) management strategies:

- Households: Initially involving 7 private residences (later 6 active) equipped with 7.4 kW chargers, energy meters, and Reduxi controllers to optimize consumption based on tariffs and local photovoltaic (PV) production.
- Public buildings (LREC): Focused on the office building of the Regional Civil Engineering Laboratory, utilizing a leased EV to test unidirectional smart charging for services like wind curtailment and congestion management.
- Companies (EDA campus): Centred at the headquarters of the Azorean Electric Utility, this was the most comprehensive site, featuring bidirectional charging and coordinated scheduling for a fleet including employees, visitors, and company vehicles.

The implementation journey began with a planning and design phase that leveraged insights from early project deliverables to define electrical, communication, and control architectures. This stage supported the specification of interoperable equipment, including Wallbox and Alfen chargers, Shelly energy meters, and both Reduxi and EDGE controllers. Installation and commissioning for the EDA campus started in early 2024, while activities for the households and LREC were primarily completed between October and November 2024. To track performance, monitoring and data collection setups were established through EV4EU dashboards and the Living Energy platform developed by SEL, providing real-time tracking at resolutions ranging from 30 seconds to 5 minutes.

An analysis of the lessons learnt during the PT demo highlights that technical success depends heavily on the seamless interplay between remote integration teams and onsite personnel. Operational findings show that early face-to-face engagement with participants is critical for building trust and ensuring a long-term project buy-in. In terms of the feasibility of bidirectional charging, it remains highly context-dependent, with current barriers including limited access to secure vehicle State of Charge (SoC) data and a lack of standardization across different EV and charger manufacturers.

1.1 Scope and objectives

The scope of this deliverable involves a comprehensive analysis of the installation, commissioning, operation, and monitoring phases across three distinct use-cases. This document specifically evaluates the performance of smart charging and bidirectional control algorithms while examining the lessons learned from both technical and operational standpoints to support the mass deployment of electric vehicles.

1.2 Structure

The present deliverable is divided into six sections. Section 1 starts by outlining the scope and the structure of the deliverable. Section 2 presents a technical assessment of the Portuguese demonstrator, describing the implemented solutions and evaluating their technical performance, including consolidated technical lessons learned. Section 3 focuses on the operational assessment of the pilot, addressing its execution under real operating conditions and reporting operational lessons learned derived from the demonstration activities. Section 4 presents the results of the demonstration, organized by pilot site, with a detailed analysis of representative sessions and the performance of the tested services. Section 5 evaluates the Portuguese demonstrator based on a selected set of KPIs and summarizes the main conclusions. Finally, Section 6, summarizes the most significant lessons learned from the Portuguese demonstrator.

1.3 Relationship with other deliverables

This deliverable is closely connected with other technical and demonstration-oriented outputs developed within the EV4EU project, particularly those addressing the Portuguese demonstrator.

It builds on Deliverable D6.1*: Implementation plan for the Azores demo*, which establishes the overall technical and operational framework of the Portuguese pilot [1]. D6.1 defines the pilot sites, equipment specifications, control and communication architectures and KPIs, forming the reference basis for the design and execution of the demonstrator.

From a technical perspective, the control logic and charging strategies applied in the Portuguese demonstrator are consistent with the methodologies developed in *Deliverables D2.1: Control strategies for V2X integration in houses* [2] and D2.2: *Control strategies for V2X integration in buildings* [3], as well as with the fleet oriented optimization approach defined in Deliverable D2.4: *Optimal management of EV fleets in companies* [4].

The present deliverable is also complementary to Deliverable D6.2: *Engagement activities report in Azores demo* [5], which documents the user engagement, stakeholder involvement, and communication actions carried out throughout the pilot. The outcomes described in D6.2 provided important information for the operation lessons learned, later described in this deliverable.

Finally, this deliverable builds upon the preparatory activities described in Deliverable D6.3: *Implementation, operation and monitoring of the Azores demo* [6]*,* and presents the results of the operation and data analysis carried out during the Portuguese pilot.

2 Technical assessment

The EV4EU PT demo involves integrating residential PV inverters, energy management units, EV chargers and associated forecasting tools into a coordinated control and data exchange environment.

The assessment details the transition from laboratory-validated configurations to field deployment, where real-world conditions required the implementation of protocol-bridging solutions to overcome vendor-specific deviations from standard communication protocols.

Tests were conducted with the aim of validating interoperability, data reliability, and enabling V2X functionalities. The deployment environment includes mixed connectivity solutions, like Wi-Fi, power Line Communication (PLC), Transmission Control Protocol (TCP), and a combination of legacy and upgraded firmware versions for both inverters and management systems.

2.1 Overview of tested solutions and deployment environments

The technical validation was conducted across three distinct environments: households, public buildings (LREC), and companies (EDA campus). Each site was equipped with a combination of Electric Vehicle Supply Equipment (EVSE), Energy Management Units (EMUs) (e.g.: Reduxi controller), and monitoring devices adjusted to its specific use case and electrical architecture

In the residential use case, solutions were tested across six active households featuring a variety of single-phase and three-phase installations, equipped with PV+BESS inverters (e.g., Huawei, Growatt, Solar X1) and Reduxi controllers used to manage Wallbox Pulsar Plus and Max chargers. The following Table 1 summarizes the installation progress and control activities for the individual houses participating in the project.

Table 1. Overview of residential user profiles, installed V2X hardware, and implementation journey

User ID	Installation type	Key Equipment	Activities
#1	- 1ph, - 1 PV (6,56 kWp) - 1 BESS (10 kWh)	- Reduxi (Wi-Fi), - Huawei SUN2000 inverter - - Wallbox Pulsar Plus (7,4kW)	Installed in late October 2024. Initial issues with inverted meter readings. From April 2025 onwards, the user no longer participates in the project due to misaligned expectations with the control algorithm.
#2	- 1ph - 1 PV (6,56 kWp) - 1 BESS (5,1 kWh)	- Reduxi (Cable), - Growatt inverter, - Wallbox Pulsar Max (7,4 kW)	Installed in early November 2024. Credentials for the app were provided on April 10th, 2025. The user reported to be using the platform frequently.
#3	- 3ph - 1 PV (10,1 kWp) - 1 BESS (10,2 kWh)	- Reduxi (Cable) - Growatt inverter - Wallbox Pulsar Max (7,4 kW)	Installed November 7th, 2024. OCPP authorized and active. Credentials provided to the user on May 9th, 2025, but lack of engagement in using the platform.
#4	- 1ph	- Reduxi (Cable), - Wallbox Pulsar Plus (7,4 kW)*	Installed November 5th, 2024. Experienced persistent Reduxi connection issues (offline) requiring user intervention. OCPP authorization from user to run tests was a common issue.
#5	- 1ph - 1 PV (2,22 kWp) - 1 BESS (5,8 kWh)	- Solar X1 Mini Inverter - Wallbox Pulsar Max (7,4 kW)	Installed November 4th, 2024. Faced charger cable problems; a replacement unit was processed. App credentials provided on May 5th, 2025.

User ID	Installation type	Key Equipment	Activities
#6	- 3ph	- Reduxi (Wi-Fi), - Wallbox Pulsar Plus (7,4 kW)*	Installed November 5th, 2024. Noted control instability during testing where current exceeded 15A. Most active user since credentials were sent April 10th, 2025.
#7	- 1ph	- Reduxi (Cable) - Wallbox Pulsar Max (7,4 kW)*	Installed November 8th, 2024. App credentials provided on April 24th, 2025; reported as a frequent user

* Previously owned by the user.

Most residential equipment was installed between October 30 and November 11, 2024, and the installations typically included Reduxi controllers for energy management and Shellys for monitoring consumption. Several houses required initial configuration to separate PV and BESS measurements in the user interface. A transition to active smart charging control occurred throughout April and May 2025 as app credentials were distributed to users. Some common hurdles included Open Charge Point Protocol (OCPP) communication errors, Reduxi units going offline, and specific hardware faults like faulty PLC repeaters or charger cables.

The LREC office building environment focused on unidirectional smart charging using Alfen Eve Single Pro Line and Wallbox Copper SB chargers integrated with Shelly 3EM energy meters to validate grid services such as wind curtailment and congestion management. The key activities and equipment at LREC are summarized in Table 2.

Table 2. Overview of LREC pilot site, installed V2X hardware, and implementation journey

Category	Component/ Equipment	Key dates	Activities
Main installation	Reduxi, Shellys (DIN rail), double post	October 28-29th, 2024	Initial installation completed. Consumption and generation data being received
Charger #1	Alfen Eve Single Pro	November 15th, 2024	Faulty controller board replaced on November 15th,2024. Connection to the platform and RFID charging orders working correctly
Charger #2	Wallbox Copper	November 19th, 2024, February 13th & 19th 2025	Initially failed authentication tests via mobile app. Resolved on November 19th, 2024, using a web-based interface. Connection issues resolved with Reduxi on February 25th, 2025
Energy Monitoring	Shelly (General measures)	October 28-29th 2024	Solar production measurements are confirmed as ok.
Control software	User interface/ Web site	November 2024 – August 2025	Shifted from a mobile app to a website for user authentication (QR code based).
Infrastructure/ IT	LREC network security	January, 2025	Control tests were temporarily paused due to LREC IT security blocks preventing firmware updates for the Wallbox Copper charger.

Both charging stations (Alfen and Copper) are operational and connected to the management platform. However, only the Copper was used since there was only one EV available, leased from a local rent-a-car company, Ilha Verde, over which we had total control for testing.

Bidirectional charging was not tested at LREC due to the fact that the Wallbox Quasar with the CHAdeMO protocol was discontinued, and the available EV was only compliant with CHAdeMO, making it incompatible with the newer Combined Charging System 2 (CCS2) alternative. As an alternative, an Intercontrol Latinki Home 11 kW was purchased and installed in December 2025 at EDA to conduct Vehicle-to-Building (V2B) tests, in which manual charging and discharging were tested. However, the integration with OCPP remained challenging and was not included in testing during the trial phase.

At the EDA campus, the most complex environment, the tested solutions included bidirectional charging and fleet management coordination through the EDGE controller. The main activities are described below in Table 3.

Table 3. Overview of EDA campus pilot site, installed V2X hardware, and implementation journey

Category	Component/ Equipment	Key dates	Activities
Wallbox Chargers	Wallbox Copper (x2) Wallbox Quasar (x1)	February 12th, 2024, February 25th, 2025, August 8th, 2024	Initial Quasar grid connection and time-sync issues were resolved by late February. Quasar has been connected to a test car on August 8th, and it required frequent reboots to stay online
Socket Outlets	Legrand Green Up – Shucko (x3)	February 12th 2024	All three Sockets were connected to the platform and were confirmed functional during initial integration tests
Gateway/ IT	EDGE	2024	The EDGE unit has frequent communication stability issues, losing its internet connection at least once a week. – continuous development
Control logic	Automated scheduling	February - August 2025	Integrated platform tests (sessions of 2.5 to 3.5 hours) successfully demonstrated automatic charging and discharging. By August, the controller was following scheduled orders correctly for most sessions
Vehicle data	On-board diagnostics (OBD)	N/A	Non-intrusive OBD hardware was found to be unreliable and insecure for reporting the SoC. The team transitioned to testing intrusive OBD units for better data performance, nonetheless, finding a certified installer posed a significant challenge.
User interface	Web-based UI	February 25th, 2025	Site-specific UI functionality was validated in February, initially without login requirements while the authentication module was in development.

Some key technical challenges were encountered throughout the pilot. A major hurdle was overcome when SEL, EDA, and INESC ID collaborated to fix incorrect date/time data being sent by the Quasar, allowing for valid charging records. Regarding bidirectional testing, while bidirectional charging has been successfully tested both manually and automatically, the lack of a reliable SoC feed remains a significant barrier to full-scale deployment of discharging strategies.

2.2 Evaluation of infrastructure readiness

The evaluation of infrastructure readiness highlighted several systemic integration challenges. Multiple Original Equipment Manufacturer (OEM) inverters (e.g., Growatt, Solax) did not fully support the communication features required for coordinated control, such as TCP connections or the reception of external setpoints, which led to the need for firmware updates and manual reconfiguration. The lack of standardization across devices resulted in inconsistencies in how inverters and chargers communicated with Reduxi, often requiring custom protocol-bridging solutions in the laboratory.

Field experience further demonstrated that some device vendors deviated from announced communication protocols, making integration dependent on external modules (e.g., Raspberry Pi). Ensuring strict compliance with open, standardized protocols at device level is therefore essential to achieve long-term maintainability and interoperability without ad-hoc fixes.

Infrastructure readiness also depends on the availability of redundant communication channels. Backup links such as PLC or Wi-Fi extenders proved important to ensure stable communication conditions and continuous algorithm execution, especially in environments with weak or fluctuating signals.

The fast coordination between on-site and remote teams also played a critical role, with several issues being resolved only due to rapid communication exchanges, underlining the importance of established escalation procedures and continuous monitoring from the outset.

Finally, the participation in curtailment or grid-support services (e.g., solar and wind curtailment) requires real-time access to dispatch centres or other grid assets such as secondary substations, PV systems or wind farms. This level of integration was not available in the Portuguese demo and represents a key prerequisite for enabling aggregated V2X participation in grid-services.

2.3 Hardware integration

During the early stages of the demonstration, the Wallbox Quasar chargers occasionally failed to receive control setpoints during joint tests with SEL, requiring support from INESC ID to restore full functionality. Connectivity also proved to be a challenge: several PLC repeaters had to be replaced to stabilize communication, and physical communication cables were reset across multiple sites when links became unreliable. In addition, some inverter Wi-Fi modules required upgrades to enable TCP communication, which led to extra on-site visits. To ensure safe installation conditions, physical protection measures such as floor markings and metal guards were implemented at selected charging locations.

These issues reinforced the value of extensive laboratory testing prior to field deployment. The lab tests significantly reduced unforeseen incompatibilities during installation, even if they could not eliminate every issue. The field experience also showed that the field team should be more involved during the laboratory phase, as this increases preparedness and accelerates commissioning.

The PT demo also revealed that OBD-based information is not universal across EV models and often requires additional interpretation or adaptation. This variability adds complexity to data collection and control strategies relying on vehicle telemetry.

In conclusion, the project revealed that access to EV and EVSE technologies is often limited, requiring additional research or manufacturer interaction. This lack of direct accessibility affects development timelines. A higher degree of standardization of EV and EVSE technologies at European Union (EU) level would improve replicability and reduce deployment effort.

2.4 Software and platforms

Dynamic Internet Protocol (IP) addressing occasionally caused Reduxi units to lose connectivity with inverters and chargers, requiring manual IP verification after software or firmware updates. Integration with certain inverter brands was also affected by protocol or firmware incompatibilities, which required updates or temporary hardware workarounds.

These observations highlight the importance of strict adherence to open and standardized communication protocols at device level. When vendors deviated from these protocols, the team had to rely on external modules to bridge formats, increasing complexity and reducing maintainability. Adding to standardized communication protocols, it is indispensable to have detailed technical specifications, such as firmware versions and control-interface requirements, to ensure a reliable integration.

Another important lesson is that forecasting-only algorithms are insufficient. Algorithms relying solely on unrestricted data forecasting could not meet user-specific requirements (e.g., minimum SOC at departure), highlighting the importance of integrating constraints, user preferences and energy-availability requirements directly into the optimization logic.

Finally, the coexistence of heterogeneous controllers (EDGE + Reduxi) exposed software-level communication-format limitations. A more flexible and interoperable software architecture is needed to ensure seamless integration of multiple controller types and reduce custom development effort.

2.5 Mitigation measures

The technical assessment identified several critical hurdles, including vendor deviations from standardized communication protocols, the instability of mixed connectivity solutions (Wi-Fi, PLC, and TCP/IP), and the limitations of forecasting-only algorithms in meeting specific user requirements.

These mitigation strategies presented in Table 4 aim to resolve the current technical issues while establishing a framework for long-term system resilience, by enforcing open communication standards, deploying redundant communication links, and implementing automated data-validation checks to bridge the gap between experimental testing and reliable real-world operation.

Table 4. Summary of technical mitigation measures and strategic recommendations

ID	Lesson learned	Mitigation measure/Recommendation
1	Vendors sometimes deviated from standardized communication protocols, requiring external bridging modules	To enforce strict compliance with standardized communication protocols at the device level, ensuring that charging infrastructure can be integrated without the need for external on-site modules, while preserving interoperability and long-term maintainability
2	Stable operation depends on redundant communication channels, especially in sites with weak or unstable connectivity	Deploy backup communication links (PLC, Wi-Fi extenders) to ensure continuous controller communication

ID	Lesson learned	Mitigation measure/Recommendation
3	Fast coordination between on-site and remote teams was essential to resolve issues quickly	Establish clear escalation pathways and continuous monitoring mechanisms to support rapid intervention
4	Participation in curtailment services (solar and wind) requires real-time access to dispatch centres or other relevant grid assets, such as secondary substations, PV systems and wind farms	The existence of a third party acting as a middleware between the grid operator and the charging-station operator, enabling the exchange of activation or price signals for service participation
5	Greater involvement of the field team during the laboratory testing phase would have reduced integration issues during deployment	Establish a detailed planning table to ensure better preparation and stronger field team involvement
6	OBD device information is not universal and requires better understanding and interpretation	Recommend higher standardization of OBD technologies at the EU level
7	The e-mobility ecosystem faces barriers from protocol standardisation, diverse EVSE brands, and infrastructure issues. This causes that optimization and real-time control must be adapted to these constraints	To prioritise strict adherence to open communication standards and to establish clear interoperability requirements across EVSE brands, reducing integration complexity and ensuring consistent behaviour in multi-vendor charging infrastructures.
8	Forecasting-only algorithms did not meet user-specific requirements (e.g., minimum SOC at departure)	Include operational and user constraints directly in the optimization logic
9	Data-quality issues (missing or incorrect signals) impacted charging schedules	Apply automated data-validation checks and generate alerts when critical signals are missing or inconsistent
10	The use of heterogeneous controllers (EDGE + Reduxi) within the same pilot highlighted communication format limitations, demonstrating the need for a more flexible and robust control architecture capable of seamlessly integrating different controller technologies	Communicate directly through the optimisation protocols instead of using different middleware.

3 Operational assessment

While the previous section focused on technical hardware and software integration, this section examines the human and systemic factors that influenced the day-to-day execution of the trials. The operational assessment is structured around three critical pillars: user engagement strategies, insurance and safety protocols, and the robustness of the UI solutions

The primary objective of this assessment is to analyse how the control architecture and its associated algorithms performed within a dynamic ecosystem where user behaviour and mobility requirements often presented constraints not seen in laboratory environments.

3.1 User engagement

Engagement with real users requires clear communication, transparent instructions, and accessible troubleshooting pathways. Backlash cases showed the need to improve homeowner satisfaction through clearer instructions and better visualizations. Additionally, technical and interoperability issues must be managed in a way that does not disrupt the user experience. Maintaining simplicity in daily interactions is essential, even when underlying systems require complex troubleshooting or coordination. Moreover, maintaining a single point of contact proved essential to ensure smooth communication, fast feedback loops, and an overall better user experience.

Users expressed limited confidence in advanced V2X functionalities, especially bidirectional charging. To address range-anxiety concerns, accurate forecasting and transparent visualization of expected energy flows should be made available in user-facing interfaces. Additionally, it should be clear to users that when participating in flexibility services, they might not receive the required amount of energy as early as possible. Otherwise, participation in flexibility or curtailment services can introduce “anxiety” if users perceive that service activation may delay their charging needs.

Finally, real-world engagement revealed that support needs sometimes to occur outside standard hours (e.g., complaints at 23:00 on a Saturday). Automated monitoring tools and support bots with predefined Q&A flows can help provide timely user assistance and detect failures earlier.

3.2 Insurance and safety

Insurance and safety considerations were relevant throughout the deployment, particularly in residential contexts where physical protection (e.g., guards and reinforced cable routing) were installed to ensure safe operation. Explicit user authorization for technical interventions was required, and clarity regarding equipment liability was essential.

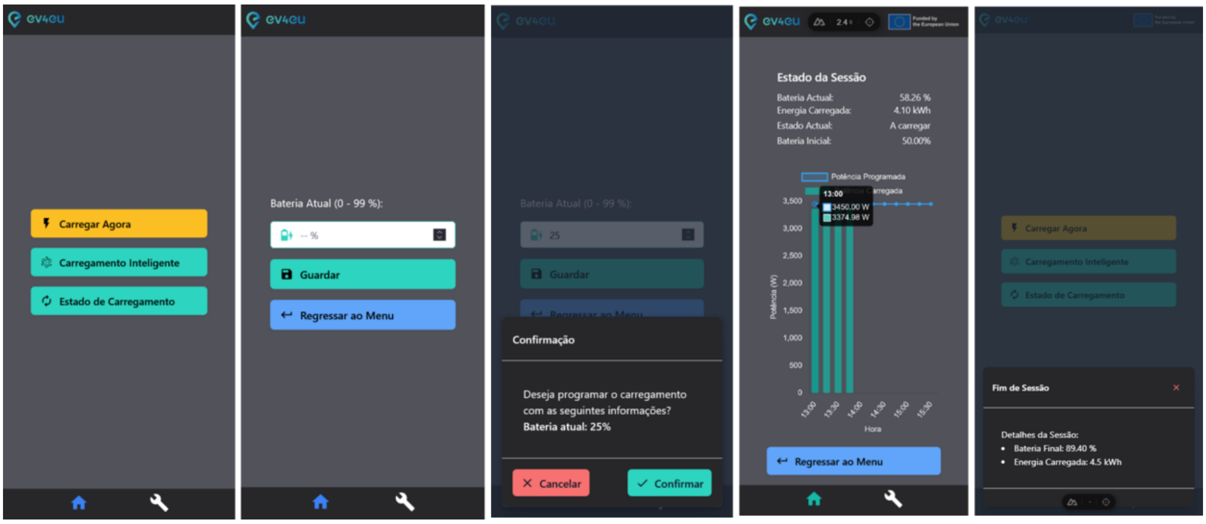
In addition, it is important that participation agreements clearly specify who owns the installed equipment, the responsibilities for its maintenance, and what happens if a participant withdraws from the project. Defining these conditions upfront reduces uncertainty for both users and project teams and helps avoid operational or legal disputes later in the demonstration. Ideally, these participation agreements and user consents must be reviewed in depth by qualified legal teams to avoid loopholes, ensure clarity on responsibilities, and protect both users and project operators.

3.3 User interface

The user interface developed for the Portuguese demonstrator (Figure 1) serves as the link between participants and the control architecture, designed to provide transparency and streamline daily interactions with the smart charging system

To ensure a high-quality user experience, the interface informs participants that the implemented algorithm prioritizes energy efficiency; consequently, a vehicle connected to a charger will not always be in an active charging state, as the system optimizes sessions based on grid conditions and local production. To reduce user effort, the platform utilizes a secure login system that saves the user's email and vehicle information, eliminating the need to re-enter data for every session.

Crucial to the ongoing refinement of the system is the feedback loop integrated into the pilot’s operation; users are encouraged to use a dedicated WhatsApp channel to report discrepancies between the requested charge percentage and the actual percentage obtained. This real-world data allows technical teams to continuously adjust and improve the algorithm's accuracy



Deseja programar o carregamento com as seguintes informações?
Bateria atual: 25%

Estado da Sessão

Bateria Actual: 58.26 %
Energia Carregada: 4.10 kWh
Estado Actual: A carregar
Bateria Inicial: 50.00%

Detalhes da Sessão:
- Bateria Final: 89.40 %
- Energia Carregada: 4.5 kWh

Figure 1. Sequential user interaction flow for a smart charging session

User-interface interactions must remain simple, robust and adapted to different user profiles. The PT pilot showed that users vary significantly in how much data they want to provide or receive. Therefore, offering multiple UI versions or profiles can improve user satisfaction and reduce friction.

The interface should also provide clear visualizations, error messages and transparent explanations of energy flows, especially when V2X actions affect the user’s expected charging plan. Automated chatbot-style support tools can complement the UI by helping users troubleshoot issues quickly and by surfacing early warnings about system failures.

3.4 Mitigation measures

The ultimate success of V2X technologies depends fundamentally on user behaviour, trust, and the clarity of daily interactions. Field experiences the different pilots demonstrated that participants often expect a level of support and system reliability comparable to commercial services, which presents a significant challenge for an experimental research pilot.

To mitigate these risks, the following strategies on Table 5 focus on streamlining the user journey and enhancing communication transparency. A primary recommendation is the implementation of a single point of contact for each use case to centralize responses. Furthermore, to alleviate concerns from the users, the mitigation framework prioritizes the development of advanced visualizations within the user interface, providing users with clear, forecasted charging outcomes and real-time energy flow data.

Table 5. Summary of operational mitigation measures and strategic recommendations

ID	Lesson learned	Mitigation measure/Recommendation
1	Clear communication, transparent instructions, and easy troubleshooting pathways are essential to engage real users	Provide clear, simple instructions and ensure troubleshooting guidance is easy to access and understand
2	Technical and interoperability challenges must be handled without disrupting user experience, preserving simplicity in interactions and system usage	Having a single point of contact offers a smoother experience to the user and centralizes the response
3	Confidence in V2X mobility solutions, especially advanced functions like bidirectional charging, remains limited, requiring transparency and proven reliability for broader adoption	Improve transparency through visualizations of expected energy flows and charging outcomes
4	Participation in flexibility services may create user “anxiety”	Clearly communicate how service participation may affect charging times and expected SOC
5	Real-world usage generated support needs outside standard working hours	Use automated monitoring tools and support bots with predefined Q&A flows to provide assistance at any time
6	Clarity regarding equipment liability was essential	Specify ownership and maintenance responsibilities in participation agreements
7	Legal review of terms and consents is needed to avoid loopholes and protect users and project operators	Ensure that all user agreements are reviewed by legal teams to clarify responsibilities and protect both parties
8	Different users might expect different levels of data input, which may require different versions of the UI	Offer multiple UI profiles with different complexity levels to accommodate different user preferences
9	Clear visualizations and error messages are necessary, especially when V2X actions affect expected charging behaviour	Ensure the UI displays transparent explanations of energy flows, forecasts and any deviations from expected charging
10	User expectations resemble standard customer-support requirements, which are demanding for research project	Define realistic support expectations and response times in participation agreement

4 Impact of V2X solutions

The deployment of V2X solutions in the Portuguese demonstrator had a meaningful impact on the learning outcomes of EV4EU, even if it did not translate into a widespread change in day-to-day operational behaviour at most sites. In most locations, V2X did not become a permanent modus operandi, mainly due to technical immaturity, integration complexity and site-specific constraints.

Nevertheless, the tests conducted were highly valuable from a technical and experimental standpoint. They enabled the project to assess the performance of control algorithms, validate system interactions across heterogeneous components, and observe user behaviour under real operating conditions. This provided concrete evidence on what works, what requires adaptation, and what remains a barrier when deploying bidirectional charging outside controlled environments.

From a project perspective, these experiences helped clarify the conditions under which V2X can deliver tangible value, as well as the trade-offs between technical ambition and operational robustness. Although the immediate behavioural impact was limited, the demonstrator highlighted the potential impact of V2X at scale, particularly if solutions are standardised, simplified and better aligned with user practices and site operation.

Importantly, the PT demo confirmed that the feasibility and relevance of V2X are strongly context-dependent, varying significantly between residential, building and company environments. For this reason, the following sections analyse the impact and lessons learned separately for households, buildings (LREC) and companies (EDA campus).

4.1 Households

The residential demonstrators provided a controlled yet realistic environment to assess the feasibility of V2X solutions at household level. By involving different electrical configurations (single- and three-phase) and households with local PV and storage, the project was able to test V2X solutions under varying conditions. Unfortunately, due to a participant having changed their vehicle (Nissan Leaf) mid-project, the only EV compliant with bidirectional charging at the home's location was no longer available. As a result, most of the charging was focused on smart charging.

The campaign started in Q4 of 2024 and extended through most of 2025, with ongoing development and refinement of the control algorithms. In order to test the full deployment of such tests, full connectivity from all devices was required (chargers, meters, and other devices such as the PV and the BESS). In some cases, users intentionally turned off the charger's OCPP connection for better control or for lack of trust in the control algorithms. Figure 2 represents the time windows in which all the above were connected. As previously mentioned, the most engaged users were #2 and #6. User #6 was the user who used the app the most to schedule and provide commands.

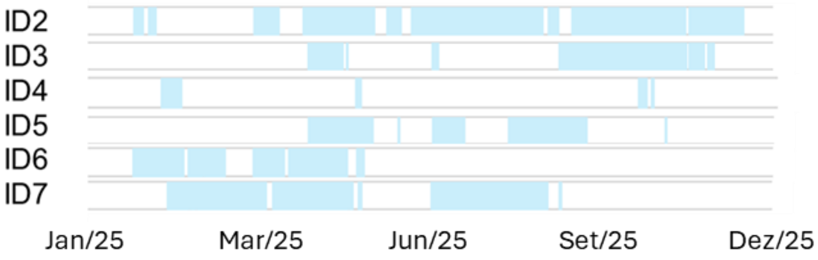


Figure 2. System uptime for household pilot sites (ID2–ID7)

The following results provide a quantitative overview of the charging activities recorded across the six active households in the Portuguese demonstrator between late 2024 and mid-2025. During this period, the control platform monitored approximately 350 sessions, delivering a total of over 5,200 kWh of energy. As noted in the technical assessment, the results are asymmetric across the pilot sites, primarily due to variations in user behaviour, connectivity stability (such as Reduxi units going offline), and hardware-specific issues like faulty charging cables.

Table 6. Summary of charging performance and economic assessment for households

Metric	ID2	ID3	ID4	ID5	ID6	ID7
Number of sessions	109	61	5	18	22	132
Total Charged (kWh)	2289	1135	111	265	466	999
Average session (kWh)	21.00	18.61	22.29	14.70	21.18	7.57
Total Price (EUR)	295.72	175.76	14.35	34.35	59.49	128.33
Total Price – uncoordinated (EUR)	323.67	176.29	17.42	35.83	64.19	148.57

Some test results are presented above, since most of the control was focused on tariff optimisation and some isolated tests on PV integration. Results ranged from almost 0% (with very optimised and literate users) to 14%, with an average value of 8.6% in cost reduction per household.

Concerning the impact of user EV literacy, a good example of this is the early tests conducted in late 2024. As can be observed in Figure 3, most users already used pre-set configurations on their EVs to charge as economically as possible. This is further exacerbated by the fixed tariff scheme in the Azores, which allows for such a fixed charging pattern. A dynamic tariff would boost the algorithm's performance.

Before control was applied in House 6, there were only small instances in which the coordination by the user was not perfect, meaning that there was very little room for the algorithm to improve the actual charging costs. After control was applied (Figure 4), the algorithm takes the connector demand and allocates it to the lowest-cost period available, thereby optimising the charging schedule within the user's defined time window.

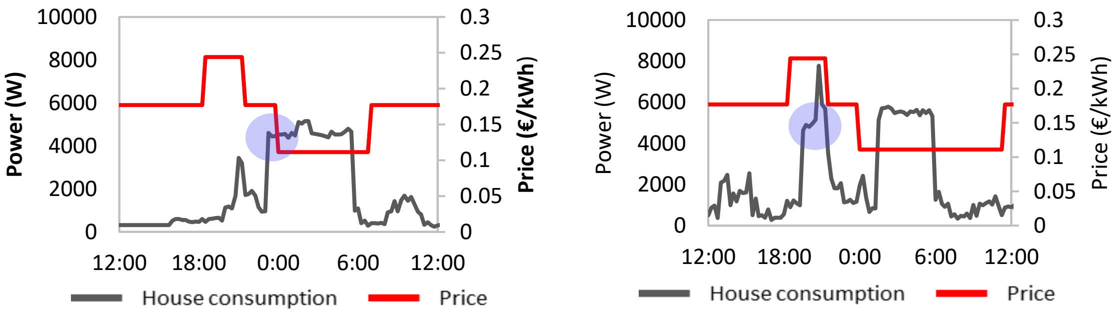


Figure 3. Examples of non-controlled charging sessions on household #6. November 27th, 2024 (weekday) with no control (left) and January 4th, 2025 (weekend) with no control (right)

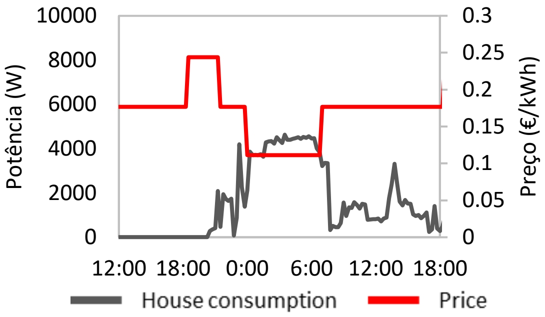


Figure 4. Early implementation of smart charging control strategies on household #6, January 20th, 2025 (weekday)

In Figure 5, it can be seen that for user #2, with no specific goal defined for the algorithm, the decision was to spread the charging across the entire off-peak tariff window. In the case of user #6, a target of 90% SoC was requested with a starting SoC of 26% (defined by the user), with the session starting at 20:45 and ending by 7:00. The algorithm chose to postpone the charging as much as possible to minimise the cost. It is worth noting that as soon as the car was plugged in, the EV started charging briefly as a verification step. This is also useful for building user trust, as it provides immediate feedback that the system is working. Some users turned off the OCPP communication because, before going to sleep, they saw no activity on the chargers and lost confidence in the system.

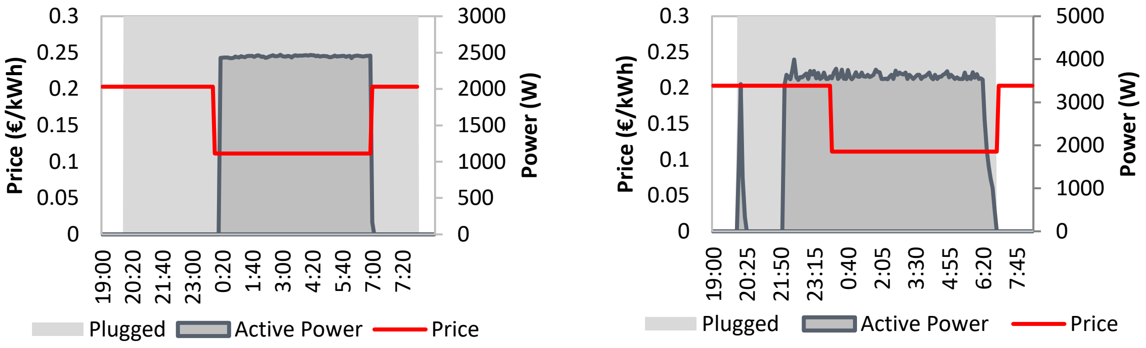


Figure 5. Comparison of smart charging behaviour: user #2 with no specific SoC goal – February 5th, 2025 (left) and user #6 with 90% SoC target – May 12th, 2025 (right)

Another relevant aspect was the limited accuracy of the SoC estimation, which did not meet user expectations. Under the OCPP 1.6 protocol, the SoC telemetry flag is not available during the charging session, requiring the algorithm to forecast the SoC trajectory based on the initial value provided by the user. As illustrated in Figure 6, during the experiment conducted on May 12th (User #6), the algorithm overestimated the final SoC at 97%, whereas the actual value reported by the user was 90%. This deviation can be attributed to multiple factors, including the State of Health (SoH) degradation of the battery and ambient temperature variations, both of which introduce non-linearities in the charging curve that affect SoC estimation accuracy. Following this observation, the estimation model was recalibrated to mitigate such overshoots and ensure a more conservative and reliable SoC prediction, thereby improving user confidence in the system.

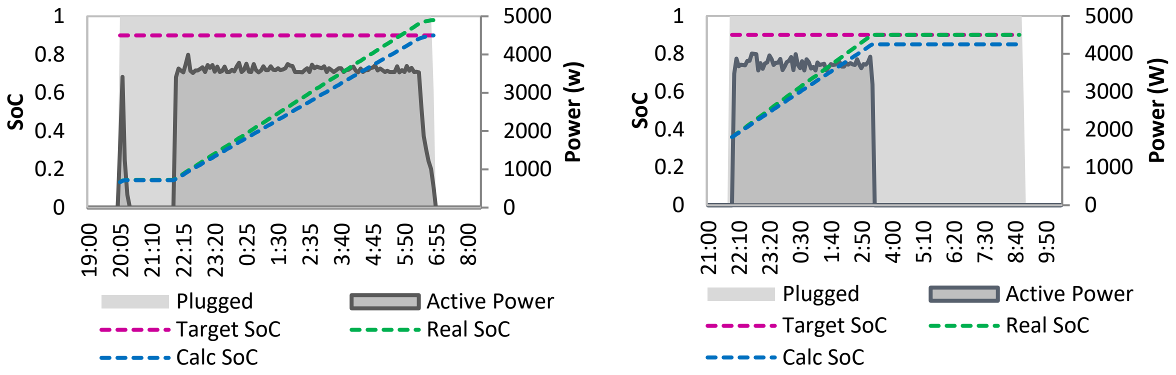


Figure 6. Example of SoC target calibration during a smart charging session: user #6 with 90% SoC goal – May 12th, 2025 (left) and user #6 with 90% SoC goal – May 17th, 2025 (right)

Another objective of the Portuguese demonstrator was the effective integration of RES, specifically by aligning EV charging with local photovoltaic surplus. While the households were equipped with PV systems and, in some cases, BESS, aligning charging sessions with PV production peaks was rare because most users maintained a strong preference for night charging.

Moreover, an additional hurdle for maximizing RES use, was justified by difficulties in integrating specific inverter models (e.g., Growatt and Solar X1 Mini) with the Reduxi controllers. These issues required firmware updates and reconfiguration to ensure the system could accurately monitor and control the PV+BEES system.

Nevertheless, among all participants, user #3 achieved a larger increase in RES integration than the other households (22%). This outcome is attributed to a higher incidence of daytime charging sessions at this site, which provided the algorithm with more opportunities (Figure 7). The forecasted PV production aligns with the smart charging session, which started immediately to maximise the use of PV generation and therefore reduce charging costs.

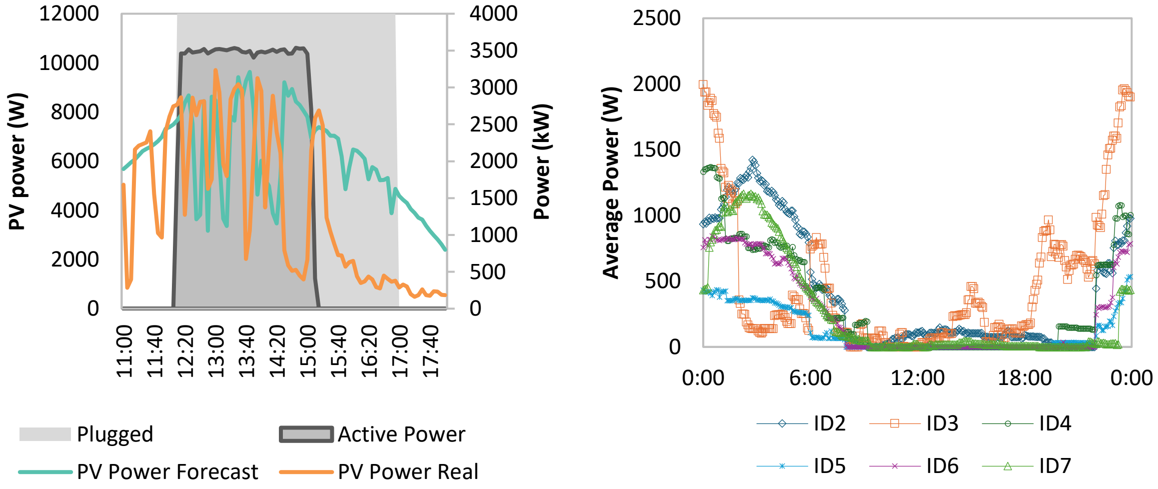


Figure 7. Example of RES coordination: user #3 - October 12th, 2025 (left) and average hourly charger power output per household (right)

4.2 Buildings

The LREC Building demonstrator tested unidirectional smart charging (since no bidirectional charger was available) for wind curtailment and congestion management services in a campus environment.

Unlike other pilots, the LREC pilot followed a more controlled environment, in which services were scheduled on specific dates to test their operation under predefined conditions. Only one EV was available during the pilot, meaning that no conclusions can be drawn regarding user behaviour or acceptance. The main objective of this site was therefore to demonstrate the technical feasibility of providing these services and to validate the correct operation of the charging and control setup. The grid services tested at the LREC pilot were designed to address two main challenges: making better use of renewable energy and supporting the local electricity grid.

The wind curtailment mitigation service aimed to increase electricity consumption during periods of excess wind generation, typically at night, to absorb renewable energy that would otherwise be curtailed. In the control model, activation was triggered by a price signal proportional to the amount of wind power curtailment, based on historical data from the Graminhais wind farm [7]. The optimization algorithm scheduled EV charging to coincide with these periods, effectively delaying charging until curtailment was expected. In this pilot, due to the absence of bidirectional charging, the service was implemented by connecting the EV in the early evening but postponing the start of charging until the forecasted curtailment window. If bidirectional charging had been available, the EV could have discharged during peak hours, starting the night with a lower state of charge and thus enabling greater absorption of surplus wind energy during curtailment periods.

The congestion management was implemented through the adjustment of EV charging behaviour to support local voltage control at the level of the secondary substation. Depending on the simulated grid conditions, EV charging was either reduced during periods of high local demand to mitigate voltage drops or increased during periods of excess local generation to absorb surplus energy and mitigate voltage rises. As the LREC site does not experience real congestion events, the operating thresholds were artificially reduced to enable service testing. Service activation was driven by price signals reflecting the simulated grid state.

Description of the Sessions during October

The conducted tests during October in the building pilot (LREC) were implemented using the connector LREC 1 namely a Wallbox Copper three-phase with 22kW of maximum charger capacity. Nevertheless, the only car charged was a Nissan Leaf, which requires a single-phase charging, resulting in lower effective charging power during the sessions.

During October, twelve charging sessions were conducted at the LREC site, accounting for a total of 193.3 kWh charged. Four sessions occurred during the night, in order to test the wind curtailment reduction use case, while five sessions took place during the day, targeting the congestion management use case. The remaining three sessions had no services scheduled and were carried out under smart charging operation only, serving as reference sessions for comparison purposes.

Figure 8 presents the distribution of charging sessions during October by service type, illustrating how the total charged energy was distributed across the different services tested.

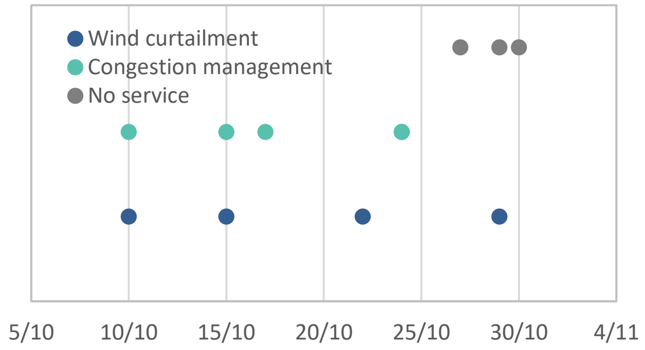


Figure 8. Charging sessions at LREC in October by service type

A detailed overview of each charging session is provided in Table 7. Overview of LREC charging sessions, conducted during October, including the session date, service type, initial and final state of charge, expected SoC, and the resulting SoC deviation. The table also highlights operational issues observed during specific sessions, such as communication/control errors, platform errors, or insufficient connection time.

Table 7. Overview of LREC charging sessions, conducted during October

Date	Service type	SoC_i	SoC_{goal}	SOC_f	SoC deviation (%)	Comments
10/10	Wind curtailment	0.41	0.7	0.7	0	-
10/10	Congestion management	0.7	0.9	1	11	Communication/control errors occurred
15/10	Wind curtailment	0.3	0.65	0.56	14	-
15/10	Congestion management - generation	0.63	0.8	0.7	13	Communication/control errors occurred
17/10	Congestion management - generation	0.15	0.9	0.9	0	-
22/10	Wind curtailment	0.23	0.9	0.72	20	-
24/10	Congestion management - consumption	0.3	0.65	0.49	25	The car had to leave unexpectedly
24/10	Congestion management - consumption	0.47	0.8	0.74	8	-
27/10	No services implementation scheduled	0.33	0.6	0.56	7	An emergency charging requirement occurred during the session
29/10	Wind curtailment	0.22	0.6	0.54	10	-
29/10	No services implementation scheduled	0.54	0.8	0.7	13	Error in the platform
30/10	No services implementation scheduled	0.36	0.8	0.7	13	Connection time was insufficient to meet desired SOC

Overall, the charging success KPI was computed based on the deviation between the target and the achieved SoC, with lower deviations indicating better performance. Overall, the average SoC deviation was 11%. For several sessions, the final SoC closely matched the target SoC, showing that the charging control logic was able to meet the expected SoC when normal operation conditions were maintained. However, some deviations between target and final SoC were observed in a subset of sessions. These deviations were largely influenced by operational issues reported in the session log, such as communication or control errors, unexpected user behaviour, platform errors, or limited connection durations. When comparing service types, a similar level of SoC deviation was observed across sessions with different services activated, indicating that, given the small number of charging sessions in the pilot, no clear correlation could be identified between the type of service provided and the SoC deviation. Figure 9 presents an overview of the SoC evolution per charging session carried out in the pilot during October.

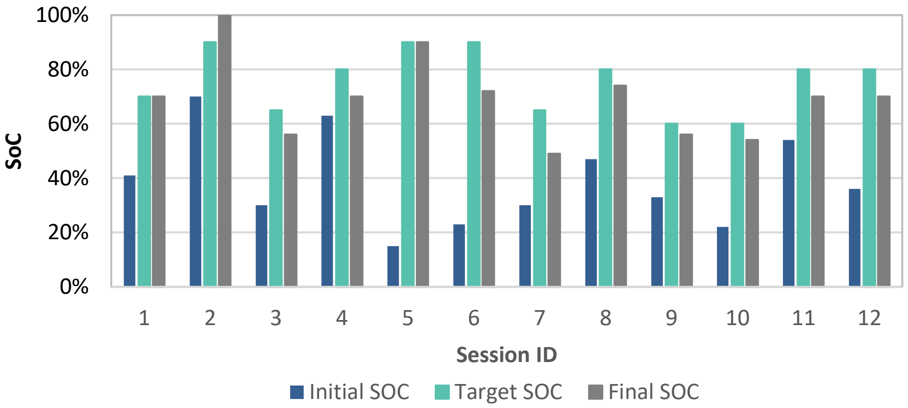


Figure 9. Overview of SoC evolution per session

To provide a more detailed view of pilot operation, selected charging sessions are described in detail below. For each session, the evolution of charging power, scheduled power, state of charge, and service activation is illustrated.

- **Wind curtailment and generation congestion management services – October 15th, 2025**

During this day, two distinct charging sessions occurred, each corresponding to a different service test, as illustrated in Figure 10. During the wind curtailment session, the service was actively delivered by executing charging during the period of expected wind curtailment, with charging power closely following the scheduled profile. However, the scheduled power was nearly double the actual charging power, as the initial scheduling did not account for the vehicle's single-phase charging limitation. As a result, the final SoC was slightly below the target. It is also notable that the service activation flag was active for a longer period than the actual charging period, reflecting the difference between the theoretical service window and the practical charging constraints.

In the congestion management session, charging power did not follow the scheduled profile due to several communication and control errors detected during the test. These issues required the scheduling to be regenerated multiple times, and consequently, the final SoC was below the expected value. Additionally, data for the service activation flag was not available for this session. The objective was to increase charging to compensate for excess local generation, but operational constraints limited the effectiveness of the test and prevented the charging from matching the planned schedule.

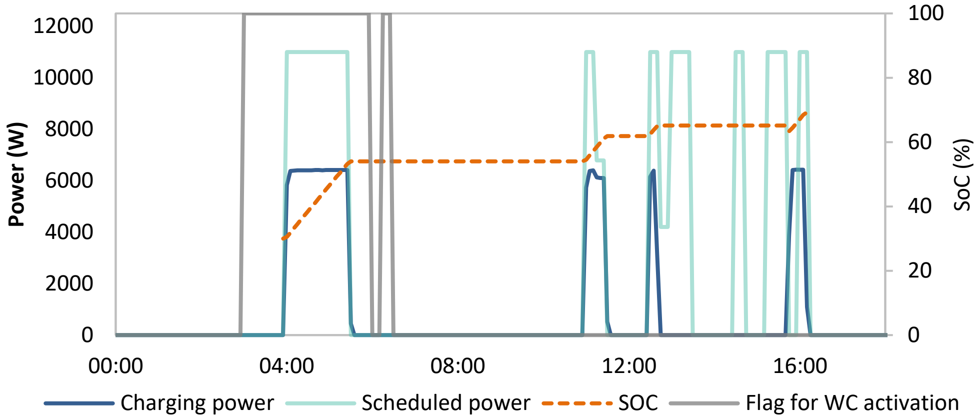


Figure 10. Session to test wind curtailment and generation congestion management services

- **Generation congestion management service – October 17th, 2025**

In this session, which focused on generation congestion management, the charging power generally followed the scheduled profile, although there was the discrepancy between the scheduled and actual values that have been explained above. The service activation flag only appeared around 13:00, but charging began earlier to ensure the desired SoC could be reached within the available window. In any case, it is worth mentioning that once the flag was active, the charging power closely tracked the service request, adjusting in response to the activation period until the target SoC was achieved. This session illustrates that, when the control logic and technical conditions are properly aligned, the system can effectively deliver the requested grid service but also highlights the importance of considering hardware limitations in the scheduling process. Figure 11 illustrates the single charging session that occurred during this day.

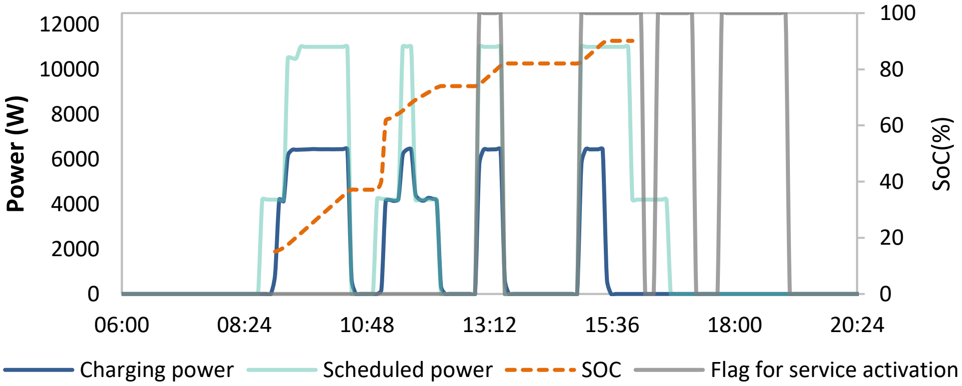


Figure 11. Session to test generation congestion management service

- **Consumption congestion management service – October 24th, 2025**

As it can be observed in Figure 12, during this day, the activated service was the consumption congestion management service. This session was, in practice, a combination of two charging periods, as the car left the site for 25 minutes between 14:15 and 14:40. For simplicity, the analysis and graphics consider the entire period as a single session. In the morning, a real activation of the voltage regulation service occurred due to an undervoltage caused by excess of consumption. In this context, the expected behaviour is for the charging power curve to move inversely to the service activation flag: when the flag is active, high consumption is detected and the car should stop charging (or discharge, if bidirectional capability were available). This pattern is observed throughout most of the first charging period, except at the beginning, where some charging occurred even with the flag active to reach the target SoC, which ultimately was not achieved. After the car returned for the second charging period, the priority shifted to achieving the desired SoC (80%), and the congestion management service was not provided during this time. The charging power remained high, regardless of the flag status, to maximize SoC within the limited available time.

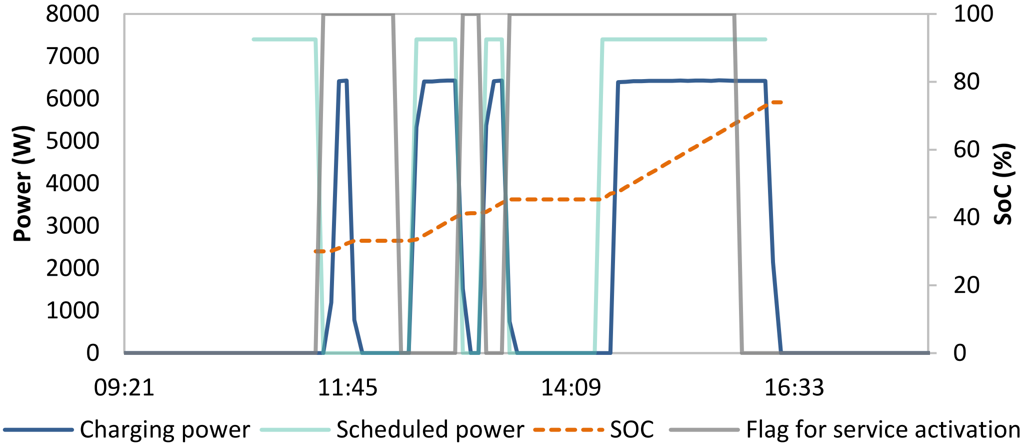


Figure 12. Session to test consumption congestion management service

4.3 Companies

The EDA Campus demonstrator was the most comprehensive and rich pilot within the Portuguese demo, both in terms of the number of users and the diversity of use cases tested. It was the only site where bidirectional charging was effectively deployed, enabling the validation of multiple services focused on sharing charging, fleet management and coordinated operation across users. The campus environment involved a wide variety of EV models and user profiles, including employees, visitors and fleet vehicles, with different priority levels, which provided a realistic setting to assess scheduling strategies, access control and system robustness.

While much of the equipment was online throughout 2025, the most intensive deployment and testing phase occurred during the last half of the year, recording over 700 charging sessions. This period resulted in more than 6 MWh of energy charged and 160 kWh discharged during specific V2G and fleet management tests, providing a substantial dataset for evaluating the impact of bidirectional energy flows (Figure 13).

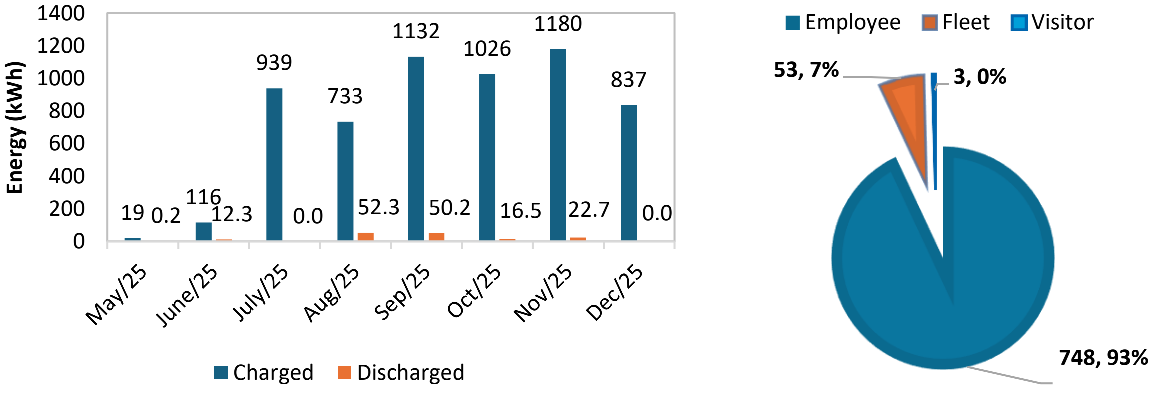


Figure 13. Total energy balance of the EDA pilot (left) and share of user type (right) during demonstration

Since most of the ecosystem in which the tests were conducted operated in a real environment with real users, the objective was to ensure a balanced approach between cost minimisation and mobility requirements. Therefore, the algorithm was calibrated to maintain this balance. Below on Figure 14 are two examples of employee charging sessions that were managed to secure a minimum required SoC and then resume the charging session later.

The difference between the image on the left and the one on the right is that, in the first case, the algorithm (based on the user’s requirements 90% SoC and the declared departure time) scheduled more than 60% of the charging demand immediately after the EV was connected. After several iterations and improved calibration, greater confidence in user behaviour was achieved. As a result, in the second example, the algorithm charges less than 40% immediately and instead allocates the remaining demand more efficiently within the available time window.

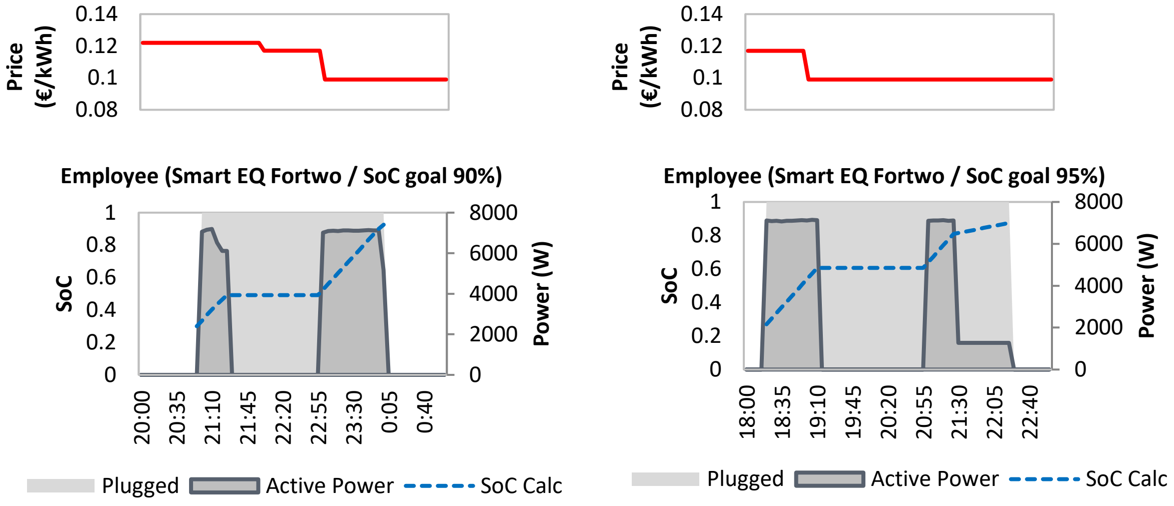


Figure 14. Example of goal function calibration: employee user with 90% SoC goal – November 23rd, 2025 (left) and employee user with 95% SoC goal – December 2nd, 2025 (right)

Another commonly tested scenario involved fleet management between two vehicles. In Figure 15, in the first example, an employee defined a very low flexibility window, which required immediate charging. At the same time, a fleet vehicle arrived and connected during the ongoing session. Since the employee’s vehicle had higher priority, the fleet vehicle paused its charging until the first EV disconnected. Afterward, the fleet vehicle followed the same dual-objective strategy: it waited for a lower-tariff period, resumed charging, and eventually completed the session with a final target SoC of 100%.

The second example illustrates a bidirectional scenario focused on a vehicle-to-vehicle (V2V) use case. Similarly, an employee vehicle with a very limited flexibility window initiated immediate charging. A few minutes later, a fleet EV connected and began discharging to reduce the peak load at the charging station and lower the charging cost during that high-tariff period. Since the session was scheduled to end at 12:00 the following day, there was sufficient flexibility to recharge the remaining SoC later. However, in this particular case, the fleet vehicle was disconnected at 04:15 for an extraordinary service, resulting in a lower final SoC than originally expected (target SoC of 90%).

In these cases, the algorithm effectively lowered peak load and kept charging costs within the expected range. By dynamically prioritising vehicles according to their flexibility windows, required SoC targets, and tariff conditions, the system was able to coordinate multiple charging sessions without compromising user mobility requirements. This approach not only mitigated simultaneous high-power demand at the charging infrastructure but also ensured that energy was allocated during more cost-efficient periods whenever possible.

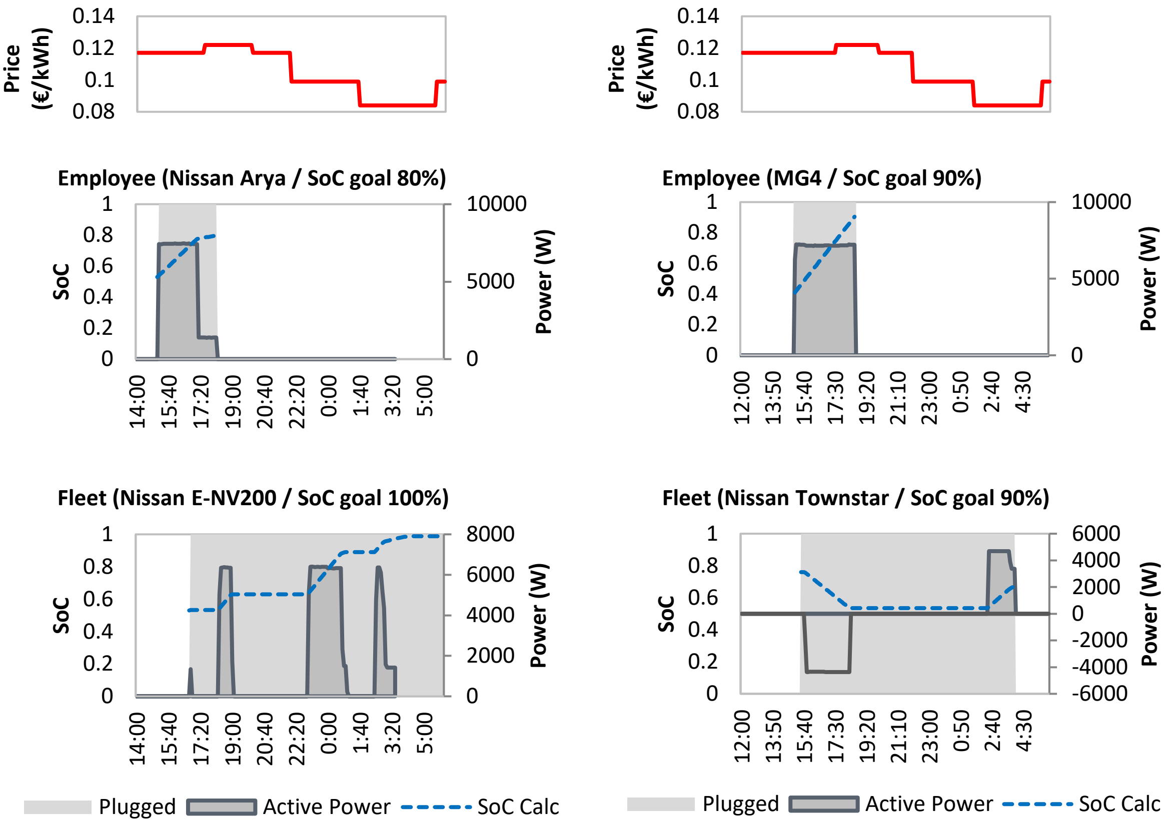


Figure 15. Example of a fleet charging management session - November 21st, 2025 (left) and example of a Vehicle-to-Vehicle session - October 30th, 2025 (right)

4.4 Impact of energy management solutions

4.4.1 Demand response

The Portuguese demonstrator contributed to validate the role of energy management systems as enablers of demand response through EV flexibility, rather than fully market-ready solutions. Across the demo sites, energy management platforms coordinated EV charging with local generation (homes case), consumption forecasts and predefined constraints in mobility requirements (EDA case), which allow the project to test in specific test sessions, peak-load mitigation, charging alignment with renewables and controlled flexibility in activation for specific grid services (LREC). For the case of LREC, some of the data to test the grid services (wind curtailment forecast) were emulated forecast due to the complexity to integrate in the dispatch centre of the local wind farm. Although the demand response actions were not systematically implemented in permanent operation, the tests provided valuable insights into control reliability, data quality requirements and latency constraints, critical to scale the concept. One big lesson learned was that effective EV-based demand response depends less on algorithmic complexity and more on robust monitoring, interoperable devices and stable communication between chargers, controllers and site energy management system, which were the main challenges of this service. These integration issues proved exceptionally complex to overcome, as many of these devices did not inherently support the necessary communication features for coordinated control, such as stable TCP connections or the ability to receive external setpoints.

Consequently, the implementation efforts were significantly hampered by the need for extensive firmware updates and manual ad-hoc reconfigurations

4.4.2 Reduction in peak load and operational costs

Among all the tested use cases, peak load reduction and operational cost optimisation were the areas where the Portuguese pilots proved most successful, delivering clear and immediate value with the current system architecture. Even under the existing fixed tariff scheme in the Azores, coordinated smart charging and local V2X control enabled effective peak shaving and load smoothing, demonstrating that tangible benefits can be achieved without the need for fully dynamic market mechanisms. Importantly, peak load management relied primarily on local control and connectivity, making it less dependent on real-time access to grid dispatch centres and more robust against external system limitations. The performed tests showed that, provided local communications are reliable, the algorithms were effective in balancing mobility requirements with peak demand minimisation, offering multiple degrees of freedom for calibration and improvement. While these results already represent a strong quick win, the lessons learned clearly indicate that a more dynamic tariff structure, aligned with increasing renewable intermittency, would significantly amplify the impact of the solutions developed in this pilot, further strengthening their scalability and long-term operational value.

4.4.3 Grid resilience support

This LREC demonstrated that it is technically feasible to provide grid services through smart charging of EVs, even in a campus environment with limited EV availability and unidirectional charging. Although only one EV was available and the site did not experience real congestion events, the pilot implemented wind curtailment mitigation and congestion management services under controlled conditions. Charging was aligned with periods of excess renewable generation, allowing the absorption of surplus energy that would otherwise be curtailed, and congestion management was tested by adjusting charging power in response to simulated voltage regulation needs.

A building like LREC, with predictable user profiles and the potential for a dedicated EV fleet, offers several advantages for grid resilience and peak shaving. The stable operating hours and centralized energy management make it easier to coordinate EV charging with grid needs and local PV production, maximizing self-consumption and reducing grid injections. Compared to individual houses, which have more variable and dispersed usage patterns, a building environment enables greater aggregation of flexibility and a more coordinated response to grid events.

Despite these strengths, the impact observed in the pilot was limited by several factors: the small scale of flexibility available, the absence of bidirectional charging, and the lack of real-time integration with the Distribution System Operator (DSO) for service activation. Operational reliability issues, such as communication and platform errors, also affected service provision during some sessions. These constraints meant that the pilot served mainly as a proof-of-concept, rather than a demonstration of large-scale grid impact.

4.4.4 Environmental benefits

The Portuguese demonstrator was not explicitly designed to target fixed CO_2-reduction objectives through dedicated environmental optimisation tests. Nevertheless, several of the activities conducted, particularly those related to cost optimisation, peak load management and renewable integration, resulted in tangible environmental benefits, mainly through reduced reliance on carbon-intensive generation periods.

In residential households and at the EDA Campus, energy management solutions prioritised charging during periods with lower grid carbon intensity, driven by cost-optimisation logic and local flexibility availability. This indirect optimisation led to an estimated average reduction of 3 %[2] in carbon emissions, primarily by shifting EV charging and energy consumption to periods dominated by renewable or less carbon-intensive sources. These results confirm that, even without explicit CO_2-driven control strategies, well-designed cost-based algorithms can already deliver meaningful environmental gains.

At the LREC site, the pilot explored participation in wind curtailment services, demonstrating the potential role of EV flexibility in accommodating excess renewable generation. Although these tests were limited in scope, the results suggest that similar mechanisms, if deployed at operational scale at LREC, could enable reductions of up to 20 %[2] in CO_2 emissions by using curtailed wind generation. These outcomes underline the environmental value of V2X solutions when aligned with renewable integration objectives.

Importantly, the lessons learned indicate that the introduction of dynamic price signals and carbon-aware control strategies, reflecting increasing renewable intermittency, could significantly amplify these benefits and unlock stronger environmental impact through the solutions developed in EV4EU.

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[2] Calculated by comparing coordinated charging with the respective uncoordinated charging on the S. Miguel island energy mix [8].

5 KPI analysis

5.1 Definition of evaluated KPIs

A comprehensive set of KPIs was initially defined to assess the performance and impact of the Portuguese demonstrators across multiple dimensions, including general, environmental, technical, economic, social, and flexibility aspects. The original list was harmonized with other European demos to facilitate comparison.

However, given the nature of the pilots and the limitations in the data collected, several KPIs from the initial harmonized list had to be excluded. For example, it was not possible to evaluate the "voltage level violation" KPI, as no real voltage violations occurred during the demonstration, with all the measured values remaining within the limits. Similarly, "grid-level storage" was not assessed, since there was no grid-scale storage implemented at any of the Portuguese sites. The final list therefore includes only those KPIs for which meaningful evaluation was possible.

Given these constraints, the set of KPIs evaluated in this deliverable covers the main dimensions considered relevant for the Portuguese demonstrators, namely general, environmental, technical, economic, and flexibility aspects. It is worth mentioning that not all the KPIs were computed for the three sites. The following indicators were calculated:

- General KPIs: which include the number of electric vehicles participating in each demonstrator, the number and total installed capacity of charging stations, and the number of low-voltage energy meters installed.
- Environmental KPIs: which focus on the calculation of CO_2 emission savings at each site, quantifying the reduction in emissions achieved through the implementation of smart and coordinated charging strategies.
- Technical KPIs: that comprise the variation in self-consumption (i.e., the increase in the share of energy self-consumed at each site), the system uptime, and the charging success rate, which measures the ratio between the requested and the actual energy (kWh or SoC) delivered per charging session.
- Economic KPIs: which assess the operational energy cost savings achieved within the facilities and EV systems, by comparing the costs under coordinated charging with those under non-coordinated charging scenarios.
- Flexibility KPIs: which are specifically addressed for the LREC site, where the analysis considers the flexibility used versus the flexibility available for wind curtailment mitigation, based on the connection and disconnection times of the EVs.

5.2 Summary of KPI results & Comparison against expected results

Table 8 presents an overview of the general KPIs with the values registered in the demo and the goals defined prior to operation. Regarding EV participation, the results vary significantly across the three pilot sites. In the residential use case, EV participation was in line with the initial expectations, reflecting the fact that participating households were selected for the pilot and benefited from close and direct interaction with the project team. At the LREC site, EV participation was substantially below expectations, as only one EV was available during the pilot, which was temporarily provided, and none of the building's employees or visitors owned an electric vehicle. In contrast, EV participation at the EDA campus was above the expected level. This can be explained by the high penetration of EVs among

EDA employees, the existence of an electric fleet, and the strong interest shown by employees once the control system started operating reliably and consistently.

With respect to the number of charging stations installed, only three charging points were installed in the residential sites, since the other three households already had compliant charging equipment installed prior to the project. At the LREC and EDA sites, the number of installed charging stations was in line with the initial deployment plan.

Regarding OBD devices, the pilot demonstrated that non-intrusive OBD solutions were not sufficiently reliable for providing accurate SoC data. As a result, intrusive OBD devices were considered as an alternative. However, no local car garages in the Azores were willing to perform the installation of these devices in EVs, which ultimately limited their deployment within the demonstrator.

Finally, the system uptime KPI was below the expected level in the residential pilot. This was mainly due to user behaviour, as some participants disabled the OCPP connection whenever they perceived issues with the charging control. In addition, in at least one household the EV was considered essential for daily mobility, leading the user to only allow the OCPP connection during weekends. For the LREC site, the calculation of this KPI is not considered meaningful, as the site was mainly used in testing mode and, outside of October, very few charging sessions were carried out.

Table 8. General KPIs

Criterion	KPI	Pilot numbers			Goal		
		Houses	LREC	EDA	Houses	LREC	EDA
General	Active participation of EVs	6	1	>40	6	4	10
	Number of CSs installed	3	2	7	6	2	6
	Total capacity of CSs (kW)	22	22	44	-	-	-
	Number of LV energy meters installed	11	2	1	-	-	-
	Number of OBD devices installed	-	-	-	-	-	-
	Number of prosumers	3	1	0	3	1	1
	System uptime (%)	58%	-	>90%	90	90	90

In what concerns environmental impact (Table 9), in the residential pilots, CO_2 emission savings remained low (around 3%), below the initial target, mainly since the optimization function did not consider emissions, but also motivated by the already optimized nigh-time charging. Shifting the preference to day-time charging could positively impact emissions by boosting the use of PV surplus. Nevertheless, smart charging proved effective from an economic standpoint. Smart charging strategies prioritized lower-tariff periods, leading to consistent electricity cost reductions for households, with an average operational cost reduction of around 9%, exceeding the defined target.

At the LREC site, CO_2 emission savings were significantly higher, reaching approximately 20%. This outcome is directly linked to the implementation of wind curtailment mitigation, with EV charging intentionally shifted to periods of excess renewable generation. While the result clearly exceeds the initial target, it remains contextual, given the limited number of charging sessions and vehicles involved. Economic KPIs were not evaluated at this site, as the pilot focused on the technical validation of grid services rather than on economic performance.

At the EDA Campus, environmental benefits were moderate, with CO_2 emission savings of around 4%, below the target, as the control strategies were not explicitly carbon-aware. In contrast, the economic objective was met with smart charging and V2G enabling charging during lower-cost periods and reducing peak demand without compromising operational requirements.

Table 9. Environmental & Economic KPIs

Criterion	KPI	Pilot numbers			Goal		
		Houses	LREC	EDA	Houses	LREC	EDA
Environmental	CO_2 emission savings (%)	3%	20%*	4%	10	3	7
Economic	Operational cost-effectiveness (%)	9%	-	5%	5	2	5

Regarding the technical KPIs, it can be observed in Table 10, that the self-consumption variation could only be assessed in the residential use case, where more detailed data was available and where EV charging was more closely integrated with local PV generation. At the LREC site, although PV production was considered within the control logic, the available data did not allow a reliable calculation of this KPI, and at EDA, this indicator was not applicable, as no PV generation was present.

With respect to charging success, the results were consistently high across all pilot sites, indicating a high level of accuracy of the control algorithms developed within the project. Charging success exceeded 90% in both the residential and EDA pilots, showing that the algorithms were generally able to meet the targeted SoC requirements. In the residential use case, this result was achieved even though two users requested a final SoC target of 90% instead of 100%, which proved more challenging to attain. In these cases, the desired final SoC was defined by the users on a session-by-session basis, and the control strategy was progressively refined by the technical team based on this feedback. At the LREC site, where the charging success value was slightly lower, deviations were mainly associated with communication issues, control-related disturbances, and occasional unexpected behavior by the vehicle user during the test sessions.

Table 10. Technical KPIs

Criterion	KPI	Pilot numbers			Goal		
		Houses	LREC	EDA	Houses	LREC	EDA
Technical	Self-consumption variation (%)	15,4%	-	-	-	-	-

Criterion	KPI	Pilot numbers			Goal		
		Houses	LREC	EDA	Houses	LREC	EDA
	Charging success (%)	>90%	89%	>90%	-	-	-

The flexibility related KPIs can also be analysed for the LREC pilot site. However, due to the lack of detailed information on the actual EV connection windows during the LREC pilot it is not meaningful to present quantitative flexibility-related KPIs. Any calculation of available or used flexibility requires assumptions on vehicle availability and user behaviour, which would dominate the results rather than reflect actual pilot operation.

Nevertheless, a qualitative assessment of flexibility potential can be provided based on pilot observations and illustrative assumptions regarding typical connection windows. For this purpose, two representative scenarios were considered. For the wind curtailment service, it was assumed that the vehicle would be connected to the charger from 18:00 onwards, reflecting a typical fleet-vehicle usage pattern. For the congestion management service, a standard worker profile was assumed, with the vehicle connected between 09:30 and 16:30. Figure 16 illustrates these assumed flexibility window in relation to the actual service activation and charging power profiles, for the wind curtailment use case.

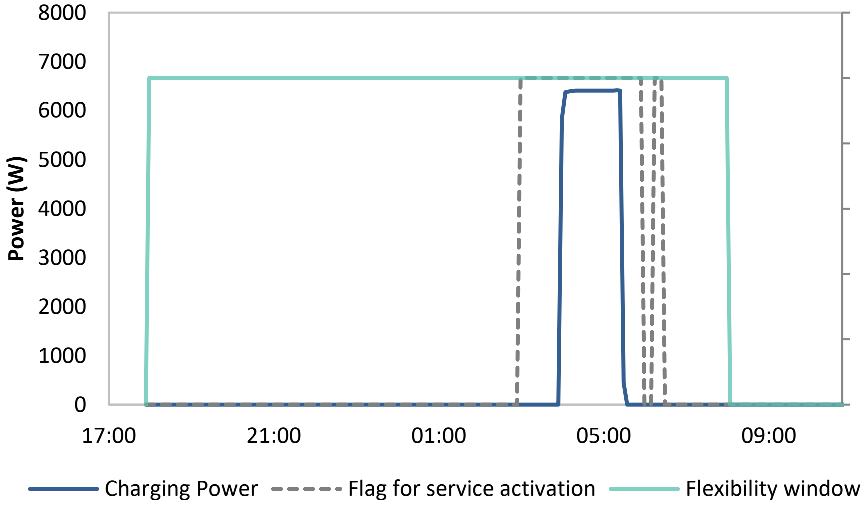

Figure 16. Flexibility window for the wind curtailment service

Based on these assumptions, it is evident that available flexibility was much higher than the flexibility utilized during the pilot. For example, wind curtailment events only occurred in the early morning, so charging started after midnight, leaving much of the potential flexibility window unused. If a bidirectional charger had been available, the car could have been discharged during peak hours and then charged during the morning to further reduce wind curtailment.

Given the high level of uncertainty and the reliance on assumptions, no quantitative flexibility KPIs are reported for this site.

6 Conclusions and future recommendations

The Portuguese demonstrator has successfully validated the technical and operational viability of V2X energy management within a real-world insular ecosystem. The pilot demonstrated that coordinated smart charging delivers immediate value, achieving an average household cost reduction of 8.6% and increasing PV integration by up to 21.9%, even for experienced users when it comes to EV charging.

The pilots revealed that the feasibility of scaling these solutions depends fundamentally on the robustness of the underlying hardware-software interface rather than the algorithmic complexity. Furthermore, the technical success of decentralized management is heavily dependent on strict adherence to open communication standards to overcome the significant integration hurdles encountered with heterogeneous equipment. Given this reliable control and connectivity, the most significant success was found in peak load reduction and operational cost minimization.

Strategic implications from the pilot highlight that user trust is a key factor of V2X adoption. The experience across São Miguel Island showed that "range anxiety" remains a critical barrier, requiring transparent communication, accurate forecasting, and single points of contact to maintain participant engagement.

The innovations outputs of the demonstrator have advanced several technologies toward higher TRLs. In the households, the integration of residential PV and BESS with smart charging algorithms was validated, despite complexities with specific inverter models and active setpoints. The LREC building site successfully demonstrated unidirectional smart charging for grid services like wind curtailment and additional demand response services. The EDA campus provided various innovation outputs, from effectively deploying and validating bidirectional charging in fleet management sessions to the development of a new patented charging station already in commercial used. Central to these outputs is the EV4EU control architecture which provides an open-source framework for managing multi-vendor charging infrastructure and metering equipment.

Moving forward, the lessons learned from the demonstrator identify a possible path to ensure mass market adoption. Future research must prioritize the development of advanced user visualisations (different user archetypes would require different UIs) to align user expectations with the control schemes to be implemented. Additionally, data acquisition methods, such as OCPP 2.0.1 and standardized EV on-board diagnostics (collect reliable SoC) can enhance significantly the control strategies capabilities. For pilot expansion and market adoption, the transition to a flexibility-aware control/ price signals is essential to unlock the full economic and environmental potential of EV flexibility. Finally, at the policy and regulatory level, there is an urgent need for EU-wide standardization of EV and EVSE technologies to reduce integration complexity and ensure long-term system maintainability. By enforcing these standards (e.g.: ISO 15118-20) and promoting legal participation frameworks, the necessary conditions for a user-centric, carbon-neutral mobility transition can be established.

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