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Horizon Europe

EUROPEAN COMMISSION

European Climate, Infrastructure and Environment Executive Agency (CINEA)

Grant agreement no. 101056765

ev4eu

Electric Vehicles Management for carbon neutrality in Europe

Deliverable D7.3

Slovenian use cases demonstration, monitoring and evaluation report

Document Details

Due date	31 – 03 – 2026
Actual delivery date	31 – 03 – 2026
Lead Contractor	Elektro Celje
Version	1.0
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Dissemination Level	Public

Project Contractual Details

Project Title	Electric Vehicles Management for carbon neutrality in Europe
Project Acronym	EV4EU
Grant Agreement No.	101056765
Project Start Date	01-06-2022
Project End Date	31-05-2026
Duration	48 months

Document History

Version	Date	Contributor(s)	Description
0.1	15.11.2025	GEN-I	Table of contents
0.2	29.01.2026	GEN-I	First draft
0.3	16.2.2026	UL, ABB, Elektro Celje, and GEN-I	Updated version
0.4	23.02.2026	DTU, EDP	Internal review
1.0	28.02.2026	GEN-I	Final version

Disclaimer

Acknowledgment

This document is a deliverable of EV4EU project. EV4EU has received funding from the European Union´s Horizon Europe programme under grant agreement no. 101056765.

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[1] https://ev4eu.eu/

Executive Summary

Deliverable *D7.3 Slovenian use cases demonstration, monitoring and evaluation report* presents the operational validation phase of the Slovenian demonstrator within the EV4EU project. Building upon the analytical, methodological, and implementation foundations defined in Deliverables D7.1, D7.2, D4.3, and D4.4, this report documents the execution, monitoring, and evaluation of Vehicle-to-Everything (V2X) solutions under real and emulated operating conditions.

The Slovenian demonstrator aims to validate the role of Electric Vehicles (EVs) as flexibility providers in electricity markets and grid services. Demonstration activities were implemented across two sites in Ljubljana and Krško, where V2X charging stations (CSs) are integrated with a Virtual Power Plant (VPP) and connected to a local flexibility market platform. In parallel, the Velenje site, based on a Battery Energy Storage System (BESS) aggregated into a VPP was used to emulate V2X behaviour and support comprehensive testing and evaluation of selected flexibility services.

The Slovenian V2X demonstrator represents an important step toward the next generation of intelligent, flexible and user centric energy systems. By combining advanced bidirectional charging technologies, real distribution grid environments, and fully integrated market and control platforms, the demonstrator provides a unique and highly realistic setting for testing how EVs can actively support the power system. Through coordinated work of GEN-I, Elektro Celje, ABB, and the University of Ljubljana, the demonstrator showcases how V2X technologies can enhance grid stability, unlock new market opportunities, and accelerate the transition to a carbon neutral energy future. The achieved results demonstrate not only the technical maturity of V2X solutions, but also the strategic potential of electric mobility to become a key flexibility resource in Slovenia and beyond.

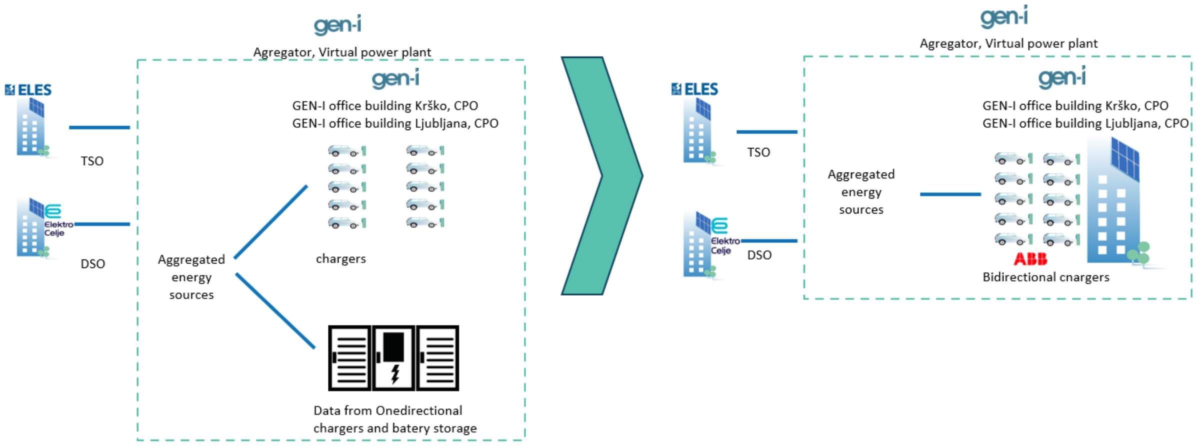
The purpose of the Slovenian demo is to demonstrate four use cases:

- **Use Case 9 (UC9)**: V2X management by a VPP (Virtual Power Plant);
- **Use Case 10 (UC10)**: Participation of V2X in electricity markets;
- **Use Case 11 (UC11)**: Participation of V2X in Grid Services;
- **Use Case 12 (UC12)**: Activation of V2X services by DSOs.

The Slovenian demonstrator followed a structured sequence of activities, beginning with the detailed planning and definition of use cases and technical requirements, followed by the installation and commissioning of the BESS in Velenje and the prototype V2X CSs in Ljubljana and Krško. All assets were integrated into GEN-I's VPP platform and interconnected with Elektro Celje's ADMS, Local Market Platform (FlexIS), and EVT platform, enabling automated flexibility activation.

Aggregated representative EV profiles were developed and validated and were used to simulate EV behaviour and flexibility potential through BESS-based emulation. Extensive monitoring, laboratory evaluations, and field testing, were conducted, covering interoperability of EVs, communication robustness, response time measurements, evaluation of more than 50 VPP activations, power tracking accuracy, forecasting models, quantification of EVs flexibility potential and selected KPI calculations.

The demonstrator concluded with validation of all four UCs (UC9–UC12), including full end-to-end activation initiated by the DSO, confirming that V2X assets can reliably deliver grid services, participate in markets, and integrate seamlessly into real distribution grid operations. Findings serve as a foundation for further analysis in Deliverable *D7.4 Lessons learned in Slovenian Demonstrator and Services Marketability report*.



Phase 1

Phase 2

Figure 1: Slovenian demonstrator Phases

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Keywords, Acronym

ADMS	Advanced Distribution Management System
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicles
BM	Business Model
BUC	Business Use Case
CSMS	Charging Stations Management System
CIM	Common Information Model
CPO	Charging Point Operator
CS	Charging Station
DER	Distributed Energy Resource
DR	Demand Response
DSO	Distribution System Operator
EC	Energy Community
EMS	Energy Management Systems
ENTSO-E	European Network of Transmission System Operators for Electricity
ESS	Energy Storage Systems
ETS	Emissions Trading System
EU	European Union
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
EVT	Unified Entry Point (slo. Enotna Vstopna Točka)
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
FMO	Flexibility Market Operator
GDPR	General Data Protection Regulation
ICE	Internal Combustion Engine
ICT	Information and Communication Technology
ID	Identification Number
KPI	Key Performance Indicators
LFM	Local Flexibility Market
LV	Low Voltage
MOL	Merit Order List
MV	Medium Voltage
PV	Photovoltaic
RES	Renewable Energy Sources
SoC	State of Charge
TLS	Traffic Light System
ToU	Time of Use
TSO	Transmission System Operator
UC	Use-Case
UL	University of Ljubljana
V1G	Smart Charging

V2G	Vehicle-to-Grid
V2X	Vehicle-to-Everything
VPP	Virtual Power Plant

1 Introduction

The large-scale deployment of Electric Vehicles (EVs) represents a fundamental shift in the interaction between the transport and energy sectors. Beyond their primary role as mobility assets, EVs equipped with Vehicle-to-Everything (V2X) capabilities can actively contribute to power system operation by providing flexibility services to distribution and transmission grids, supporting renewable energy integration, and enabling new market-based business models. However, the practical realisation of such concepts requires validation in real-world environments, considering technical feasibility, market integration, grid impacts, and user behaviour.

Within the EV4EU project, the Slovenian demonstrator plays a central role in bridging the gap between conceptual V2X service design and their practical implementation. Building upon the analytical, methodological and implementation foundations established in earlier project deliverables—namely D7.1 [1], D7.2 [2], D4.4 [3], and D4.3 [4]—the Slovenian use cases (UCs) are designed to test V2X solutions under realistic operating conditions. These demonstrations address both grid-oriented and market-oriented perspectives and involve key stakeholders, including Distribution System Operators (DSOs), aggregators, Charging Point Operators (CPOs), and EV users.

The deliverable *D7.3 Slovenian use cases demonstration, monitoring and evaluation report* documents the execution, monitoring, and evaluation of the Slovenian demonstrator activities. The report covers demonstration sites in Krško and Ljubljana, where V2X charging stations (CS), VPP aggregation, and interaction with a local market platform are being demonstrated. In addition, results from the Velenje demonstration site are presented, where a Battery Energy Storage System (BESS) aggregated into a VPP was used to emulate a V2X environment and support the testing and validation of selected flexibility services.

1.1 Scope and objectives

The deliverable D7.3 *Slovenian use cases demonstration, monitoring and evaluation report* entails the operation, monitoring, and evaluation of the Slovenian demonstrator within the EV4EU project. The deliverable covers the demonstration of Slovenian UCs and three demonstration sites defined in *D7.1 Detailed definition and implementation plan of Slovenian Demonstrator* [1] and the collection of data required for the validation of their results. The deliverable D7.3 is the result of the tasks T7.3 – Operation and Monitoring and T7.4 – Analysis of Results.

Additionally, D7.3 provides evaluation of the Slovenian demonstrator related to the performance of VPP energy management algorithms, local market platform operation and demonstration of VPP aggregated V2X EVs participation in selected flexibility services at local (DSO) and system level (TSO).

The purpose of this deliverable is to present the complete implementation, operation, monitoring, and evaluation of the Slovenian V2X demonstrator within the EV4EU project. It covers the full lifecycle of the demonstrator—from initial setup and integration of hardware and software components to the execution and assessment of all four Slovenian use cases (UC9–UC12). The scope includes detailed descriptions of the three demonstration sites in Velenje, Ljubljana and Krško, the deployment of prototype V2X charging infrastructure, and the integration of all assets into GENI's Virtual Power Plant and Elektro Celje's ADMS, FlexIS, and EVT platforms.

The document aims to demonstrate how V2X technologies can be incorporated into real electricity market and grid operation environments, and to provide technical evidence supporting the feasibility of V2X based flexibility services. Its objectives are market and grid operation environments, and to provide technical evidence supporting the feasibility of V2Xbased flexibility services. Its objectives are to:

- validate the performance of V2X assets in market participation, grid services, and aggregator managed operation;
- evaluate end-to-end activation processes triggered by the DSO using real communication interfaces and platforms;
- analyse flexibility potential through both real measurements and simulated EV profiles;
- assess system behaviour through response time measurements, voltage analyses, forecasting models, and KPIs;
- document technical, operational, and interoperability challenges encountered in deploying V2X technologies in real-world conditions.

By fulfilling these objectives, the deliverable provides a comprehensive overview of the Slovenian demonstrator’s capabilities and establishes a solid foundation for large-scale deployment of V2X services, future business models, and regulatory frameworks supporting flexibility in electricity systems.

1.2 Structure

This deliverable begins with an introduction outlining the objectives, structure, and context of deliverable D7.3. Following the introductory section, Section 2 presents the Slovenian demo team, Section 3 provides the grid, flexibility, and eMobility landscape in Slovenia. Section 4 describes the Slovenian demonstrators, including the BESS site in Velenje and the V2X CSs locations in Ljubljana and Krško.

Section 5 presents the Slovenian UCs demonstrations and the development of aggregated representative EV profiles relevant to the BESS demonstration site. Section 6 provides monitoring results and analysis, including BESS testing insights and outcomes, selected Key Performance Indicators (KPI) calculations relevant to Velenje demonstrator, and flexibility-related quantifications for Krško demonstrator. Section 7 presents standalone and EV-based testing of V2X CSs and evaluates executed activations, including the evaluation of the complete communication chain from DSO to EV.

Finally, Section 8 summarises the evaluation of Slovenian use cases and Section 9 concludes the deliverable.

1.3 Relationship with other deliverables

Deliverables *D7.1 Detailed definition and implementation plan of Slovenian Demonstrator* [1] and *D7.2 Detailed definition and implementation plan of Slovenian Demonstrator* [2], served as a basis for the deliverable D7.3, since they provided definition and implementation plan of Slovenian demonstrator and commissioning and start-up report. The operation, monitoring and evaluation of Slovenian demonstrator is presented in mentioned deliverable *D7.3 Slovenian use cases demonstration, monitoring and evaluation report*. Thus, D7.3 is relevant with the corresponding deliverables of the other three demos, i.e., D6.4, D8.3, and D9.3.

The deliverable *D4.4 Impact of mass deployment of V2X in energy markets and services* [3] provided an overview of services for the participation of EVs in the energy market, which are being demonstrated and evaluated in the Slovenian demonstrator as part of the *BUC 1 'Participation of Vehicle to Everything in the electricity markets through a virtual power plant'* and *BUC 6 'Participation of Vehicle to Everything in local Flexibility Markets'* described in *D7.1 Detailed definition and implementation plan of Slovenian Demonstrator* [1]. VPP energy management algorithms that are being tested are presented in deliverable *D4.3 Integration of V2X in Charging Point Operators and Virtual Power Plants Aggregation* [4]. Innovative demand response programs focusing on V2X end-users, fleet operators and aggregators are presented in deliverable *D4.5 Demand Response Programs Design for EVs* [5]. D4.5 methodology related to Slovenia was used to inform testing procedures on the demonstrator.

Further testing and monitoring of the Slovenian demonstrator will also serve as an input for the future deliverable *D7.4 Lessons learned in Slovenian Demonstrator and Services Marketability report*.

2 Slovenian demo team

This chapter contains general information about the partners in the Slovenian demonstrator, while subchapter 2.1 describes the partners roles.

Figure 2: Map of Slovenia with marked partners and their headquarters

Four partners from Slovenia are actively involved in the EV4EU project, with GEN-I leading the Slovenian demonstrator. The partners within Slovenian demo are: Elektro Celje; ABB inženiring; and University of Ljubljana, Faculty of Electrical Engineering.

GEN-I, d.o.o., is a leading Slovenian energy company specializing in the trading and supply of electricity and natural gas, with operations across 20 European markets. It is part of the GEN Group and plays a central role in promoting the green energy transition through innovative services, including solar power solutions, energy efficiency consulting, and digital energy platforms. GEN-I serves households, businesses, and industrial clients, offering tailored energy products and participating actively in regional and international energy exchanges. The company is recognized for its dynamic growth, commitment to sustainability, and leadership in smart energy innovation. The company is actively involved in European research projects such as EV4EU and OneNet, where GEN-I has been recognized as a highly advanced and reliable partner.

Elektro Celje, d.d., is one of Slovenia's five electricity Distribution System Operators (DSOs), responsible for managing and maintaining a network that spans 4,345 km^2—about 22% of the country's territory—and serves over 173,000 customers. Founded in 1913 and headquartered in Celje, the company operates a vast infrastructure including 20 primary and 3,500 secondary transformer substations, with 94% smart meter coverage. Elektro Celje is majority state-owned and actively participates in European R&D projects, contributing to smart grid innovation and sustainable energy development. It is certified under ISO 9001, ISO 14001, and ISO 45001 standards, and is recognized for its commitment to quality, environmental responsibility, and occupational safety.

The third partner in the Slovenian demonstration is the **University of Ljubljana (UL)**, Slovenia's leading higher education institution and one of the top researching institutions. The **Faculty of Electrical Engineering** leads the EV4EU project at the UL. The Faculty of Electrical Engineering at the University of Ljubljana is a high-tech educational and scientific research institution in the field of electrical engineering. Its main activity is the education of the best personnel in the field of electrical engineering. In addition to electronics and electrical engineering, we are developing and building up the fields of information communication technology, automation, robotics, biomedical engineering, mechatronics, renewable energies, multimedia communications… All these fields are permeated with computing and informatics, with state-of-the-art communications, with the use of the World Wide Web and multimedia solutions. The faculty also actively participates in various Horizon 2020 and Horizon Europe projects such as EV4EU and OneNet, dealing with the green transition and smart grids.

ABB Slovenia is the local branch of the global ABB Group, a leading technology company in electrification and automation headquartered in Zürich, Switzerland. Established in Ljubljana in 1992, ABB Slovenia specializes in energy distribution, industrial automation, and infrastructure solutions, offering both product sales and project execution tailored to customer needs. The company supports digitalization and sustainability through advanced technologies like ABB Ability™, and contributes to smart grid development, electric mobility, and flexible energy systems. ABB Slovenia also plays a key role in European innovation projects such as EV4EU, where it provides advanced V2X-capable charging infrastructure and energy management systems.

2.1 Slovenian partners roles

The consortium of Slovenian partners has been assembled with great care, bringing together organizations with complementary expertise and strategic relevance. Each partner was selected based on a clear vision and long-term project goals, ensuring strong synergies and effective collaboration. GEN-I leads the consortium and coordinates the activities, providing strategic direction that aligns the project's development with actual market needs. Furthermore, each partner has a well-defined role and responsibility, which supports efficient execution and reinforces accountability throughout all stages of the project.

GEN-I is the lead partner of the Slovenian demonstrator, responsible for overall coordination, infrastructure deployment, and market integration. Their role includes managing the installation of V2X charging stations at their Krško and Ljubljana offices, operating the VPP, and leading tasks related to marketability and business model validation. As an aggregator and charge point operator (CPO), GEN-I integrates electric vehicles into its VPP, enabling participation in electricity markets, grid services, and flexibility activation GEN-I also contributes to the development of flexibility services and integration with national platforms like EVT. The company also manages the marketability analysis of V2X services and contributes to the development of business models and service catalogues aligned with national and Transmission System Operators (TSO) platforms. GEN-I collaborates closely with partners like Elektro Celje, ABB, and the University of Ljubljana to ensure technical validation, grid integration, and scalability of V2X technologies.

The **University of Ljubljana (UL)**, specifically its **Faculty of Electrical Engineering**, leads the planning and analysis phases of the demonstrator. It plays a role in the integration of V2X technology into smart grids and electricity markets by providing the theoretical background for the development of strategies for planning, scheduling, and operation of the distribution grid, considering V2X and RES. In addition, UL is involved in DR programmes and services for EVs, enabling participation in local and regional markets. UL is responsible for defining KPIs and evaluating the performance of V2X algorithms. Additionally, UL is also developing a tool related to the Vehicle-to-Grid (V2G) flexibility potential estimation for participation in energy markets and analysis of KPIs. Their academic expertise supports the technical depth of the project.

Elektro Celje, the regional DSO, plays a critical role in enabling grid services and flexibility activation. They lead the operation and monitoring phase of the demonstrator and provide the backend infrastructure for real-time transformer monitoring and grid analytics. Elektro Celje also supports the integration of the FlexIS platform with ADMS and EVT, ensuring seamless communication between DSOs and aggregators.

ABB contributes its technological expertise in V2X hardware and energy management systems. Although the project had to adapt due to ABB's discontinuation of CHAdeMO-based chargers, ABB continues to support the deployment of CCS-compatible infrastructure and the evaluation of energy management algorithms. For the purposes of the project, ABB developed prototype advanced charging stations designed to enable efficient and intelligent electric vehicle charging. Their role includes hardware commissioning and participation in all technical work packages.

Within the Slovenian demonstrator GEN-I acts as an aggregator, integrating EVs with its VPP. In addition, GEN-I acts as a CPO and works closely with the DSO Elektro Celje, one of the key players in the Slovenian electricity distribution network, consisting of five DSOs. Elektro Celje facilitates the connection of the ADMS with the Vehicle-to-Grid (V2G) technology. ABB inženiring, part of the global ABB group, supplied prototype V2G chargers for the EV4EU demonstration sites in Slovenia. The fourth partner in the Slovenian demonstration is UL, Slovenia's leading higher education institution and one of the top researching institutions. Within the EV4EU project, the UL plays a role in the integration of V2X technology into smart grids and electricity markets (Figure 3) by providing the theoretical background for the development of strategies for planning, scheduling, and operation of the distribution grid, taking into account V2X and Renewable Energy Resources (RES).

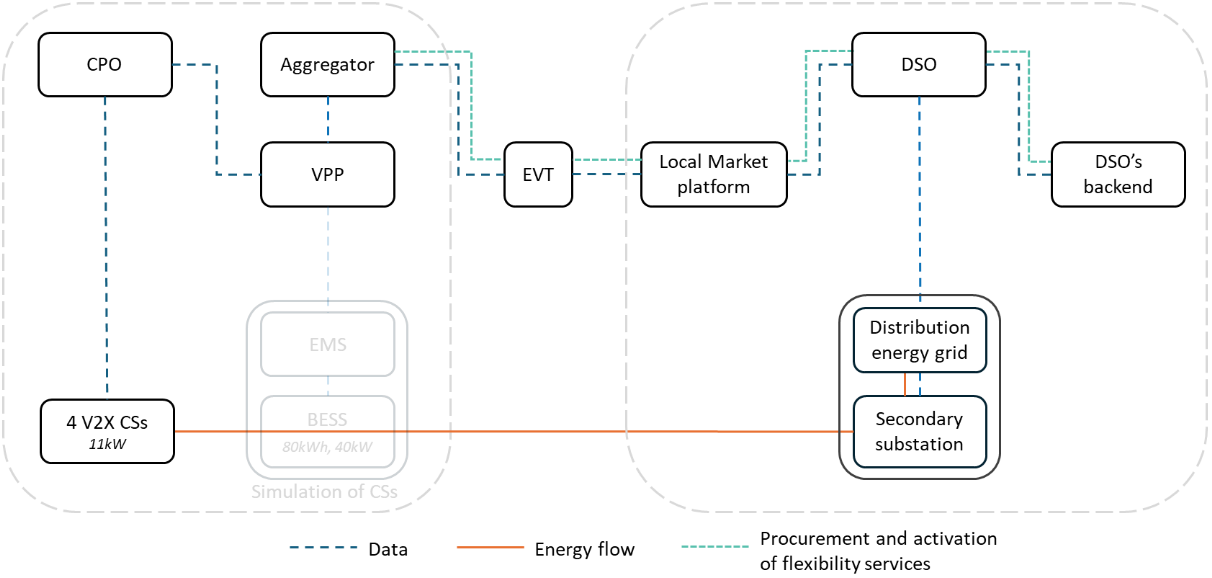

Figure 3: Layout of the Slovenian demonstrator

3 Slovenian grid and e-mobility overview

3.1 Grid and Flexibility Landscape in Slovenia

The Slovenian electricity grid is a compact but highly interconnected power system that combines a dense distribution network with a strategically important transmission backbone. As a small EU member state with strong cross border interconnections and rapidly increasing renewable integration, Slovenia has become a relevant test environment for modern flexibility mechanisms, digitalization frameworks, and advanced V2X applications. The Slovenian transmission network is 2,859 km long, consisting of 400 kV, 220 kV, and 110 kV high voltage lines. [6] According to Open Infrastructure Map (based on OpenStreetMap data), Slovenia has 6,313 km of distribution and transmission power lines recorded, across multiple voltage levels from low-voltage (LV) to high-voltage (HV), including border interconnections and rapidly increasing renewable integration. [7] Slovenia has become a relevant test environment for modern flexibility mechanisms, digitalization frameworks, and advanced V2X applications.

Slovenia's power grid consists of a national transmission network operated by the TSO ELES and a distribution network operated by five DSOs. [8] The transmission grid links major generation assets: hydroelectric, thermal, and solar, with regional load centres and cross border exchange points. They describe Slovenia as a highly monitored system with high real time observability and significant deployment of smart metering and digital infrastructure [7].

Slovenia is actively developing its Local Flexibility Markets (LFMs) as part of a broader transition toward a smarter, more resilient power system. The initiative is being led by the Energy Agency of Slovenia, which is preparing the regulatory and operational framework for DSOs to procure flexibility from distributed resources at the local level. DSOs are therefore positioned to become key stakeholders in enabling and operating these emerging LFMs. [9]

On the national level, the TSO (ELES) has already established a national flexibility market, providing a centralized platform for trading ancillary services and flexibility products that support grid stability. This is complemented by Slovenia's high real time observability of the electricity grid, which enables more efficient monitoring, forecasting, and integration of distributed energy resources (DERs).

The distribution grids, operated by five DSOs, are facing escalating operational challenges: increasing rooftop PV penetration, electrification of transport and heating, voltage deviations, thermal congestion, and demand peaks. To address these pressures, Slovenia is developing LFMs, where DSOs will procure local flexibility services for congestion management, voltage control, and power-quality stabilization.

The Slovenian LFMs are designed to shift DSOs from traditional reinforcement strategies—new cables, new transformers—to flexibility focused operational solutions. Flexibility procurement allows DSOs to defer infrastructure investments, improve operational reliability, and integrate more DERs at lower cost, especially during short duration overloads and voltage excursions. [9]

As mentioned, Slovenia has a comparatively high degree of distribution grid observability. Each EV4EU Slovenian demo sites was equipped with smart meters, phase level voltage and current measurements, and additional IoT devices that transmit real-time data to DSOs and VPP backend systems.

DSOs have begun installing monitoring equipment at MV/LV substations, enabling near real-time situational awareness—an essential pillar for automated flexibility activation, advanced forecasting, and adaptive protection schemes.

Renewable energy already plays a visible role in the Slovenian electricity mix: RES share reached 41.89% in 2023 (SiStat), reflecting the country's ongoing commitment to decarbonization and sustainable system development.

However, the intermittency of solar and hydro inflows introduces new system balancing challenges:

- Mid-day PV surpluses require down-regulation or storage.
- Winter hydro variability limits renewable output during peak heating load.
- Reverse power flows in distribution networks are becoming more frequent.

These factors amplify the need for distributed flexibility, particularly from flexible loads, energy storage systems, and emerging V2X technologies.

Slovenia experiences moderate annual consumption, but weather extremes can cause sharp peaks. A notable event occurred during the cold wave of January 2025, when transmission grid demand reached a record 2,299.70 MW, driven by widespread use of heat pumps and electric heating. This exceeded previous records from 2018 and illustrates the growing influence of electrification on peak loads. [10]

3.2 eMobility in Slovenia

Slovenia's eMobility sector is developing steadily, though it still trails behind the EU average in EVs uptake. In 2023, EVs accounted for 4.04% of the national vehicle fleet (SiStat), confirming a gradual but meaningful shift towards cleaner transportation. This growth is occurring in parallel with broader power system changes, including the rising share of renewable electricity (41.89% in 2023) and the planned introduction of LFMs.

While EV share is increasing, the uptake remains slower than expected, as highlighted among the challenges in the EV4EU Slovenian demonstrator deliverables. Several factors influence this dynamic: consumer hesitancy, relatively high upfront costs, charging convenience, and varying levels of municipal readiness.

Despite this, Slovenia is aligned with EU climate expectations: projections indicate that by 2030, EVs should represent 12% of the entire national vehicle fleet and 55% of all new registrations [11].

The development of eMobility is strongly supported through national legislation, especially the Slovenian Electricity Supply Act (ZOEE) [12], which transposes EU-level requirements and enables the integration of DERs, including EVs and V2X technologies. Slovenia also benefits from significant EU funding streams, such as the Modernisation Fund and Cohesion Fund, which support the deployment of charging infrastructure and municipal and regional sustainable urban mobility planning.

Slovenia has made considerable progress in expanding its public charging network. More than 200 public charging points were already interconnected under the national e-mobility card system, facilitating easier access for users and businesses. Continued investment is planned through 2026, supported by public grants and co-financed infrastructure programs.

The charging ecosystem is also evolving in terms of user behaviour and regulation. Efficient use of public charging infrastructure remains essential to ensure availability and fair cost distribution among EV users.

3.3 Role of eMobility in Flexibility Markets

EVs are increasingly recognised as flexibility assets within the electricity system. The Slovenian EV4EU demonstrator, is testing V2X participation in energy markets, with a focus on integrating EV flexibility into VPPs and future LFMs. Key objectives include upgrading VPP and local market platform functionalities, while implementing selected flexibility services with minimal user involvement. This positions EVs not only as clean mobility solutions but also as active participants that can support grid stability, especially as renewable energy production increases and system operators require more distributed, responsive resources.

Looking forward, eMobility will play an increasingly central role in achieving national climate energy targets, particularly the reduction of non-ETS transport emissions, where transport accounts for roughly 50% of the national non ETS share [12]. Accelerating EV adoption is therefore essential not only for decarbonising transport but also for delivering flexibility to Slovenia’s evolving power system.

4 Slovenian demonstrators

The purpose of the Slovenian demonstrator within the Horizon Europe project EV4EU – Electric Vehicles Management for carbon neutrality in Europe is to validate advanced V2X strategies that support the large-scale integration of EVs into the energy system and markets. It focuses on four key use cases: V2X management by a VPP, participation of V2X in electricity markets and grid services, and activation of V2X services by DSOs, both manually and automatically. The demonstrator includes the deployment of bidirectional V2X chargers at GEN-I's office buildings, and aims to assess flexibility potential, support grid balancing, and enable green charging and smart energy services. Through collaboration with partners GEN-I, University of Ljubljana, Elektro Celje, and ABB, the Slovenian demo contributes to the development of scalable business models and technical solutions for carbon-neutral mobility.

Section 4 contains general information about the Slovenian demonstrators and their locations. Subsections 4.2-4.4 describes the demonstration sites with its equipment and architecture.

The purpose of the Slovenian demonstrator is to demonstrate and test the following UCs:

- Use-Case 9 (UC9): V2X management by a VPP. This UC aims to test the algorithms developed in task T4.4 and document in D4.4 [3], considering the aggregation of V2X flexibilities with other resources (generation, storage, etc.), taking into account the participation in multiple services and markets.
- Use-Case 10 (UC10): Participation of V2X in electricity markets. Demonstrate and evaluate the participation of V2X, aggregated with other resources, in markets at the national level such as energy market, Frequency Containment Reserve (FCR), and Fast Frequency Response (FFR) ancillary services markets (T4.4). This UC intends to understand the users' advantages of V2X participation in these markets (T4.5) and the impact that mass participation of V2X can have in these markets. The models are integrated into real tools, but participation in real markets is dependent on the market pre-qualification process that can take a long time. If participation in selected markets is not possible, the services will be validated using market emulation tools.
- Use-Case 11 (UC11): Participation of V2X in Grid Services. Demonstrate and evaluate the participation of V2X, aggregated with other resources, in markets and services at the local level (T4.4 and T4.5). In that case, the demonstration focuses on the contribution of V2X to solve problems in distribution systems, such as congestion management and voltage control. The goal of this UC is to evaluate the advantages for the users and DSO.
- Use-Case 12 (UC12): Activation of V2X services by DSOs. Before the market clearing, the DSO should be able to activate the services to be provided by V2X (T4.2). The activation is made in the Advanced Distribution Management System (ADMS) of the DSO in real time. In the first stage, integration and communication verification between VPPs and ADMS is performed, which is crucial for services activation. In this stage, V2X assets must be modelled appropriately in ADMS so that advanced functions can use V2X data. In the second stage, activation is triggered by the VPP operator (decision on the side of the aggregator). This aims to evaluate the activation of VPPs for the ADMS system, which can model EVs in different ways. In a third stage, the activation is triggered by the ADMS operator (decision on the side of DSO), considering the results of the market and the operation conditions of the distribution system [1].

The Slovenian demonstrator within the EV4EU project plays a strategic role in accelerating the green transformation of the energy and mobility sectors. By deploying bidirectional V2X charging infrastructure and integrating EVs into VPPs, the demonstrator enables dynamic energy exchange between vehicles and the grid, which enhances system flexibility and supports grid stability without requiring costly infrastructure upgrades. This approach facilitates the seamless integration of renewable energy sources (RES) into the distribution network, contributing to reduced greenhouse gas emissions and aligning with the EU's climate neutrality targets for 2050. Additionally, the demonstrator fosters innovation and competitiveness in the Slovenian energy sector by developing scalable business models and creating high-value jobs, thereby supporting both environmental and economic sustainability. The demonstrator contributes to the development of market-attractive solutions that support transport decarbonization, increase grid flexibility, and enable greater integration of renewable energy sources, in line with national and European climate goals.

4.1 Timeline of Slovenian demonstrators

In the EV4EU project proposal, Slovenian partners identified advanced CSs using the CHAdeMO protocol as the most suitable technology for demonstration purposes. At the time of the proposal preparation, CHAdeMO was considered the most appropriate and widely adopted solution on the market that enabled bidirectional charging (V2X). However, following the submission, the European Commission introduced new guidelines favouring the ISO 15118 standard for V2X communication. This shift influenced the further development of the project and required technological adjustments to align with the updated regulatory and interoperability expectations.

To support the demonstration activities, ABB developed prototype V2X-capable charging stations that comply with the updated communication protocols and standards introduced by the European Commission. These prototypes are equipped with advanced power electronics and control systems that enable bidirectional energy flow, allowing both charging and discharging of electric vehicles. They support interoperability with multiple protocols, including ISO 15118 and the latest versions of OCPP, ensuring compatibility with evolving grid and vehicle requirements. Due to the complexity of integrating these functionalities, such as secure communication, dynamic load management, and grid responsive behaviour, the development process required significant time and technical effort.

As part of the project, we aimed to ensure excellent results. During the development of the prototype charging stations, we simulated V2X behaviour and vehicle interaction using various advanced models and a BESS. Through these simulations and analyses, we defined the capacities that vehicles can represent within the V2X framework. Overview of Slovenian demonstrators' sites and their timeline are presented in Figure 4.

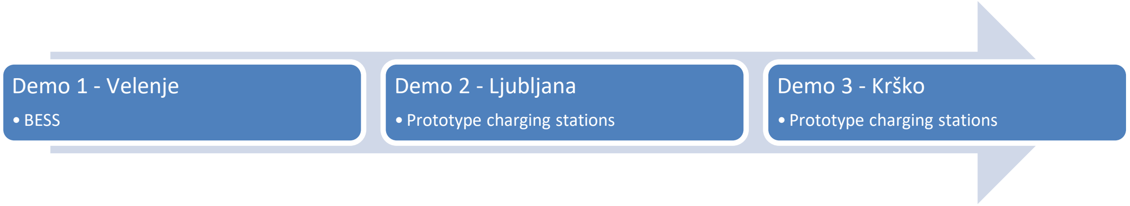

Figure 4: Timeline of the Slovenian Demonstrators' sites

The Velenje demonstrator, as an intermediate step before the delivery of the newly developed prototype V2X CSs, was successfully finished and very useful for the simulations. The V2X CSs have been delivered beginning of 2025 by ABB, additionally the CSs had been certified. All together 4 CSs have been installed in Ljubljana. V2X CSs in Ljubljana were connected to the grid, which enables preliminary testing, while integration into a VPP was performed in the fourth quarter of 2025. Additionally, testing of VPP aggregation was performed in Ljubljana. Preliminary testing of V2X CSs and a large set of relevant EVs was performed in the second quarter of 2025. The first CS, which had already been tested, failed during testing and was then replaced with other one. Four CSs were installed in Krško and are connected to the grid. The final update of CSs in Krško and connection of the V2X CSs to the VPP was established in the fourth quarter of 2025. The local market platform was developed in the first quarter of 2025, which was also preliminary tested in the scope of the Velenje demonstrator. Connection of energy meters with “push option” at the V2X CSs distribution box in Krško with GEN-I and Elektro Celje IT infrastructure was established and tested in the fourth quarter of 2025. This enables the establishment of the whole communication chain (connection between VPP and local market platform). The full operation of the Krško demonstrator was ensured in the fourth quarter of 2025.

Several EVs had been tested. Additionally, to fulfil the requests, vehicles have to be V2X ready and support the right standards of energy transfer and communication. Namely, CSs produced by ABB in Europe no longer support CHAdeMO standard as first planed but transferred to CCS2 standard. In addition, there are currently only a few EVs supporting CCS2 standard on the European car market, limiting the options for the demonstrator.

4.2 Demonstration site 1 – Battery energy storage system

Location:

Velenje

Address:

Vodnikova cesta 2, 3320 Velenje

Figure 5: Location of the Demo 1 in Velenje, Slovenia

Velenje is a modern Slovenian town known for its rich industrial heritage, beautiful surrounding nature, and the scenic Velenje Lake. The town offers a blend of cultural attractions, outdoor activities, and a strong community spirit, making it a vibrant place to live and visit. Today, it stands as a symbol of successful transformation, balancing its past with a forward-looking vision.

Velenje is part of the electricity distribution network managed by Elektro Celje, which ensures a reliable power supply and infrastructure across the region. This connection supports both residential and industrial energy needs, contributing to the town’s development and sustainability efforts. Elektro Celje plays a key role in maintaining energy efficiency and implementing modern technologies that align with Velenje’ s vision of becoming a smart and environmentally conscious community.

The Velenje site plays a key role in the Slovenian EV4EU demonstrator, since it was used to simulate V2X environment, estimate the impact of it and simulate participation of EVs in flexibility services. It includes BESS that is integrated in the broader VPP architecture and Elektro Celje's backend systems, enabling real-time monitoring, activation forecasting, and secure communication between stakeholders. By developing the aggregated representative EV profiles, BESS acted in a similar way as V2X CSs and consequently EVs.

The Velenje setup supports the validation of V2X UCs such as grid service activation, market participation, and green charging, while also contributing to the harmonization of flexibility products with TSO standards. This simulation-based approach allows for testing and performance evaluation without requiring direct interaction with EV users, making Velenje a strategic location for advancing scalable and interoperable energy solutions.

The Slovenian BESS demonstration site is located in the school district of the town Velenje. The BESS, named AMBER, is an LFP 80 kWh (409.6 V, 200 Ah) battery system equipped with a 40 kVA converter and a 40 kVA disconnector with a built-in HMI panel, owned by Elektro Celje. It is connected to the LV side of the secondary substation at TP Gimnazija Velenje. A 630 kVA transformer at this substation supplies 17 business customers with rated power 663 kW and 4 producers who have connected small solar power plants with a combined power of 198 kWp. All connected users are equipped with remotely readable smart electricity meters that record data in 15-minute intervals (A+, A-, R+, R-, V, I)[2]. The location is presented on the Figure 6.

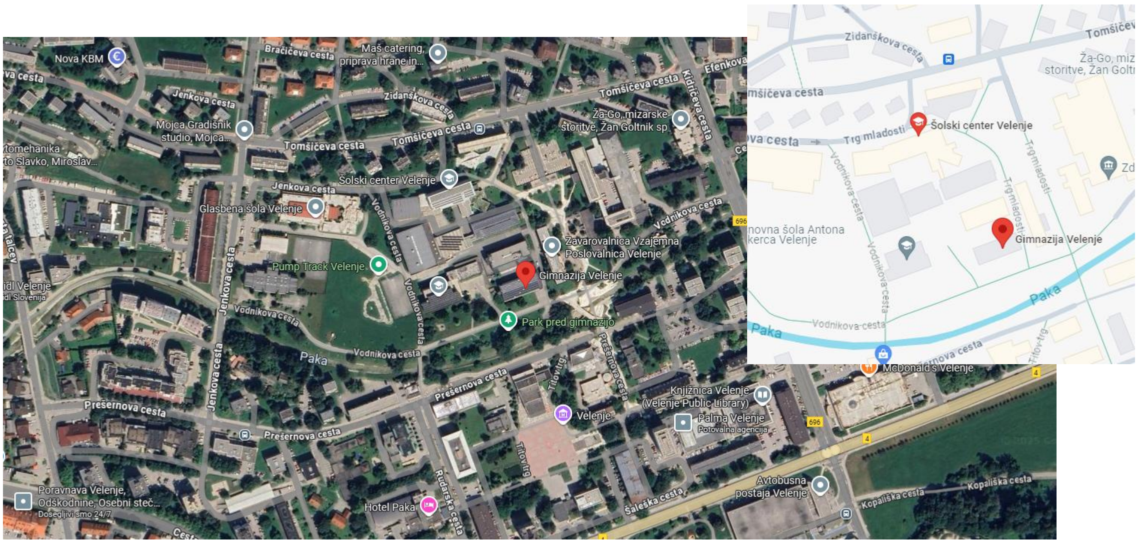

Figure 6: Accurate location of the Demo 1 in Velenje

To ensure coordinated operation within a broader flexibility framework, the BESS was integrated into Gen-I's VPP. The VPP has been in operation for nearly ten years and aggregates more than 200 assets across several European countries. Through this aggregation platform, flexibility resources participate in balancing markets and provide balancing services to multiple TSOs.

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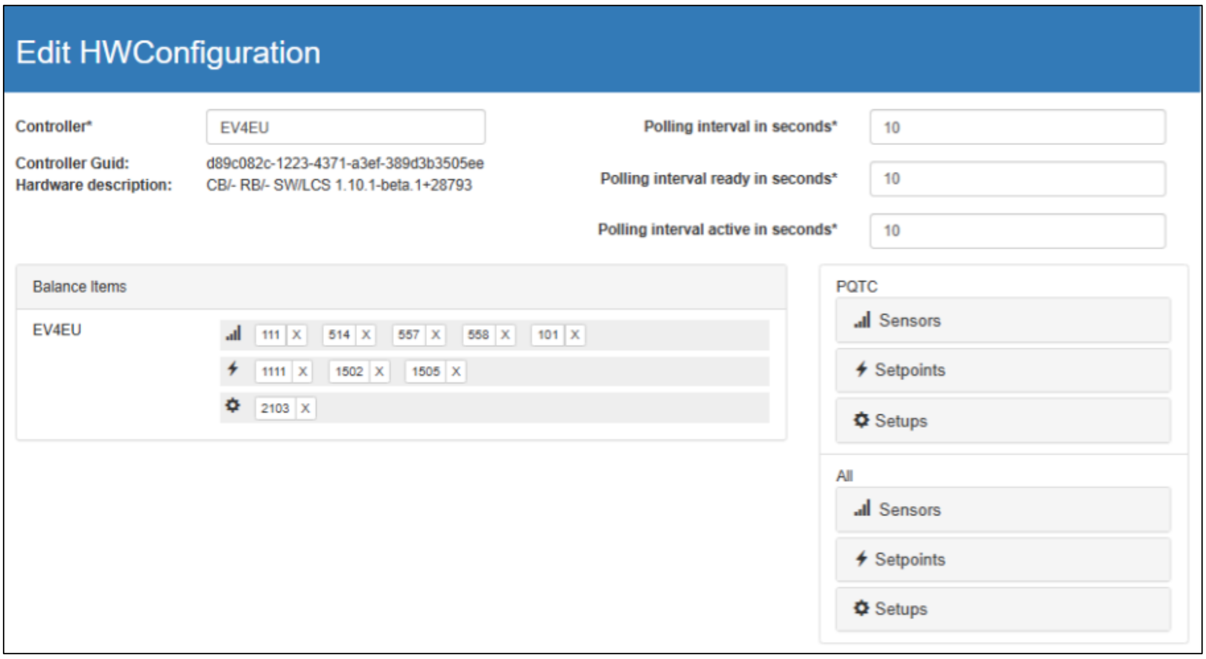
[2] Register data (Real power +/- (A+ and A-); Reactive Power +/- (R+ and R-); idle current (V); and current flow (I) in Link)

For the integration of this asset, a hardware controller called Reduxi was installed at the secondary substation where the BESS is located. Communication between the controller and the VPP was established using the MQTT protocol. In this architecture, both the BESS and the VPP operate as MQTT publishers and subscribers connected to an MQTT broker, as shown in the Figure 7.

Figure 7: Concept of MQTT communication protocol

The BESS publishes measurement data, including operating power, state of charge (SoC), remaining capacity, availabilities, which are continuously received and processed by the VPP. In the opposite direction, the VPP sends control setpoints to the controller, which forwards them to the battery management system (BMS). This configuration enabled near real-time monitoring and control with high temporal resolution. The Figure 8 shows the setup of sensors and setpoints in the VPP.



Edit HWConfiguration

Controller*: EV4EU
Controller Guid: d89c082c-1223-4371-a3ef-389d3b3505ee
Hardware description: CB/- RB/- SW/LCS 1.10.1-beta.1+28793

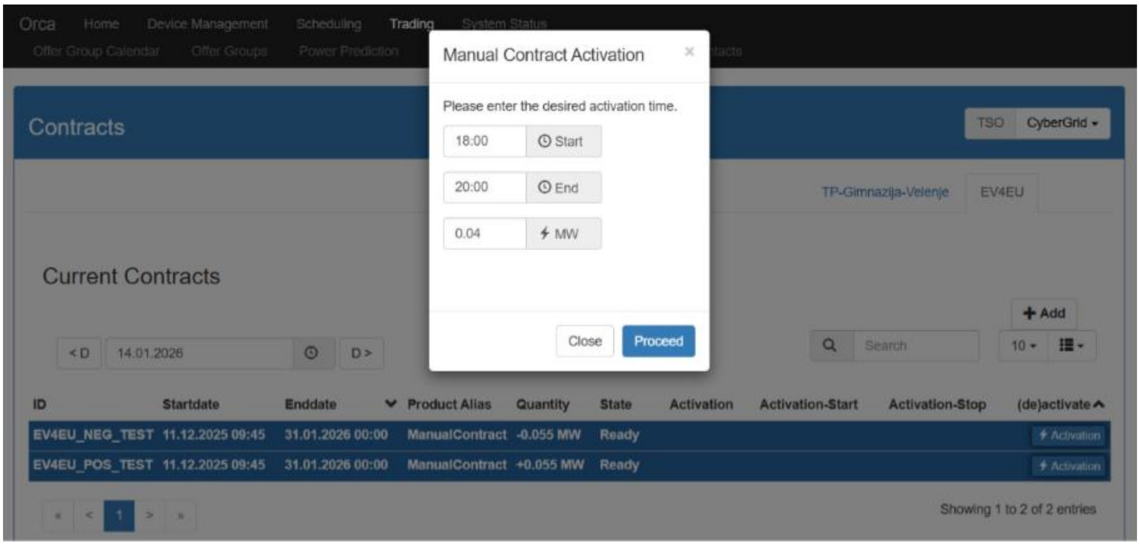
Polling interval in seconds*: 10
Polling interval ready in seconds*: 10
Polling interval active in seconds*: 10

Balance Items

EV4EU
111 X 514 X 557 X 558 X 101 X
1111 X 1502 X 1505 X
2103 X

Figure 8: Setup of communication in VPP

During activation events, flexibility is triggered either manually, as shown in the Figure 9, or automatically through an API-based contract activation mechanism. Once activated, the VPP sends setpoints to the BESS in accordance with the defined scenario. Measurements such as requested power, delivered power, available flexibility range, SoC, and capacity are monitored continuously, while discrete signals such as availability and activation status are also tracked.



Manual Contract Activation

Please enter the desired activation time.

18:00 Start
20:00 End
0.04 MW

ID	Startdate	Enddate	Product Alias	Quantity	State	Activation	Activation-Start	Activation-Stop	(de)activate
EV4EU_NEG_TEST	11.12.2025 09:45	31.01.2026 00:00	ManualContract	-0.055 MW	Ready				Activation
EV4EU_POS_TEST	11.12.2025 09:45	31.01.2026 00:00	ManualContract	+0.055 MW	Ready				Activation

Showing 1 to 2 of 2 entries

Figure 9: Manual import of contract activation

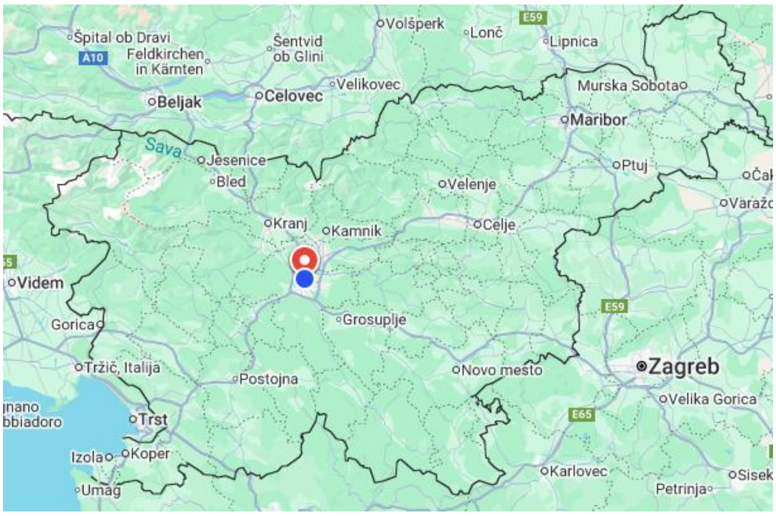
Figure 10 shows the dashboard for monitoring the activation status, where the start and end times are visible, as well as the activated quantity in MW. The activated contract is coloured in red.

ID	Startdate	Enddate	Product Alias	Quantity	State	Activation	Activation-Start	Activation-Stop	(de)activate
EV4EU_NEG_TEST	11.12.2025 09:45	31.01.2026 00:00	ManualContract	-0.055 MW	Ready				Activation
EV4EU_POS_TEST	11.12.2025 09:45	31.01.2026 00:00	ManualContract	+0.055 MW	Running	+0.020 MW	16.12.2025 11:30	16.12.2025 11:45	Change

Showing 1 to 2 of 2 entries

Figure 10: Contract activation status monitoring

4.3 Demonstration site 2 – V2X charging stations – Ljubljana



Location:

Ljubljana

Address:

Dunajska cesta 119, 1000 Ljubljana

Figure 11: Location of the Demo 2 in Ljubljana, Slovenia

Ljubljana, the capital of Slovenia, is a vibrant and charming city that blends historical elegance with modern innovation. Nestled between the Alps and the Adriatic Sea, it serves as the country's political, cultural, and economic center. The city is known for its picturesque old town, where Baroque and Art Nouveau architecture line the cobbled streets, and the iconic Ljubljana Castle overlooks the city from a hilltop. The Ljubljanica River, which flows through the heart of the city, is flanked by lively cafés, bridges, and green spaces, contributing to Ljubljana's reputation as one of Europe's greenest capitals.

Ljubljana is also a hub for education and research, home to the University of Ljubljana, the largest and oldest university in Slovenia. The city has a strong commitment to sustainability, with an efficient public transport system, pedestrian-friendly zones, and numerous environmental initiatives. Its dynamic cultural scene includes museums, galleries, theatres, and festivals that reflect both Slovenian heritage and global influences.

The city is part of the electricity distribution network managed by Elektro Ljubljana, which operates the largest energy distribution system in Slovenia, covering over 6,166 km^2—about 30% of the country. Elektro Ljubljana ensures a reliable and high-quality electricity supply to Ljubljana and its surrounding areas, supporting both residential and industrial energy needs. Its infrastructure and services are essential for maintaining energy efficiency and enabling the city's continued growth as a smart and environmentally conscious urban hub.

The parking facility at Dunajska cesta 119 is located beneath the office building currently rented by GEN-I, one of Slovenia's leading energy companies. The building is situated in the Bežigrad district, a well-connected and prominent business area along one of Ljubljana's main arterial roads.

This underground garage serves as a private parking area for GEN-I employees, business partners, and registered visitors. It is not open to the general public and is managed internally by GEN-I's facility services team. This location is also used as a demonstration site for innovative energy solutions in Slovenia. As part of GEN-I's broader commitment to sustainability and smart energy systems, the garage and surrounding infrastructure support pilot projects and demonstrations related to:

- BESSs,
- Electric vehicle (EV) integration and
- Flexible energy services and grid balancing.

The site plays a role in showcasing how urban infrastructure can support the energy transition, making it not just a functional parking space but also a living lab for energy innovation.

The office building in Ljubljana, serves as a key demonstration site for testing advanced V2X (Vehicle-to-Everything) charging prototypes developed by ABB for the purposes of a strategic innovation project.

This location provides GEN-I's experts in V2X technology and charging infrastructure with a controlled environment to analyse charging and discharging behaviour across different types of EVs. The underground garage at this site is already equipped with 5 CSs, monitoring by GEN-I, which form the foundation for ongoing testing and data collection.

The installation of these prototypes required careful planning and execution, especially due to their technological sophistication. All legal and regulatory requirements were strictly followed, with particular emphasis on fire safety and electrical standards. The chargers were precisely positioned to ensure safe operation, optimal cooling, and integration with the building's infrastructure, enabling GEN-I to lead the way in smart energy solutions and grid flexibility.

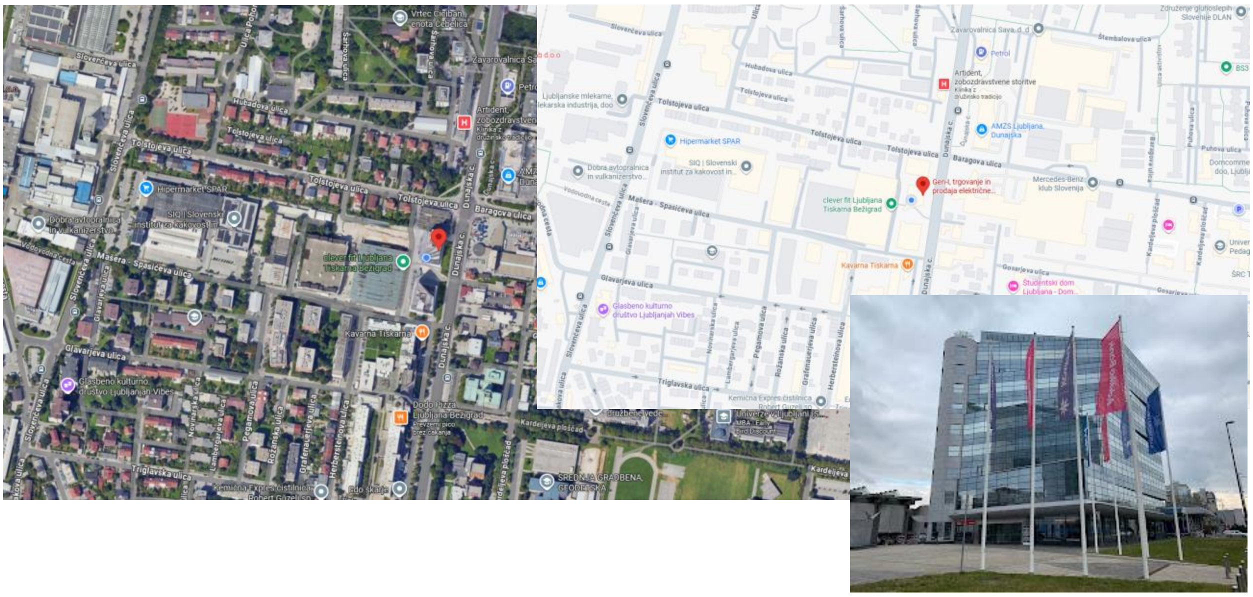
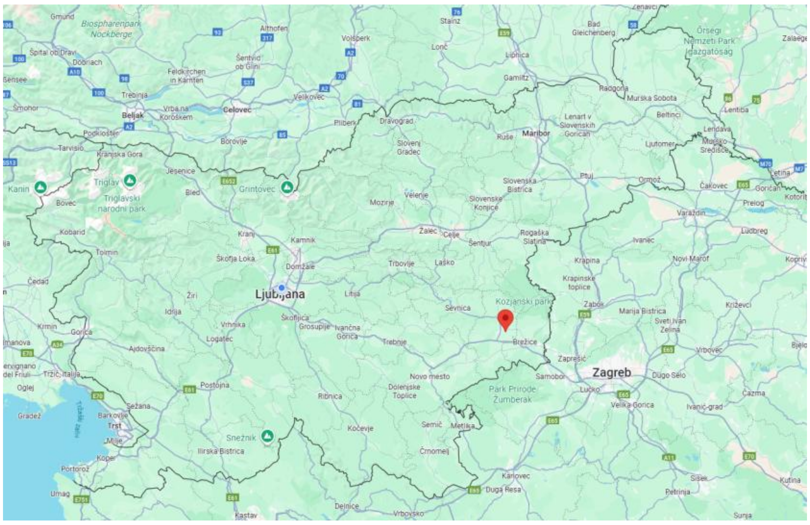


Figure 12: Accurate location of Demo 2 in Ljubljana

At this location, GEN-I is actively conducting research and development focused on understanding the impact of EV charging on the broader electricity grid. The insights gained are used to develop next-generation smart energy solutions that will help ensure grid stability, even as the number of CSs continues to grow.

By combining innovative V2X technology with real time data analysis, partners are contributing to the development of scalable infrastructure that supports both electrification of transport and resilience of the energy system.

4.4 Demonstration site 3 – V2X charging stations – Krško



Location:

Krško

Address:

Vrbina 17, 8270 Krško

Figure 13: Location of the Demo 3 in Krško, Slovenia

Krško is a town located in southeaster Slovenia, along the banks of the Sava River. It lies in the heart of the Lower Sava Valley, a region known for its fertile land, vineyards, and growing industrial sector. Krško has a rich historical background, with archaeological finds dating back to Roman times, and it continues to be an important cultural and economic centre in the region.

One of the town's most prominent features is the Krško Nuclear Power Plant (NEK), situated just a few kilometres from the town centre. Operational since 1983, NEK is the only nuclear power plant in Slovenia and a cornerstone of the country's energy infrastructure. It is jointly owned by Slovenia and Croatia, and supplies electricity to both countries, covering a significant portion of their energy needs. The plant is known for its high safety standards and plays a key role in Slovenia's transition to low-carbon energy sources.

In Slovenia, the practical demonstration will take place also at the office building of GEN-I (Figure 14) in Krško. A town of 7.200 inhabitants, which is the centre and the largest town in both the municipality (26.000) and the statistical region (76.000). In the Posavsko statistical region, to which Krško belongs, 606 BEVs and 1513 hybrids were registered at the end of 2024 [13]. Due to its proximity to the highway and the large number of commuters, the test site also has potential beyond the project. In the future, it could offer its services to a wider range of users after it has been tested and updated in the framework of this project to achieve an optimal outcome for all stakeholders, both the VPP and the EV users or owners.

Krško is also part of the electricity distribution network managed by Elektro Celje, one of Slovenia's major electricity providers. This connection ensures a stable and efficient power supply to the town and surrounding areas, supporting both residential and industrial energy needs. Elektro Celje's infrastructure and services are essential for maintaining energy reliability and enabling future-oriented development in the region.

Figure 14: Accurate location of the Demo 3 in Krško

The office building, where demonstration will take place, has Photovoltaic (PV) systems on the roof of the building with a rated power of 100 kWp. This facility is part of the VPP portfolio operated by GEN-I. As part of the broader infrastructure upgrade, solar panels have been installed on the building where the V2X charging infrastructure is located. This addition opens up new possibilities for future energy optimization, particularly in terms of utilizing surplus solar production for EV charging.

At the Krško demonstration site, 4 newly installed prototype V2X CSs enable partners to conduct in-depth analysis of the impact of vehicle charging and discharging on the electricity grid. Additionally, local market platform and near real time data from the secondary substation will enable Elektro Celje, the DSO, to define when the procurement and activation of flexibility services through platform will be needed. This location plays a crucial role in evaluating how EVs, through their integrated battery systems, can contribute to grid flexibility and energy balancing.

The chargers and local market platform will also allow experts to study the flexibility potential that EVs represent when connected to smart infrastructure. By simulating various charging and discharging scenarios, the team will assess how EVs can act as mobile energy storage units, helping to stabilize the grid during peak demand or surplus generation periods.

In Krško, the full demonstrator with VPP and local market platform was tested for the procurement and activation of flexibility from V2X EVs and consequently testing of BUCs presented in D7.1 [1]. Therefore, all objectives related to the Slovenian demonstrator were tested in Krško.

This research is essential for developing advanced control strategies and scalable solutions that support the integration of a larger number of CSs without compromising grid stability.

4.5 Voltage analysis and day-ahead forecasting at TP Inkubator Vrbina

This section presents the voltage condition analysis and day-ahead overvoltage forecasting methodology developed for the TP Inkubator Vrbina secondary substation pilot site. TP Inkubator Vrbina is TP where Demo in Krško is connected. The work addresses the challenge of voltage deviations in low-voltage distribution networks with high penetration of distributed energy re-sources, particularly photovoltaic systems and BESS. The methodology contributes to demonstrator KPIs related to voltage quality improvement, grid constraint mitigation, and effective activation of flexibility services, by enabling the DSO to anticipate overvoltage conditions and proactively prepare V2X and storage resources for corrective control actions.

Objectives

The primary goal of this analysis is to assess voltage conditions at the secondary substation and identify potential deviations from nominal operating ranges. Overvoltage events in distribution networks can originate from different causes and may require different mitigation actions depending on the underlying physical mechanisms. By characterising these events and classifying them into distinct operating regimes, the analysis provides a foundation for targeted control strategies.

A key component of this work is the development of a day-ahead forecasting model capable of predicting overvoltage event types. Such forecasts enable proactive system preparation, allowing V2X operators and BESS to be configured appropriately before voltage issues materialise. The envisioned pilot workflow follows a three-stage process: the distribution system operator signals the expected system state for the following day based on the forecast, the V2X operator prepares the system accordingly, and rule-based control actions are applied based on actual measurements during operation.

Pilot site description

TP Inkubator Vrbina is a low-voltage transformer station located in west part of Slovenia, near Krško. The network segment serves a mix of commercial and light industrial loads, including research facilities and office buildings. Several prosumers operate photovoltaic installations that feed excess generation back into the grid, and a battery storage system provides flexibility for local energy management.

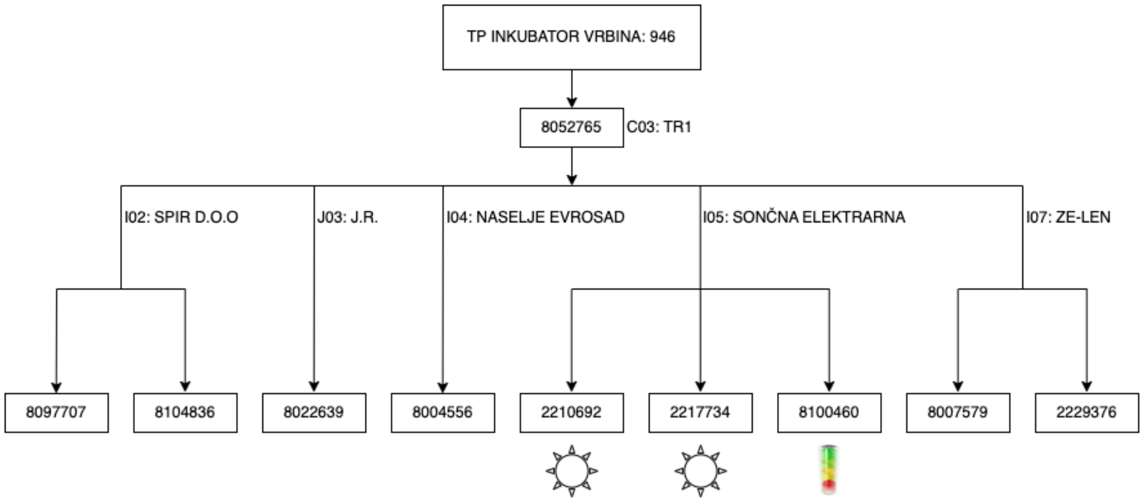


Figure 15: Network topology of TP Inkubator Vrbina showing the transformer and connected feeders with prosumer installations

The network configuration, illustrated in Figure 15, shows the transformer station feeding multiple low-voltage feeders. The presence of distributed generation, particularly photovoltaics, creates bidirectional power flows that can lead to voltage rise during periods of high generation and low local consumption.

4.5.1 Data and overvoltage event definitor

Available measurements

The analysis utilises 15-minute interval measurements recorded at the secondary substation over a period of approximately two years. The measurement set comprises active power flows captured as A+ (import from the medium-voltage network) and A- (export to the medium-voltage network), reactive power measurements recorded as R+ and R-, and three-phase voltage measurements VL1, VL2, and VL3. The complete dataset contains 68,160 measurement entries spanning from 2023-12-31 to 2025-12-10, providing a comprehensive view of seasonal and daily patterns in the network's electrical behaviour.

Overvoltage event definition

Overvoltage events are defined according to the EN 50160 voltage quality standard[3], which specifies that supply voltage in low-voltage networks should remain within ±10% of the nominal 230 V under normal operating conditions. For this analysis, a more conservative threshold of 5% above nominal voltage (241.5 V) was adopted to identify periods where voltage regulation may benefit from active intervention. Each 15-minute interval where any phase voltage exceeds this threshold is classified as an overvoltage event.

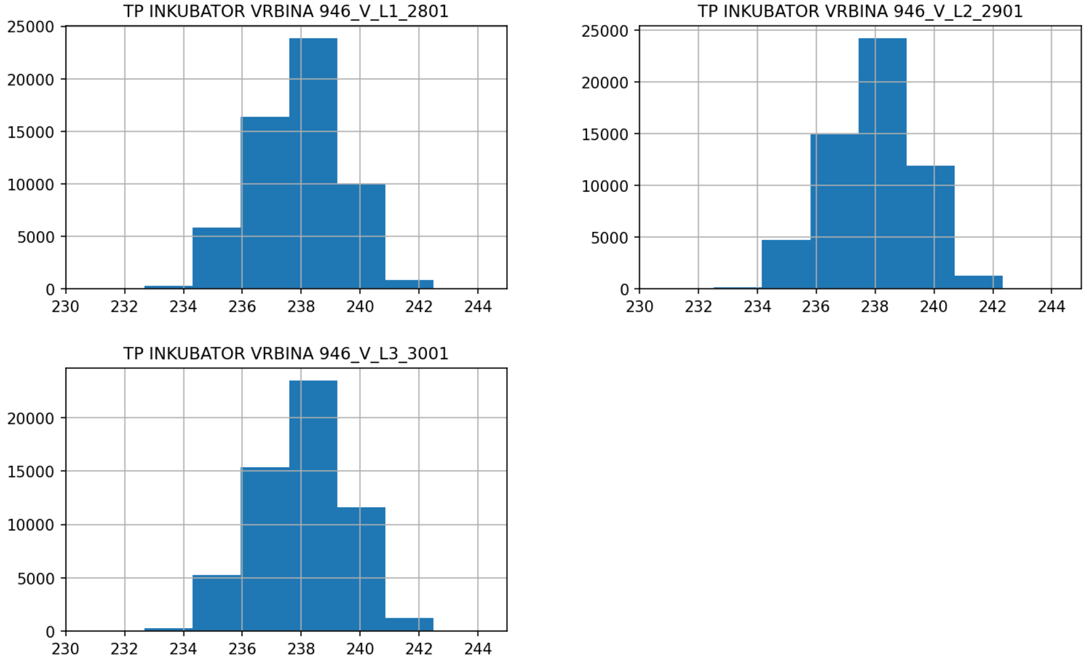


Figure 16: Voltage distribution histogram for phase L1 at TP Inkubator Vrbina, showing the measurement range concentrated between 234 V and 242 V with the majority of readings near 238 V

The voltage distribution shown in Figure 16 reveals that the network operates with a slight positive bias above the nominal 230 V, with median values around 238 V across all phases. This elevated baseline is typical of distribution networks designed to compensate for voltage drops along feeders, but it also means that conditions favouring voltage rise can push measurements above acceptable limits.

Event statistics

Analysis of the voltage measurements identified 409 individual 15-minute intervals exhibiting overvoltage conditions, distributed across 42 distinct days within the 711-day observation period. This corresponds to approximately 6% of days experiencing at least one overvoltage event. The relatively low frequency of overvoltage (OV) days, combined with their significant operational impact, makes accurate forecasting both challenging and valuable.

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[3] CENELEC, *EN 50160:2022/A1:2025 — Voltage characteristics of electricity supplied by public electricity networks*, European Committee for Electrotechnical Standardization, 2025.

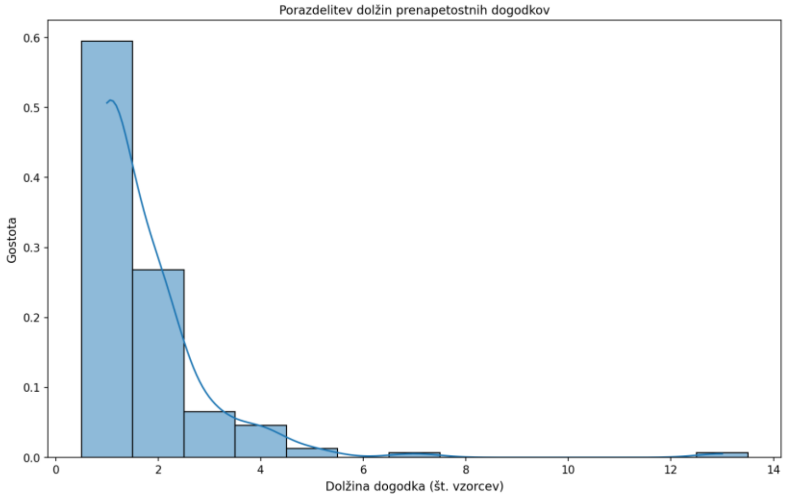


Figure 17: Distribution of overvoltage event durations measured in number of consecutive 15-minute intervals, showing that most events are short-lived, but some persist for extended periods

Examination of event durations reveals that the majority of overvoltage episodes are short-lived. Most events persist for only one or two consecutive 15-minute intervals, corresponding to durations of 15-30 minutes. However, some events extend over multiple hours, with the longest observed sequence spanning 13 consecutive intervals (over 3 hours). This distribution, illustrated in Figure 17, suggests that while many voltage excursions are transient, longer-duration events may require sustained intervention from storage or flexible loads.

Phase asymmetry analysis

An important characteristic of the overvoltage events at TP Inkubator Vrbina is the high degree of symmetry observed across the three phases. Phase asymmetry, measured as the difference between the highest and lowest phase voltages at each measurement interval, provides insight into whether voltage issues are system-wide phenomena or localised to individual phases.

Statistical analysis of the inter-phase voltage difference reveals remarkably symmetric operation. The mean difference between the maximum and minimum phase voltages is only 0.41 V, with a standard deviation of 0.24 V. Even under the most extreme conditions observed in the dataset, the maximum inter-phase difference reached only 1.67 V. These thresholds are consistent with the voltage unbalance limits defined in EN 50160 (≤ 2 %, less than 4.6 V) when expressed in absolute voltage values.

The correlation analysis between phase voltages further confirms this symmetric behaviour. Pearson correlation coefficients between all phase pairs exceed 0.98, with VL1-VL2 correlation at 0.993, VL1-VL3 at 0.993, and VL2-VL3 at 0.986. These near-perfect correlations indicate that the three phases move together almost in lockstep, rising and falling in response to common system-level factors rather than phase-specific disturbances.

This high degree of phase symmetry has important implications for the analysis and control strategy. It indicates that overvoltage events at TP Inkubator Vrbina are predominantly caused by system-wide factors such as overall power balance at the transformer rather than single-phase issues like unbalanced loads or single-phase PV inverters. Consequently, control actions that affect the aggregate power flow at the transformer station, such as coordinated battery charging or V2G activation across all phases, are likely to be effective in addressing the voltage deviations.

Given the low level of voltage asymmetry, the subsequent analysis is based on the mean voltage across all three phases, denoted as U_{mean}.

4.5.2 Overvoltage regime classification

P-Q space analysis

Examination of overvoltage events in the two-dimensional space defined by active power (P) and reactive power (Q) revealed that these events do not occur uniformly across all operating conditions. Instead, they cluster into distinct regions that suggest different underlying physical mechanisms driving the voltage elevation.

Figure 18 shows the relationship between active power, reactive power, and voltage at the secondary substation. The left panel displays all measurements coloured by mean voltage, revealing that higher voltages tend to occur in specific regions of the P-Q space. The red points marking overvoltage samples clearly concentrate in two distinct areas, suggesting at least two different operating regimes where voltage problems occur.

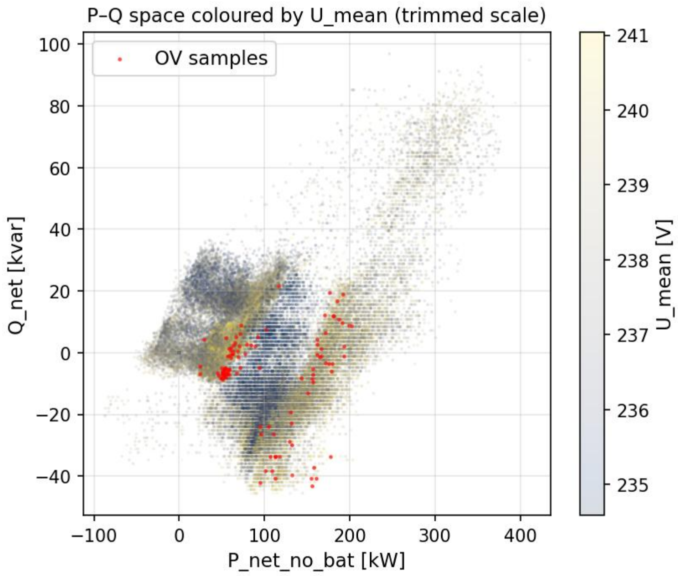
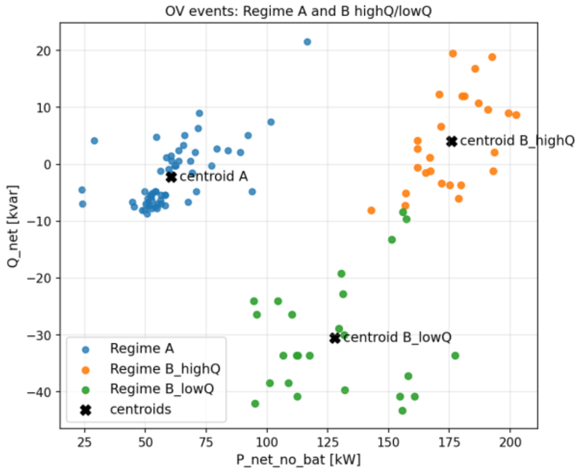


Figure 18: P-Q space scatter plot with all measurements coloured by mean voltage (left panel) and OV events classified into three regimes with cluster centroids marked (right panel)

Clustering methodology

To formally identify and characterise these operating regimes, a two-stage classification approach was employed. First, K-means clustering with k=2 was applied to the overvoltage samples using standardised P and Q coordinates as features. This initial clustering separated the events into Regime A and Regime B based on their position in the P-Q space.

Examination of the resulting clusters revealed that Regime B contained events with notably different reactive power characteristics. To capture this heterogeneity, Regime B was further subdivided using the median value of Q_{net} within the cluster as a threshold. Events with reactive power above the median were classified as B_{highQ}, while those below were classified as B_{lowQ}.



The resulting three-regime classification, shown in Figure 19 provides a physically interpretable partitioning of overvoltage events. The cluster centroids, marked with black crosses, serve as reference points for regime identification during real-time operation.

Figure 19: Final classification of overvoltage events into three regimes showing Regime A (blue), B_{highQ} (orange), and B_{lowQ} (green) with their respective centroids

4.5.3 Daily profiles by regime

Analysis of average daily profiles for each regime provides insight into the temporal patterns of voltage, active power, and reactive power that characterise different types of overvoltage events.

Voltage profiles

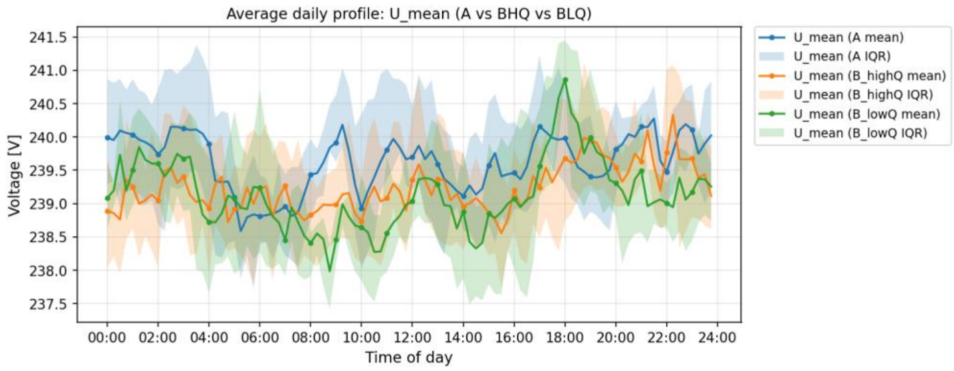


Figure 20: Average daily voltage profiles comparing the three OV regimes, showing U_{mean} with interquartile range bands

The voltage profiles presented in Figure 20 demonstrate that there is no clear difference between the regimes and their voltages daily profile despite different overvoltage conditions as indicated in the clustering results in Figure 19. It needs to be stressed that the profiles are based on daily profiles of the days exhibiting the overvoltage events. In most of the cases, see Figure 17, the overvoltage events are rare during the day. From the average profiles in Figure 20 it can be seen that the voltages are in general high for all three regimes.

Active power profiles

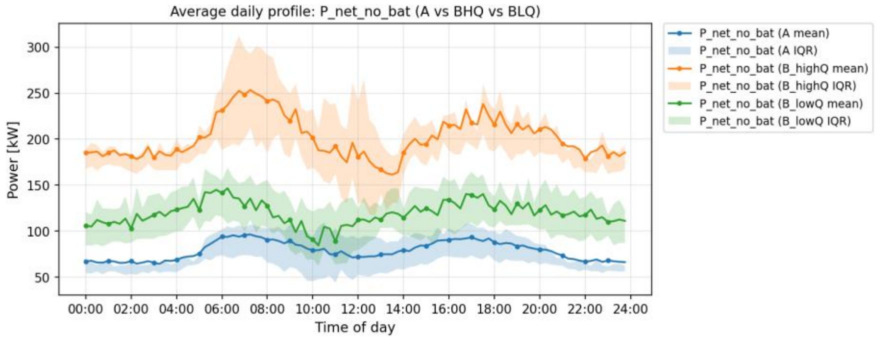


Figure 21: Average daily active power profiles (excluding battery contribution) for each regime, revealing the substantially higher power levels in B regimes

The active power profiles shown in Figure 21 reveal a fundamental distinction between Regime A and the B regimes. Both B_{highQ} and B_{lowQ} operate at substantially elevated power levels throughout the day, with peak values reaching 200-250 kW during mid-day hours. In contrast, Regime A maintains more moderate power levels in the range of 75-125 kW. This clear separation in power magnitude confirms that the clustering has captured physically meaningful operating states rather than arbitrary divisions.

Reactive power profiles

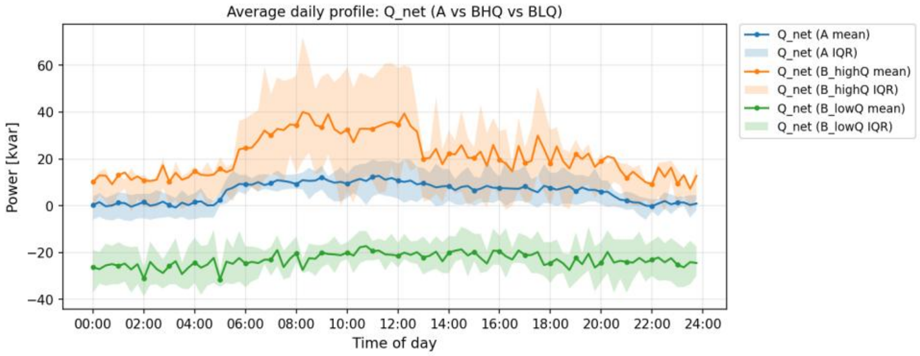


Figure 22: Average daily reactive power profiles distinguishing the three regimes by their characteristic Q behaviour

The reactive power profiles in Figure 22 provide the clearest visual differentiation between regimes. Regime B_{highQ} shows consistently positive (inductive) reactive power throughout the day, peaking at 40-60 kvar during afternoon hours. Regime A hovers near zero with a slight positive tendency. Most distinctively, Regime B_{lowQ} exhibits strongly negative (capacitive) reactive power, reaching -30 to -40 kvar. This capacitive behaviour in B_{lowQ} likely results from the aggregate effect of PV inverters and other power electronic equipment operating at leading power factor, which partially counteracts voltage rise but does not eliminate it entirely.

4.5.4 Sensitivity analysis

Background and methodology

Understanding how voltage responds to changes in active and reactive power is essential for designing effective control strategies. While the clustering analysis identified distinct operating regimes, it does not directly quantify how much power adjustment is needed to achieve a given voltage reduction. To address this question, a sensitivity analysis was conducted using Ordinary Least Squares (OLS) regression to estimate the relationship between voltage and power flows within each regime.

The underlying physical model assumes that mean voltage at the transformer station can be approximated as a linear function of active and reactive power:

$$U_{mean} \approx U_0 + \alpha P_{net} + \beta Q_{net}$$

In this formulation, U_0 represents the baseline voltage when power flows are minimal, $\alpha = \partial U / \partial P$quantifies the voltage sensitivity to active power in units of V/kW, and $\beta = \partial U / \partial Q$quantifies the sensitivity to reactive power in V/kvar. The sign and magnitude of these coefficients reveal which power component has greater influence on voltage and in which direction.

It is important to note that this regression model is not intended to predict absolute voltage values with high accuracy. The relatively modest R^2 values obtained (discussed below) reflect the simplified linear assumption and the influence of factors not captured in the model, such as upstream network conditions and load diversity. Rather, the purpose is to estimate the marginal sensitivity of voltage to power changes, which provides actionable guidance for control system design.

The regression was performed using the statsmodels[4] library with heteroscedasticity-consistent (HC3) standard errors to ensure robust statistical inference despite potential non-constant variance in the residuals.

Sensitivity results and interpretation

The regression analysis was applied separately to each operating regime, yielding the results summarised in the Table 1.

Table 1:TP Inkubator Vrbina overvoltage regimes sensitivity analysis

Regime	Samples	R^2	α [V/kW]	β [V/kvar]	abs(α/β)	Dominant
A	1,534	0.107	+0.0046	-0.0519	0.09	Q
B_{highQ}	1,180	0.096	-0.0028	-0.0095	0.29	P > Q
B_{lowQ}	1,177	0.043	+0.0083	-0.0145	0.57	P

The coefficient of determination (R^2) indicates that the linear model explains approximately 10% of voltage variance in Regimes A and B_{highQ}, and about 4% in B_{lowQ}. While these values may appear modest, they are statistically significant and consistent with expectations for a simplified two-variable model applied to a complex physical system. The remaining unexplained variance reflects factors such as upstream voltage fluctuations, transformer tap position, and non-linear relationships that the linear model cannot capture.

The sensitivity coefficients reveal fundamentally different voltage behaviour across regimes. In Regime A, the active power coefficient α is small and positive (+0.0046 V/kW), while the reactive power coefficient β is much larger in magnitude and negative (-0.0519 V/kvar). The ratio abs(α/β) = 0.09 indicates that reactive power has roughly eleven times greater influence on voltage than active power in this regime. This Q-dominated behaviour is characteristic of networks where line reactance plays a

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[4] https://www.statsmodels.org/stable/index.html

significant role, and it suggests that reactive power compensation would be the most efficient control approach for Regime A events.

Regime B_{highQ} presents a notably different picture. Here, the active power coefficient α is negative (-0.0028 V/kW), meaning that increasing active power actually reduces voltage in this regime. This counterintuitive result reflects the physics of a heavily loaded network: additional power flow increases current, which in turn increases resistive losses (I^2R) and the associated voltage drop. The system is operating near its capacity limit, and the voltage drop from losses outweighs any voltage rise from power injection. The reactive power coefficient remains negative but is smaller in magnitude than in Regime A. The ratio abs(α/β) = 0.29 indicates that while Q still has some influence, active power becomes relatively more important for control in this regime.

Regime B_{lowQ} exhibits the strongest response to active power, with α = +0.0083 V/kW being the largest positive coefficient observed. This means that each additional kilowatt of active power produces a measurable voltage increase. The reactive power coefficient is also significant (-0.0145 V/kvar), but the ratio abs(α/β) = 0.57 indicates that active power is the dominant lever for voltage control. This regime represents the most critical operating condition, where high active power directly drives voltage elevation and control actions must prioritise power absorption.

Practical control implications

The sensitivity coefficients can be inverted to estimate how much power adjustment is required to achieve a 1 V reduction in mean voltage. This translation from sensitivities to actionable quantities provides direct guidance for control system sizing and strategy. Practical control implications are summarised in Table 2.

Table 2: TP Inkubator Vrbina sensitivity analysis practical control implications

Regime	P for -1 V	Q for -1 V	Recommended Strategy
A	~217 kW	~19 kvar	Q-control primary; V2G/battery secondary
B_{highQ}	~357 kW	~105 kvar	P-absorption via V2G charging or load shift
B_{lowQ}	~120 kW	~69 kvar	Aggressive P-reduction plus Q-compensation

For Regime A, achieving a 1 V voltage reduction through active power alone would require absorbing approximately 217 kW, while the same reduction could be achieved with only 19 kvar of reactive power absorption. This order-of-magnitude difference strongly favours reactive power compensation when it is available. Inverters capable of reactive power control, including modern PV inverters operating in volt-var mode, would be particularly effective in this regime.

In Regime B_{highQ}, the negative α coefficient means that increasing active power (e.g., through EV charging) actually helps reduce voltage. However, the required magnitude of approximately 357 kW for a 1 V reduction is substantial and may exceed the available flexibility from V2G resources alone. Reactive power adjustment requires about 105 kvar per volt, which is also a significant demand. This regime benefits from coordinated action across multiple resources.

Regime B_{lowQ} is the most amenable to active power control, requiring only about 120 kW to achieve a 1 V reduction. This is well within the capability of a modest fleet of electric vehicles or a medium-sized battery storage system. The 69 kvar required for equivalent reactive power control is also feasible. Given the high effectiveness of P-control in this regime, V2G strategies should prioritise B_{lowQ} events.

These power requirements should be understood as sustained loads rather than transient pulses. An overvoltage event lasting one hour in B_{lowQ} regime would require maintaining 120 kW of additional load for the full hour, corresponding to 120 kWh of energy. For reference, a typical V2G-capable electric vehicle can provide 10 kW of power with 20-40 kWh of available energy, suggesting that 4-12 vehicles would be needed to address a typical event depending on its duration.

4.5.5 Temporal characteristics of OV events

Seasonal distribution

The occurrence of overvoltage events shows strong seasonal dependence, with a clear concentration during colder months. Table 3 presents the distribution of OV days across seasons for each regime.

Table 3: TP Inkubator Vrbina regimes seasonal distribution

Season	**Regime A**	**B_{highQ}**	**B_{lowQ}**	**Total**
Winter	9	9	5	23
Spring	0	1	4	5
Summer	0	0	0	0
Autumn	7	0	5	12

The complete absence of OV events during summer months is a notable finding that warrants explanation. In many networks with high PV penetration, summer would be expected to produce the most overvoltage events due to maximum solar generation. However, the TP Inkubator Vrbina network serves loads that apparently scale with solar availability, maintaining power balance even during peak generation periods. The winter concentration of events likely reflects the combination of lower solar generation reducing the self-consumption of prosumers while commercial and industrial loads maintain elevated consumption, creating conditions favourable for voltage rise through different mechanisms than simple PV oversupply.

Weekday distribution

Analysis of OV event distribution across weekdays reveals relatively uniform occurrence without strong weekly patterns. The number of OV days by weekday ranges from 3 (Thursday) to 9 (Tuesday), with no systematic difference between weekdays and weekends. This uniform distribution suggests that the factors driving overvoltage events at TP Inkubator Vrbina are not strongly correlated with typical weekly activity patterns.

Hourly distribution

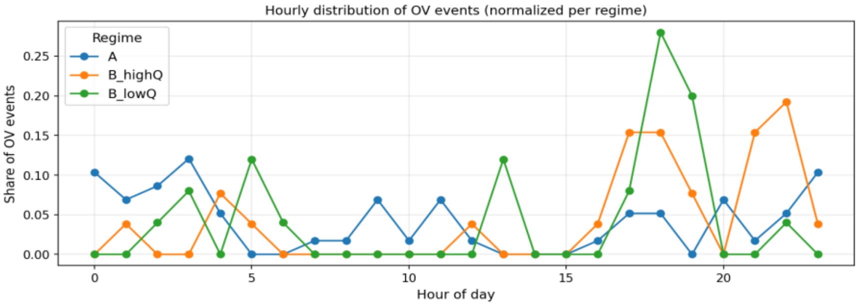


Figure 23: Hourly distribution of OV events normalised within each regime, revealing the afternoon concentration of events and distinctive temporal signatures for each regime type

The hourly analysis presented in Figure 23 reveals that overvoltage events concentrate heavily in afternoon hours, with peak occurrence between 12:00 and 18:00. Morning events before 10:00 are rare across all regimes. Interestingly, each regime shows a somewhat different temporal signature: B_{highQ} events peak sharply around 14:00-16:00, while B_{lowQ} events spread more broadly across the afternoon. Regime A shows the most diffuse temporal pattern with a secondary peak in early evening hours.

Regime co-occurrence

An important question for forecasting is whether OV days tend to exhibit a single regime type or multiple regimes within the same day. Analysis of the 42 OV days reveals that most days are characterised by a single dominant regime: 16 days showed only Regime A events, 10 days showed only B_{highQ}, and 14 days showed only B_{lowQ}. Only 2 days exhibited events from multiple regimes, and no days showed all three regime types. This clean separation supports the feasibility of day-ahead regime prediction, as the forecast needs to identify a single expected regime rather than predicting a complex mixture of conditions.

4.5.6 Day-ahead forecasting mode

Problem formulation and challenges

The forecasting task aims to predict OV event occurrence and type for day D+1 using features available at day D-1, creating a 2-day forecast horizon. This lead time enables the DSO to signal expected conditions and allows V2X operators to prepare appropriate control strategies in advance.

The forecasting problem presents several significant challenges. The data is highly imbalanced, with only 43 OV days out of 709 total days representing approximately 6% positive class prevalence. This imbalance means that a naive classifier predicting "no OV" for every day would achieve 94% accuracy while being completely useless for the intended application. The multi-class nature of the problem adds further complexity, as the forecast must not only distinguish OV from non-OV days but also classify the expected regime type for OV days.

The critical operational requirement is high recall: the cost of missing an OV event (leaving the system unprepared) substantially exceeds the cost of a false alarm (unnecessarily preparing the system). This asymmetry drives the model design toward sensitivity at the expense of some specificity, accepting a higher false alarm rate to ensure that genuine OV events are rarely missed.

Model architecture

A hierarchical XGBoost classification approach was implemented to address the multi-class prediction problem. Rather than attempting to predict all four classes (NV, A, B_{highQ}, B_{lowQ}) simultaneously, the model decomposes the problem into three sequential binary classifications.

At the first level, the model distinguishes between Normal Voltage (NV) days and OV days of any type. This is the most critical decision, as errors here propagate through the entire prediction. At the second level, conditional on predicting an OV day, the model classifies between Regime A and Regime B. At the third level, conditional on predicting Regime B, the model further distinguishes B_{highQ} from B_{lowQ}.

Each level uses an XGBoost classifier with adaptive probability thresholds tuned to optimise recall while maintaining acceptable precision. The threshold tuning prioritises catching OV events at Level 1 and correctly identifying the more critical B regimes at subsequent levels.

Feature engineering

A total of 90 features were engineered from D-1 measurements and D+1 weather forecasts. The feature set encompasses several categories designed to capture different aspects of network behaviour and external conditions.

Voltage statistics from the previous day include percentile values (particularly Up99 capturing near-maximum voltage), voltage margin to the OV threshold, minimum and maximum phase voltages, and the phase voltage floor representing the lowest observed value across phases. Power statistics include mean and extreme values of active power, as well as reactive power variability captured through standard deviation and range metrics.

Temporal aggregates provide time-of-day specific information, including evening voltage means, morning and midday power imbalances, and peak-hour statistics. Weather forecasts for the target day, obtained from the Open-Meteo API, include global tilted irradiance predictions (mean and variability), cloud cover forecasts, and temperature. Calendar features encode season and day of week to capture any systematic patterns.

Feature importance analysis, shown inFigure 24, reveals that voltage-related features dominate the prediction. The 99th percentile of voltage (Up99) and voltage margin to the OV threshold are the most informative predictors, followed by phase-level voltage statistics. Weather features, particularly irradiance forecasts, contribute secondary predictive value. Notably, consumer and prosumer level data showed only marginal impact on prediction accuracy, suggesting that transformer-level measurements capture the essential information for forecasting.

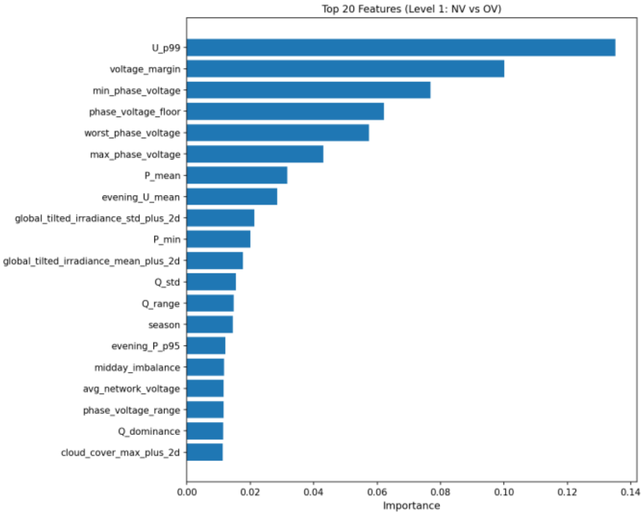


Figure 24: Top 20 feature importance for the NV vs OV classification, demonstrating the dominant role of voltage-related features in predicting overvoltage days

Model performance

The hierarchical model achieves strong performance on the primary objective of detecting OV days while maintaining acceptable false alarm rates.

Table 4: TP Inkubator Vrbina overvoltage regime forecasting model performance

Metric	Value
OV Recall (any type)	79%
False alarms	1.02 / week
Cold-start OV recall	100%
Regime A recall	88%
B detected as OV	73%

The 79% overall OV recall means that approximately four out of five OV days are correctly predicted in advance. The false alarm rate of approximately one per week represents an operationally acceptable trade-off, as the cost of unnecessary preparation is modest compared to the benefit of catching true events.

Particularly noteworthy is the 100% recall for cold-start OV events, defined as OV days that follow a sequence of NV days. These events, which occur without recent precedent, are often the most difficult to predict but also the most important to catch, as the system has had no recent opportunity to learn from similar conditions. The model's perfect performance on this subset indicates that it has learned to identify the underlying conditions that presage OV events rather than simply extrapolating recent trends.

Limitations

Several limitations should be acknowledged. The model does not predict the specific time of day when OV events will occur, providing only day-level forecasts. While the temporal analysis suggests that afternoon hours are most likely, this information is not incorporated into the forecast output.

The dominance of transformer-level features suggests that the model's performance might be improved by incorporating additional data sources, such as medium-voltage network measurements or transformer configuration parameters. Such data could help distinguish between locally-driven and system-wide voltage conditions.

Finally, the limited number of OV days in the dataset (43) constrains the statistical confidence in regime-level predictions. As more operational data accumulates, the model's regime classification capabilities should be re-evaluated and potentially retrained.

Conclusions

The analysis has established a comprehensive framework for understanding and predicting overvoltage events at the TP Inkubator Vrbina demonstration site, yielding several findings with direct implications for voltage regulation strategy.

The identification of three distinct overvoltage regimes through P-Q space clustering represents a key contribution. Rather than treating all OV events as equivalent, the analysis reveals that Regime A events are primarily driven by reactive power and respond most efficiently to Q-control, while Regime B_{lowQ} events are strongly sensitive to active power and are ideal candidates for V2G-based intervention. Regime B_{highQ} presents an intermediate case where the network is operating near capacity limits and multiple control resources may need to be coordinated.

The sensitivity analysis quantifies these differences precisely, showing that reducing voltage by 1 V in Regime A requires approximately 19 kvar of reactive power but 217 kW of active power, while the same reduction in Regime B_{lowQ} requires only 120 kW of active power. These values provide concrete design targets for control systems and resource sizing.

The high phase symmetry observed throughout the dataset confirms that overvoltage at TP Inkubator Vrbina is a system-level phenomenon rather than a single-phase issue, validating the use of aggregate power measurements and balanced control strategies.

The day-ahead forecasting model achieves 79% OV recall with approximately one false alarm per week, providing actionable predictions that enable proactive system preparation. The 100% recall on cold-start events is particularly valuable for operational deployment, as it ensures that unexpected OV conditions are anticipated even without recent precedent. Performance results also inform KPIs related to the Slovenian demonstrator.

5 Slovenian use cases demonstration

The Slovenian demonstrator involves three distinct business roles. The first role is the DSO, which acts as a user and procurer of local flexibility services enabled by V2X technologies. The second role is the aggregator, which acts as a flexibility service provider by aggregating V2X-based flexibility together with other flexibility resources within its portfolio. The third role is the Slovenian national data hub, Enotna Vstopna Točka (EVT), which performs the role of a market platform supporting the procurement and activation of local flexibility services.

From a technical perspective, the main technical components on the DSO side are the Advanced Distribution Management System (ADMS), the big data platform LAMBDA and the local flexibility market platform (FlexIS). On the aggregator side, flexibility resources are managed through a VPP. This pilot configuration enables the demonstration of the following EV4EU use cases:

- Use-Case 9 (UC9): V2X management by a VPP,
- Use Case 10 (UC10): Participation of V2X in electricity markets,
- Use Case 11 (UC11): Participation of V2X in grid services,
- Use Case 12 (UC12): Activation of V2X-based flexibility services by DSOs.

EVT acts as a neutral market platform enabling the registration of flexibility service providers, publication of local flexibility tenders, submission and forwarding of bids, and support for flexibility activation processes. As Slovenian DSOs are already connected to EVT for the exchange of smart metering data, EVT can be used as an intermediate component to collect information on flexibility providers, publish tenders for local flexibility services, forward received bids to the DSO, and transmit activation requests. In this setup, EVT operates the market platform, while bid evaluation and selection remain the responsibility of the DSO.

The overall concept of the Slovenian demonstrator is based on the use of ADMS functionalities providing observability of both MV and LV distribution networks. When a violation of normal operating conditions is detected, the ADMS triggers a signal to the FlexIS platform to activate appropriate flexibility services and mitigate the identified issue. On the other hand, the operator can manually activate a flexibility service for any available and valid flexibility contract directly via the platform with a single action. This additional functionality enables the operator to initiate flexibility activation in cases where the ADMS has not detected or flagged the need for corrective action. This concept is schematically illustrated in Figure 25.

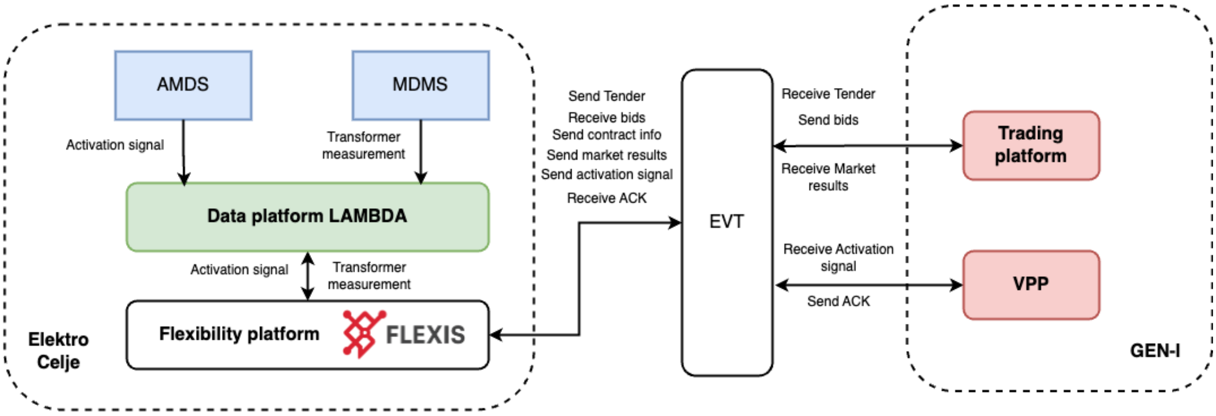
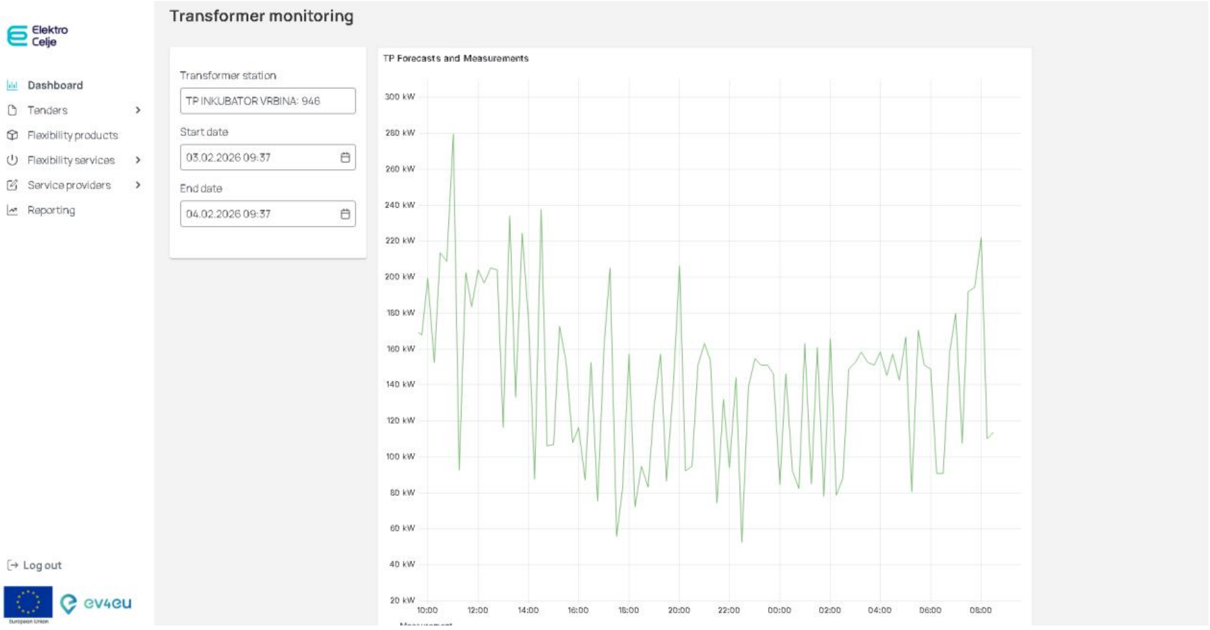


Figure 25: Slovenian demonstrator architecture concept

From the perspective of Elektro Celje (DSO), flexibility products are defined in a technology-agnostic manner, meaning that any flexibility resource capable of meeting the required technical attributes of a given flexibility product can be used. These technical attributes include parameters such as time of activation, activation duration, required power volume, activation direction, and location within the distribution network. Flexibility services are offered by the aggregator (GEN-I), which aggregates heterogeneous flexibility resources, including V2X-enabled assets, through its VPP.

FlexIS offers the possibility of monitoring measurement and forecast data. The user is redirected to the Dashboard upon successful login to the system. In Figure 26, the graph presents a time-series visualization of transformer power consumption, allowing operators to monitor load behaviour, identify peaks, and analyse performance over a selected period. As shown in Figure 25 ADMS and LAMBDA are the main gateways to FlexIS, and data is provided near-real time.



Transformer station: TP INKUBATOR VRBINA: 946

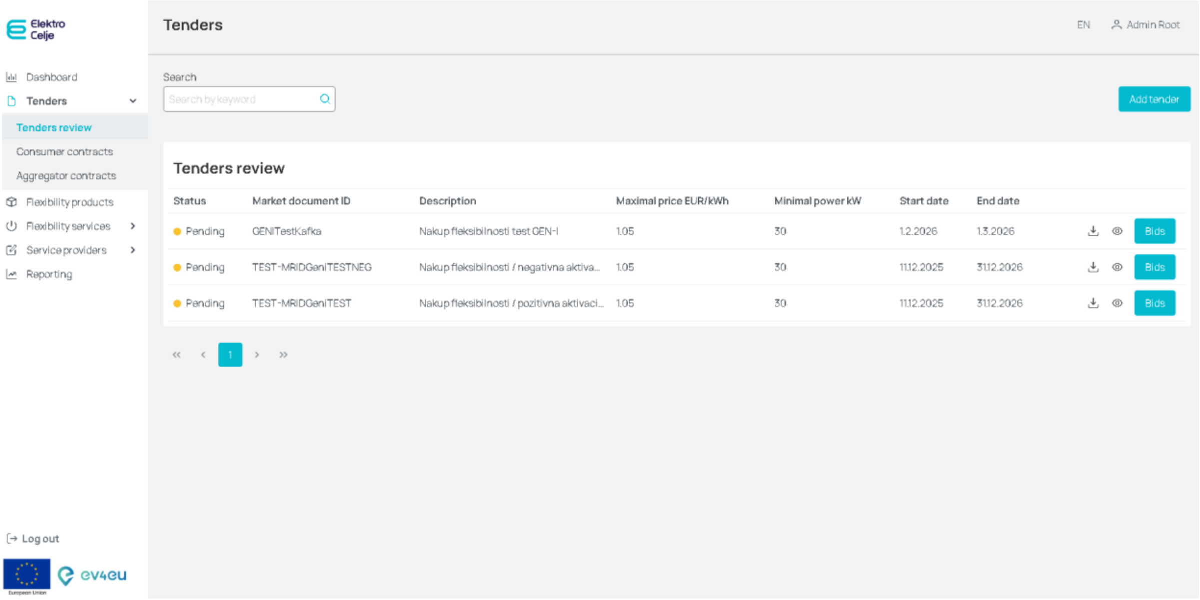
Start date: 03.02.2026 09:37

End date: 04.02.2026 09:37

Figure 26: Transformer monitoring

The user can select the desired transformer station and the period (start and end date) for displaying data. The Figure 27 shows an example of a dashboard from the flexibility platform.

Elektro Celje continuously analyses the state of the distribution grid and identifies time intervals, such as specific seasons, days of the week, or hours of the day, during which flexibility services are required to resolve operational constraints. Based on these analyses, the DSO defines the required volume and direction of corrective flexibility products and prepares tenders for flexibility services. These tenders are submitted to EVT and published for the relevant distribution area. A list of published tenders in FlexIS is shown in Figure 27.



Tenders review

Status	Market document ID	Description	Maximal price EUR/kWh	Minimal power kW	Start date	End date
● Pending	GENITestKafka	Nakup fleksibilnosti test GEN-I	1.05	30	1.2.2026	1.3.2026
● Pending	TEST-MRIDGeniTESTNEG	Nakup fleksibilnosti / negativna aktiva...	1.05	30	11.12.2025	31.12.2026
● Pending	TEST-MRIDGeniTEST	Nakup fleksibilnosti / pozitivna aktivaci...	1.05	30	11.12.2025	31.12.2026

Figure 27: Tenders review table in FlexIS

Registered flexibility service providers that have registered eligible flexibility resources within the affected network area can participate in the tendering process. The registering of flexibility service providers (consumers and aggregators) is possible via the FlexIS platform as shown in Figure 28 and Figure 29.

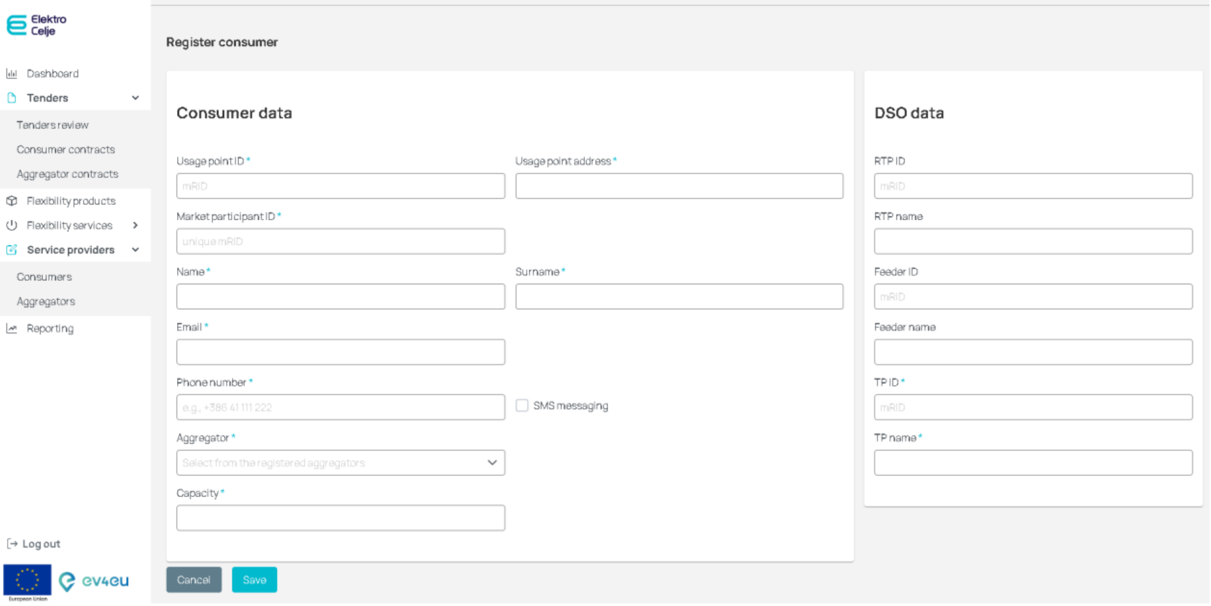
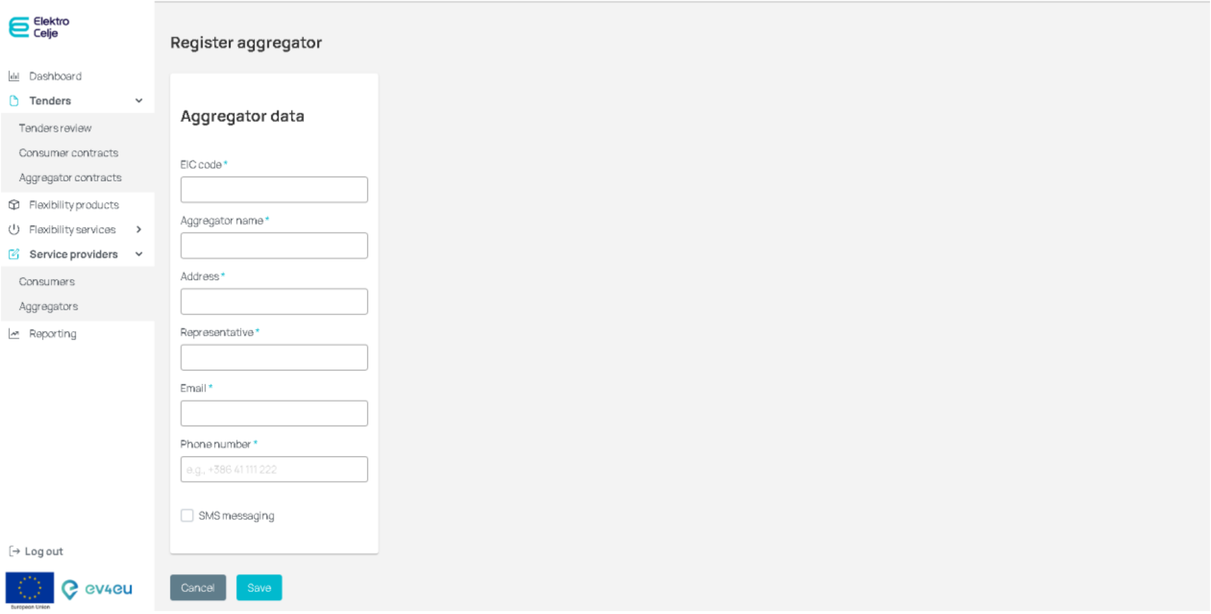


Figure 28: Consumer registration form



Register aggregator

Aggregator data

EIC code *

Aggregator name *

Address *

Representative *

Email *

Phone number *

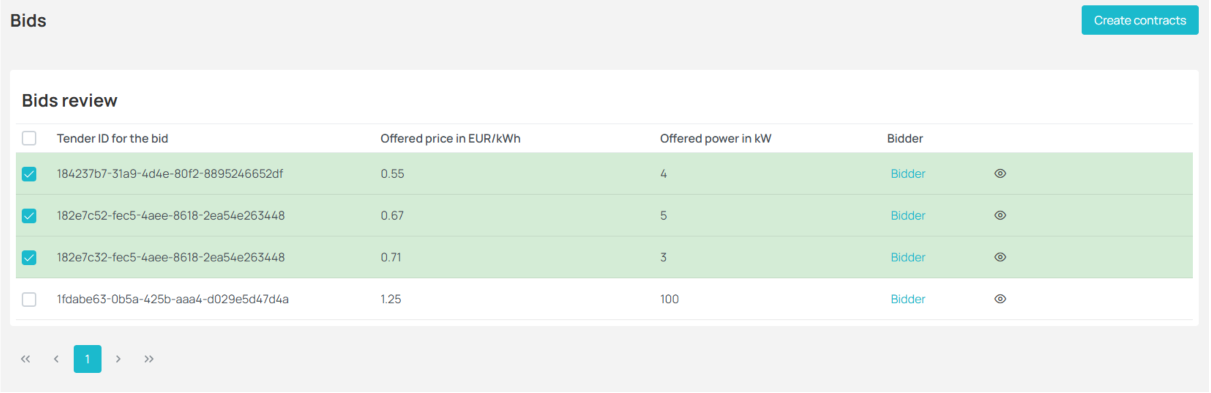
e.g., +386 41 111 222

☐ SMS messaging

Figure 29: Aggregator registration form

During the tender opening period, the aggregator submits bids via EVT. EVT disseminates these bids using a publish/subscribe communication model, enabling the FlexIS platform, deployed in the IT environment of Elektro Celje, to receive all bids associated with a specific tender.

FlexIS automatically processes the received bids, sorts them into a Merit Order List (MOL), and selects the most cost-effective bids (highlighted in green) until the required flexibility volume is satisfied as shown in Figure 30. This selection process is fully automated.



Bids

Bids review

☐	Tender ID for the bid	Offered price in EUR/kWh	Offered power in kW	Bidder	
☑	184237b7-31a9-4d4e-80f2-8895246652df	0.55	4	Bidder	👁
☑	182e7c52-fec5-4aee-8618-2ea54e263448	0.67	5	Bidder	👁
☑	182e7c32-fec5-4aee-8618-2ea54e263448	0.71	3	Bidder	👁
☐	1fdabe63-0b5a-425b-aaa4-d029e5d47d4a	1.25	100	Bidder	👁

Figure 30: Bids MOL list

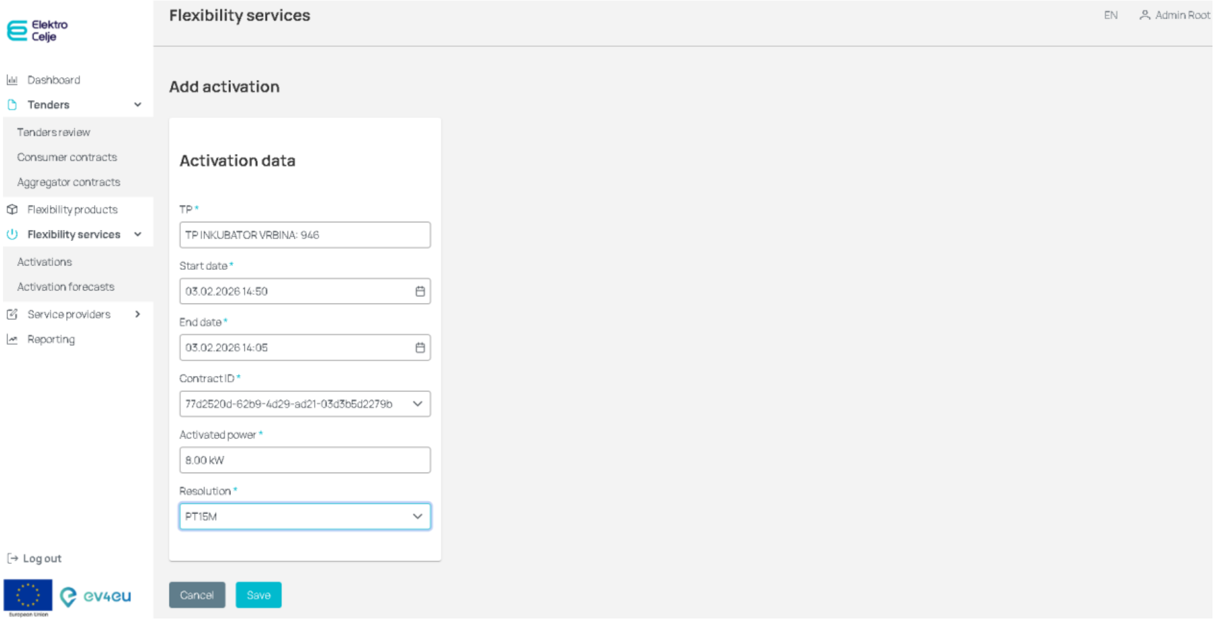
For the selected bids, contracts are generated and transmitted to the respective bidders. Once signed, the contracts are uploaded to the FlexIS platform and automatically registered in EVT. Only flexibility services covered by valid and signed contracts are eligible for activation.

On the DSO side, flexibility service activation can be performed either manually or automatically, with automatic activation being the default mode. When the ADMS detects a potential violation of normal operating conditions (e.g., transformer overload at a substation), it sends a notification to the big data platform Lambda within the Elektro Celje IT environment. Lambda subsequently sends an activation request to FlexIS in the form of an XML message containing information on the affected asset, activation time, and required flexibility volume. Manual activation was used only for demonstration purposes during the pilot in order to illustrate the functionality of the flexibility activation process.

FlexIS verifies whether a valid contract exists for the requested flexibility product. If a valid contract is available, FlexIS sends an activation signal to EVT, which forwards the activation request to the contracted flexibility service provider. The activation event is recorded in FlexIS and marked as activated.

Once the flexibility service provider activates the requested flexibility resources at the specified time, an acknowledgement message is sent back to the DSO. This confirmation message, formatted as a CIM XML message, is received by FlexIS, which updates the activation status accordingly.

For manual activation of a flexibility service, the activation data form in Figure 31 must be completed in the FlexIS UI. The user selects the relevant transformer station, the start and end dates, the contract ID for either upward or downward activation, the activated power, and the 15- or 30-minute resolution. Once the *Save* button is pressed, the activation signal is sent to EVT and forwarded to the contracted flexibility service provider.



Add activation

Activation data

TP *: TP INKUBATOR VRBINA: 946

Start date *: 03.02.2026 14:50

End date *: 03.02.2026 14:05

Contract ID *: 77d2520d-62b9-4d29-ad21-03d3b5d2279b

Activated power *: 8.00 kW

Resolution *: PT15M

Figure 31: Manual activation of flexibility services

5.1 Aggregated representative EV profiles

To simulate V2X environment on the Velenje demonstrator where BESS was aggregated into a VPP, Slovenian partners developed aggregated representative EV profiles, which enabled BESS to act in a similar way as V2X CSs and consequently EVs. EV profiles were developed for different UCs and participation in selected local and national flexibility services defined in deliverable D4.4 [3], which enabled comprehensive estimation of V2X impact and its flexibility potential.

Aggregated representative EV profiles were developed using a data-driven approach that combines statistical mobility data, historical distribution grid measurements, and market-specific information to realistically represent the collective behaviour of multiple V2G-enabled EVs. The objective of this approach was to enable a practical and scalable assessment of EV flexibility under real operating conditions, while avoiding the need for direct physical integration of a large number of EVs into the demonstrator. Instead, the aggregated EV behaviour was emulated using a BESS aggregated into a commercial VPP [14].

The development process starts with statistical data on vehicle user behaviour, which is used to derive probability distributions of trip start times for different travel purposes (e.g., work and leisure). These distributions define the arrival and departure times of individual EVs, which are then aggregated to determine average plug-in and plug-out times for each aggregated representative EV profile. This ensures that the resulting EV profiles reflect realistic connection patterns for selected use cases, including home charging, workplace charging of employees' EVs, and company EV fleets, during workdays and weekends. The state of charge SOC at plug-in and the target SOC at plug-out are defined based on typical charging behaviour and battery usage assumptions, ensuring that user requirements are preserved despite flexibility services participation [14].

In parallel, historical distribution grid load measurements and balancing market data are analysed to identify high-probability time windows for the activation of local flexibility services, mFRR and aFRR. These time windows are matched with the connection periods of the aggregated EV profiles to determine feasible participation intervals for each flexibility service. Based on the defined connection times linked with specific UCs, SOC constraints, and service participation windows, a time-varying power signal $P(t)$ is constructed for each aggregated representative EV profile. This signal specifies when and at what power level the emulated EV aggregation charges or discharges, either to provide flexibility services or to reach the required SOC at plug-out [14].

Based on the developed approach, a total of 20 aggregated representative EV profiles were created to cover the main use cases and flexibility service participation scenarios addressed in the Slovenian demonstrator. The profiles were developed for three core UCs: EVs charging at home, EVs charging at work (employees' vehicles), and company EV fleets, with each UC related to home and EV fleet further differentiated by workday and weekend behaviour. For each UC, EV profiles were defined for participation in individual services—local flexibility services, mFRR and aFRR—as well as for combined participation across all three services. All the developed EV profiles are presented in Figure 32.

Each aggregated EV profile represents a group of five V2G-enabled EVs and captures realistic charging, discharging, and state-of-charge trajectories aligned with user behaviour and service activation requirements. Resulting in a single equivalent flexibility resource that can be uploaded to the VPP and activated on the BESS. By activating these profiles on the demonstrator, the approach enables controlled, repeatable, and realistic testing of EV flexibility provision, quantification of negative and positive flexibility, and assessment of grid impact at both local and national levels [14].

Figure 32 illustrates how EVs can provide different types of flexibility services depending on their charging location and user profiles. Three representative use cases are included—Home, Workplace (employees), and Workplace (company EV fleet)—each analysed for typical workday and weekend charging patterns. For every scenario, the battery State of Charge (SoC) is compared across four operational modes:

- Local flexibility services;
- mFRR (manual Frequency Restoration Reserve);
- aFRR (automatic Frequency Restoration Reserve);
- Combined operation (local services + mFRR + aFRR).

These modes demonstrate how the available battery capacity, plug-in durations, and user behaviour influence the EV's potential contribution to grid services.

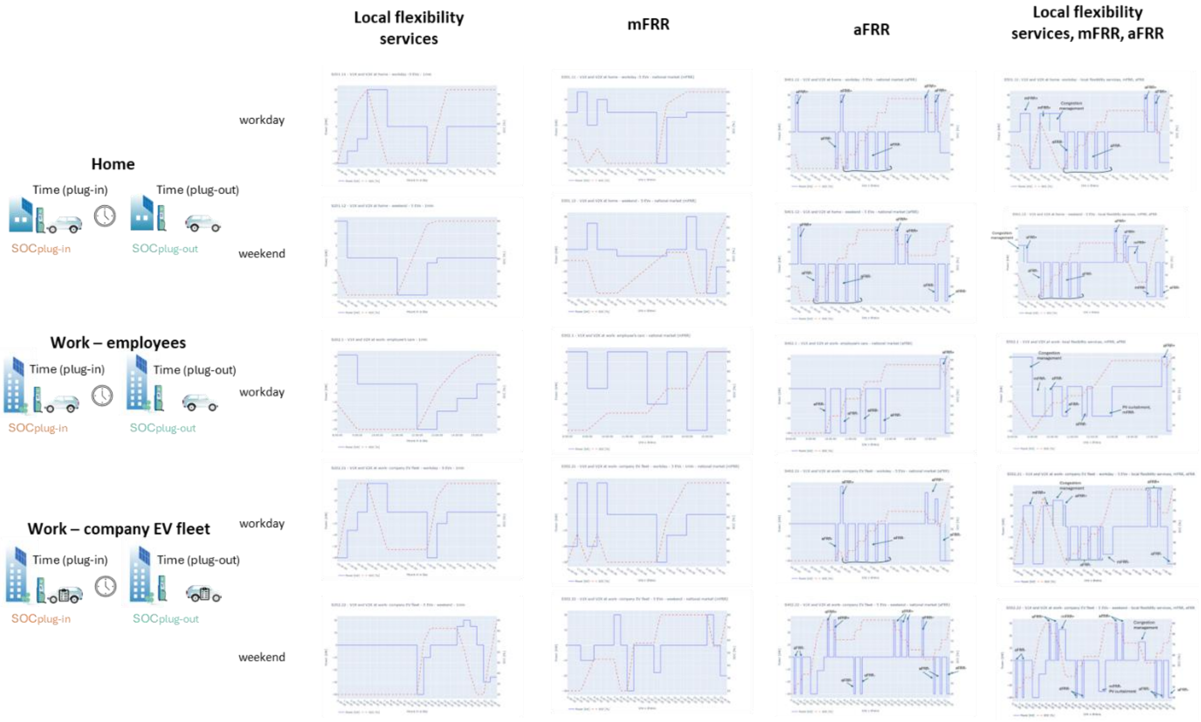


Figure 32: Aggregated representative EV profiles developed for different use cases and flexibility services

5.1.1 Home Charging

During workdays, EVs at home are typically unplugged throughout daytime and only connect to the charger in the evening or overnight, which shapes their flexibility potential. During workday in Slovenia, EVs are in average plugged from 16:00 till 8.00 in the morning. In this setting, local flexibility services rely on steady night time availability and therefore show smooth modulation of charging power. mFRR introduces occasional short charging or discharging events, demonstrating the ability of home-charged EVs to support slower reserve-activation signals. aFRR, in contrast, requires fast and frequent adjustments, resulting in more pronounced fluctuations in power. When local services, mFRR, and aFRR are activated simultaneously, the combined mode exhibits layered, frequent interventions, yet the vehicle still reliably reaches the required SoC before the morning departure.

On weekends, EVs tend to remain plugged in for much longer periods (on average from 19:00 till 11:00), significantly increasing the flexibility available to the system. This extended plug-in window enables richer participation across all flexibility services, with aFRR and combined modes showing the most dynamic profiles. The longer availability allows the vehicle to respond more often and more intensively to activation signals while maintaining user requirements for SoC.

5.1.2 Workplace Charging

Employee vehicles at workplace chargers generally follow predictable daytime plug-in patterns, creating a stable foundation for flexibility provision. Average working hours in Slovenia are from 8:00 till 16:00. Local flexibility services typically operate during midday, when renewable energy production—especially solar—is high, enabling controlled and efficient charging, while they are also important during evening peak loads. Both mFRR and aFRR align with working-hour availability, with aFRR displaying the most rapid oscillations due to its continuous balancing function. In combined mode, the EV provides the broadest flexibility range, actively responding to various grid needs while still ensuring enough charge for the employee's departure.

Because employee vehicles are rarely present on-site during weekends, their contribution to flexibility services is minimal. The limited plug-in occurrences are reflected in the graphs, which show very low or even no activation of local services, mFRR, or aFRR, resulting in negligible flexibility value in this scenario.

5.1.3 Company EV Fleet

Company fleet vehicles follow consistent operational schedules (on average connected from 16:00 till 8:00) and remain connected for extended periods, making them highly suitable for delivering diverse flexibility services. Local services create a clear, step-wise SoC profile as controlled charging progresses throughout the day. mFRR introduces structured charging and discharging events that align with reserve dispatch requirements. aFRR produces rapid and frequent power fluctuations, reflecting its real-time frequency regulation role. When operating in combined mode, fleet vehicles achieve the highest density of flexibility actions, showcasing their strong capability for multi-layered grid support without compromising operational readiness.

If the company fleet remains parked over the weekend, flexibility potential increases even further due to long and uninterrupted availability. In this setting, the combined mode shows extensive and diverse activation, with the battery engaging simultaneously in local services, mFRR, and aFRR. This makes fleet EVs one of the most valuable assets for providing continuous and high-impact system flexibility.

6 Slovenian demos monitoring and results

The Slovenian demonstrators form a key part of the EV4EU project, providing real-world environments for testing advanced V2X functionalities, flexibility activation mechanisms, and interoperability between vehicles, charging infrastructure, and upstream control platforms. Throughout the demonstration period, comprehensive monitoring was performed across all three sites—Velenje, Ljubljana, and Krško—to validate the technical performance of the deployed systems and to assess their readiness for large-scale integration.

The results presented in this section and section 7 summarise the findings from a series of controlled tests and live demonstrations, each conducted with specific configurations, vehicle models, and prototype charging equipment. The monitoring data captures both the expected behaviour and the limitations observed during operation, offering valuable insights into system reliability, communication flows, and EV/BMS-dependent responses.

Together, these outcomes provide a detailed evidence base on the effectiveness of the Slovenian demonstrators, highlighting achieved functionalities, identified constraints, and lessons learned that will inform future deployment and standardisation efforts within the EV4EU framework.

6.1 BESS demonstrator - measurements from testing and analysis

During the activations of the aggregated representative EV profiles on BESS, real-time data is monitored by both VPP and DSO backend systems. The gird data is measured on 15-minute periods while VPP data is measured on 10-seconds intervals. After activation, data from VPP and BESS are collected, including power signals and SOC, which are ready for analysis. Additionally, grid measurements are collected from the secondary substation to assess the grid impact. The analysis verifies whether the BESS accurately followed the VPP activation signal within predefined response time and evaluates the success of flexibility services provision, using power grid data and VPP measurements. The mentioned data are available for 50+ VPP activations.

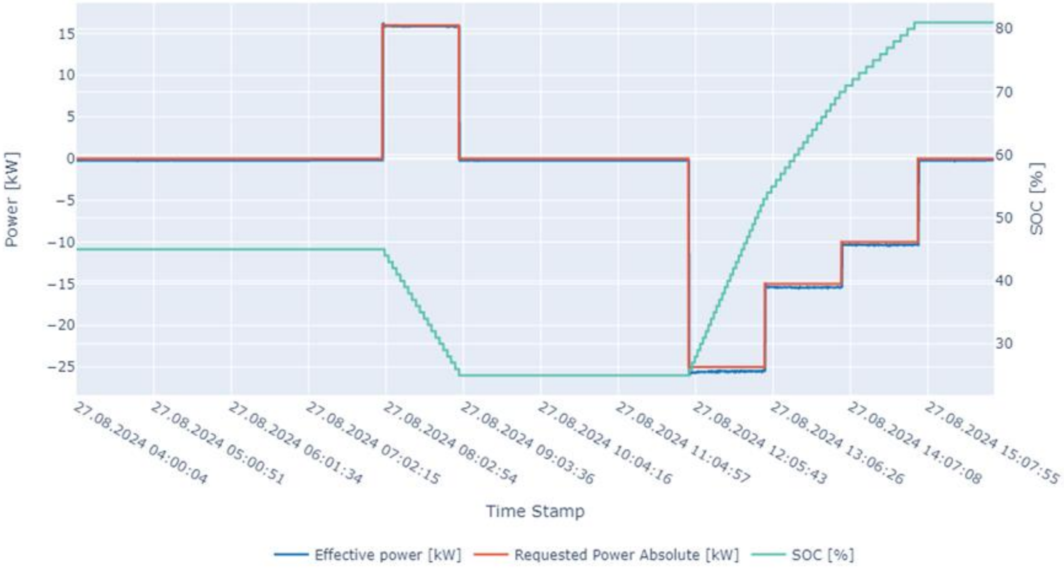


Figure 33: Example of VPP measurements for activation signal of EV profile related to UC_employees' for participation in local flexibility services on BESS demonstrator

The example of VPP measurements for activation signal of EV profile related to UC_employees' for participation in local flexibility services are presented on Figure 33. The red line represents the VPP activation signal sent by the VPP to BESS. The blue line represents the power response of the BESS (positive numbers represent discharging, while negative numbers represent charging), and the green line represents the SOC of the BESS during activation [14].

From Figure 33 it is evident that the power response of the BESS correctly followed the power setpoint sent by the VPP through the activation signal. We can conclude that the activation was successful if we consider the VPP and BESS measurements.

To assess whether participation in local flexibility services was successful, we analysed the measurements from the secondary substation in combination with the data from the VPP for the observed period of the activation. A visualization example of the measurements from the SS and the VPP is shown in Figure 34.

The "congestion management+" rectangle in Figure 34 indicates the provision of the positive congestion management service, which was activated in anticipation of a peak load at the selected secondary substation. Once activated, a reduction in substation load (A+) is observed, confirming the effectiveness of the service. During the positive congestion management service, 16 kWh of energy was discharged to the grid.

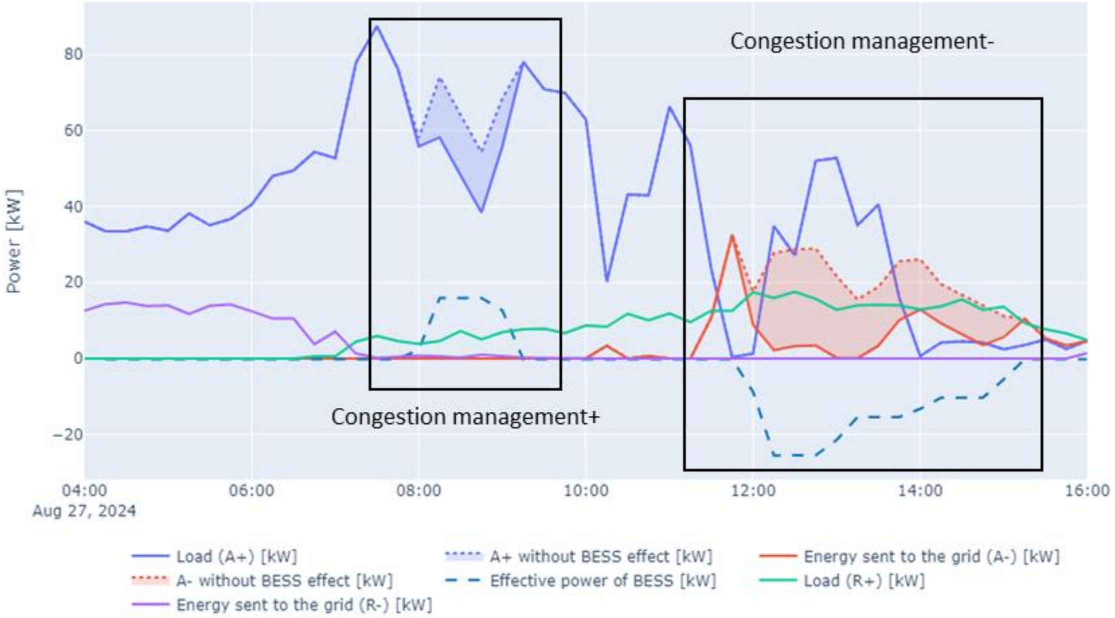


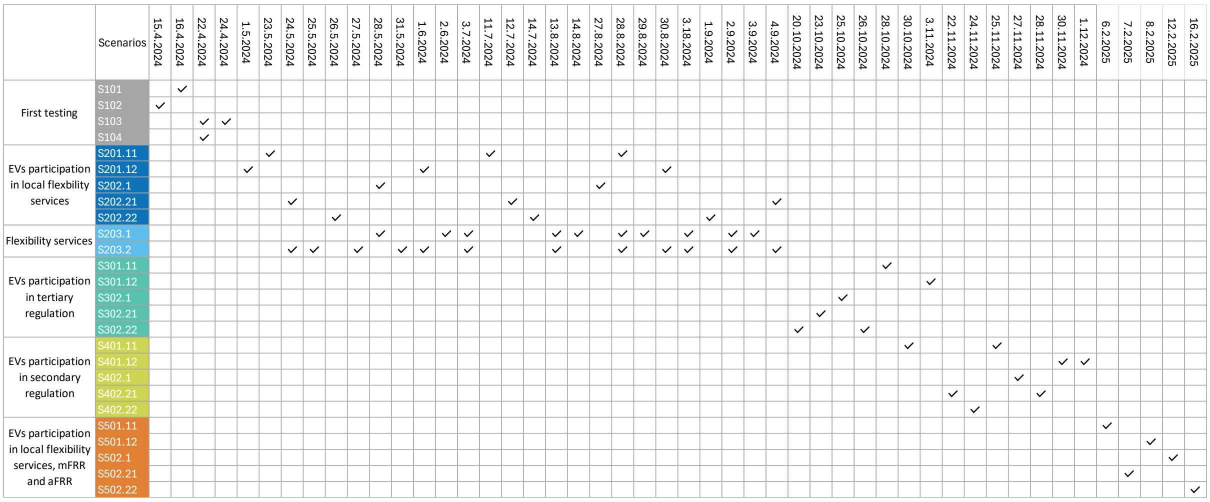
Figure 34: Example of measurements of active and reactive power at selected secondary substation for VPP activation signal of EV profile related to UC_employees' for participation in local flexibility services on BESS demonstrator.

The "congestion management−" rectangle in Figure 34 shows the activation of negative flexibility, with the BESS charging after 12:00 to absorb expected excess PV generation. The resulting decrease in excess PV production at the secondary substation (A−), highlighted by the difference between the dotted and solid lines, confirms the effective mitigation of PV surplus during the observed period. During the negative congestion management service, 48 kWh of energy was used from the grid for charging of BESS.

The analysis and visualisation presented in the Figure 33 and Figure 34 was done for 40+ VPP activation of 20 aggregated representative EV profiles. The measurements of successful activations for 20 EV profiles are the foundation for the relevant KPIs calculations presented in the subsection 6.3.

6.2 Testing on BESS demonstrator

During the demonstration period from April 2024 to January 2025, a total of 60 activations were performed on the demonstrator, including testing activities. These activations covered 20 aggregated representative EV profiles, enabling systematic testing of flexibility service provision and validation of the developed EV profiles. The testing confirmed technical readiness and operational robustness of the Slovenian demonstrator.



	Scenarios	15.4.2024	16.4.2024	22.4.2024	24.4.2024	1.5.2024	23.5.2024	24.5.2024	25.5.2024	26.5.2024	27.5.2024	28.5.2024	31.5.2024	1.6.2024	2.6.2024	3.7.2024	11.7.2024	12.7.2024	14.7.2024	13.8.2024	14.8.2024	27.8.2024	28.8.2024	29.8.2024	30.8.2024	3.18.2024	1.9.2024	2.9.2024	3.9.2024	4.9.2024	20.10.2024	23.10.2024	25.10.2024	26.10.2024	28.10.2024	30.10.2024	3.11.2024	22.11.2024	24.11.2024	25.11.2024	27.11.2024	28.11.2024	30.11.2024	1.12.2024	6.2.2025	7.2.2025	8.2.2025	12.2.2025	16.2.2025
First testing	S101		✓																																														
	S102	✓																																															
	S103			✓	✓																																												
	S104			✓																																													
EVs participation in local flexbility services	S201.11						✓										✓						✓																										
	S201.12					✓								✓											✓																								
	S202.1											✓										✓																											
	S202.21							✓										✓												✓																			
	S202.22									✓									✓								✓																						
Flexibility services	S203.1											✓			✓	✓				✓	✓		✓	✓		✓		✓	✓																				
	S203.2							✓	✓		✓		✓	✓		✓				✓			✓		✓	✓		✓		✓																			
EVs participation in tertiary regulation	S301.11																																		✓														
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EVs participation in secondary regulation	S401.11																																			✓				✓									
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EVs participation in local flexibility services, mFRR and aFRR	S501.11																																												✓				
	S501.12																																														✓		
	S502.1																																															✓	
	S502.21																																													✓			
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Figure 35: Overview of VPP activations and test scenarios at the Velenje demonstrator

6.3 Calculation of KPIs related to the BESS demonstrator

As defined in Deliverable D7.1 [1], 19 KPIs structured across 5 categories are relevant for Slovenian demonstrator. KPIs are divided between three demo sites in Krško, Ljubljana and Velenje. Specifically, 12 KPIs are relevant for the BESS demonstrator in Velenje, and their calculations performed with BESS Demonstrator’s KPI Analysis Support Tool are presented in subsection 6.4.

All 12 KPIs were calculated for 20 aggregated representative EV profiles of which VPP activations were performed on BESS, covering five use cases and three flexibility services (local flexibility services, mFRR, and aFRR). Two KPIs (KPI 9 and 10) were calculated using estimated values, due to limited availability of forecasting data. The estimations relied on historical average load profiles and scenario-based assumptions reflecting typical daily variability. Therefore, KPI 9 and KPI 10 values represent indicative performance rather than fully operational forecasting accuracy.

Table 5 presents the average KPI values calculated across 20 aggregated representative EV profiles activated on the BESS demonstrator. These average values provide an insight into BESS demonstrator in Velenje.

Table 5: Calculations of 12 KPIs relevant to the demonstrator in Velenje for 20 VPP activations of EV profiles

KPI	Name of KPI	Target	Unit	Average values for 20 EV profiles
KPI 1	Demonstrator accuracy	50	%	270
KPI 2	V2G success level	15	%	25
KPI 3	Profit for aggregator	50	€/CS	9.7
KPI 4	Cost reduction for DSO	5	%	0.009
KPI 5	User satisfaction	50	%	
KPI6	Reduction of CO2	6	kg/day	133.4
KPI 7	Technical operation of CS	97	%	
KPI 8	Data reliability	95	%	
KPI 9	Flexibility forecast accuracy	50	%	83.4
KPI 10	Generation and consumption forecast accuracy	50	%	65.6
KPI 11	Voltage compliance	100	%	100
KPI 12	Additional potential for services	20	%	0.35
KPI 13	Occupancy of the charging station	2	h/day	
KPI 14	Increased flexibility for grid	35	%	11.3
KPI 15	Flexibility from EV availability	35	%	
KPI 16	Request fulfilment ratio of flexibility by DSO	70	%	
KPI 17	Technical operation of BESS	97	%	99.9
KPI 18	Successfulness of aggregator activations	70	%	96.3
KPI 19	Aggregators bidding performance	100	%	

Although Table 5 presents the average KPI values calculated across 20 aggregated representative EV profiles activated on the BESS demonstrator. These average values provide an insight into BESS demonstrator in Velenje.

Table 5 presents average values, the underlying results show that performance varies across individual EV profiles and service types. Technical KPIs related to system reliability and operational stability remain consistently high, indicating robust system integration. In contrast, flexibility-related and economic KPIs demonstrate greater sensitivity to operational conditions, EV availability, and service characteristics. This suggests that while the technical framework is stable, the delivered flexibility performance is influenced by contextual and behavioural factors.

This section 6.3 serves as a guideline for further analysis of KPIs that will follow in the Deliverable *D7.4 Lessons learned in Slovenian Demonstrator and Services Marketability report.*

6.4 Flexibility related discussion

Subsection 6.4 focuses on the analysis of flexibility-related aspects of VPP activation of individual EV profiles, as this represents one of the key elements for providing additional insights to stakeholders regarding which UCs deliver the highest flexibility potential in the selected services.

The Table 6 provides a representation of the relative difference between activated positive and negative flexibility delivered by individual EV profiles across different UCs and participations in different flexibility services. Directional symbols indicate which type of flexibility prevails, while the number of symbols reflects the magnitude of the difference. The symbol “>” denotes a higher level of activated positive flexibility compared to negative flexibility, whereas “<” indicates the opposite. The repetition of symbols (e.g., “>>” or “<<<”) represents increasing magnitude of the difference, with “<<” corresponding to a difference below 30 kWh and “<<<” indicating a difference above 30 kWh. The symbol “=” denotes approximately balanced levels of positive and negative activated flexibility.

Table 6: Relative difference between activated positive and negative flexibility provided by individual EV profiles across UCs and services

Flexibility services	EV profile	Activated negative flexibility [kWh]	Activated positive flexibility [kWh]
Local flexibility services	S201.11: V1X and V2X at home – workday – 5 EVs	>>	
	S201.12: V1X and V2X at home – weekend – 5 EVs	>	
	S202.1: “V1X and V2X at work - employee’s cars – 5 EVs”	<<	
	S202.21: “V1X and V2X at work- company EV fleet – 5 EVs - workday	>>>	
	S202.22: “V1X and V2X at work- company EV fleet 5 - EVs – weekend	=	
mFRR	S301.11: “V1X and V2X at home – workday - national market (mFRR)”	<<	
	S301.12: “V1X and V2X at home – weekend - national market (mFRR)”	<	
	S302.1: “V1X and V2X at work - employee’s cars - national market (mFRR)	<<	

	S302.21: “V1X and V2X at work- company EV fleet – workday - national market (mFRR)	>
	S302.22: “V1X and V2X at work- company EV fleet – weekend - national market (mFRR)	>
aFRR	S401.11: “V1X and V2X at home – workday - national market (aFRR)”	>
	S401.12: “V1X and V2X at home – weekend - national market (aFRR)”	<<<
	S402.1: “V1X and V2X at work - employee’s cars - national market (aFRR)	<<
	S402.21: “V1X and V2X at work- company EV fleet – workday - national market (aFRR)	<<<
	S402.22: “V1X and V2X at work- company EV fleet – weekend - national market (aFRR)	<
All three services combined	S501.11: “V1X and V2X at home -workday - local flexibility services, mFRR, aFRR”	<
	S501.12: “V1X and V2X at home -weekend - local flexibility services, mFRR, aFRR”	<<<
	S502.1: “V1X and V2X at work- local flexibility services, mFRR, aFRR”	<<
	S502.21: “V1X and V2X at work- company EV fleet – workday – local flexibility services, mFRR, aFRR”	>>
	S502.22: “V1X and V2X at work- company EV fleet – weekend – local flexibility services, mFRR, aFRR”	<<

The results presented in Table 6 indicate that the selected use cases (UCs) demonstrate a considerable potential for the provision of both negative and positive flexibility. While the magnitude of activated flexibility varies across individual EV profiles, the analysis shows that several profiles are capable of delivering substantial flexibility volumes in both directions. When aggregated, the cumulative contribution of EV profiles represents a meaningful flexibility resource for grid operation and market-based services, highlighting the relevance of VPP-aggregated EVs in supporting local and system-level flexibility needs.

6.5 Quantifying flexibility potential for Krško demonstration site based on simulation

Quantification of flexibility potential was done by V2GFlex tool which is a simulation based and demonstrator related assessment tool designed to assess EVs flexibility potential and to support feasibility analysis of EV participation in selected local flexibility services using historical datasets from the Slovenian demonstrator. The tool is mentioned in D3.4 and in article [15]. The V2GFlex is also linked with KER14B of the EV4EU project.

The development of the tool was based on the previous activities done in the scope of the EV4EU project, for example space-time modelling of local traffic for quantifying EV impact [16], investigating optimization scheduling of EVs [17] and evaluation of pure PV-EV system at the country level [18].

6.5.1 Quantification of flexibility potential for one day

In the paper [19] we have evaluated flexibility potential of a selected UC of a parking lot with 10 EVs aggregated in a VPP, which is connected with Slovenian demonstrator. The study estimates the negative and positive flexibility potentials that aggregated EVs can offer, as well as the ability for participation in the markets in the scope of one day. The conclusion is that EVs in such a constellation can offer a negative and positive flexibility potential of 880 kWh within one day. Taking into account the specifications of the charging stations (CSs), the potential is 550 kWh [19].

Figure 36 shows the available negative and positive flexibility potential of EVs considering the CSs limitations related to maximal charging and discharging power. It also shows the unavailable flexibility of EVs due to CSs constraints. The specifications of the CSs limit the utilisation of the full flexibility potential EVs have. This means that development of powerful V2G CSs is just as important as development of EVs that are compatible with V2G technology.

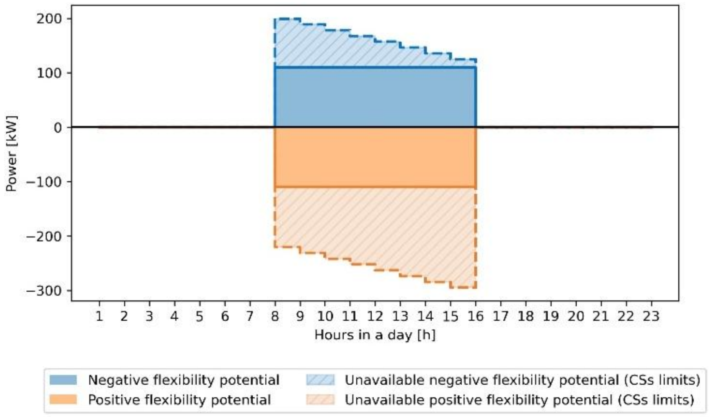

Figure 36: Example of flexibility potential of EVs for selected UC per hour for one day, considering CSs limitations [19]

6.5.2 Quantification of flexibility potential for longer period

In the paper [15], for the selected case, which aligns with the Slovenian demonstrator of the EU project EV4EU, we simulated and assessed flexibility potential of V2G EVs and their capability for participation in local flexibility services. The results are presented for the selected case, where the simulation covers one month (Figure 37 and Figure 38). The case includes 10 bidirectional CSs connected to the same secondary substation with consumers and two solar power plants, for the Krško location.

Figure 37 shows the secondary substation loading (blue) for the selected simulation period, expressed as a percentage. The red line indicates the threshold at which the congestion management service, provided by EVs, was activated.

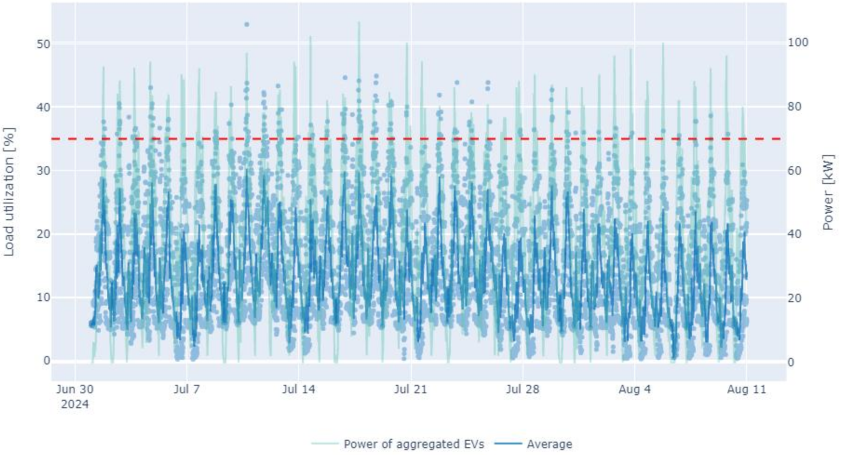

Figure 37: Simulated secondary substation loading for the selected case: participation of EVs in the congestion management flexibility service. The substation loading is indicated in blue, while the power of the aggregated EVs is shown in green

Figure 38 presents the assessed negative and positive flexibility potential of aggregated V2G EVs for the selected simulation period. The dark blue line in Figure 38 represents the average value of the negative EV flexibility potential, together with the range of its variation across the ten simulation iterations. The same applies to the positive EV flexibility potential, which is shown in orange.

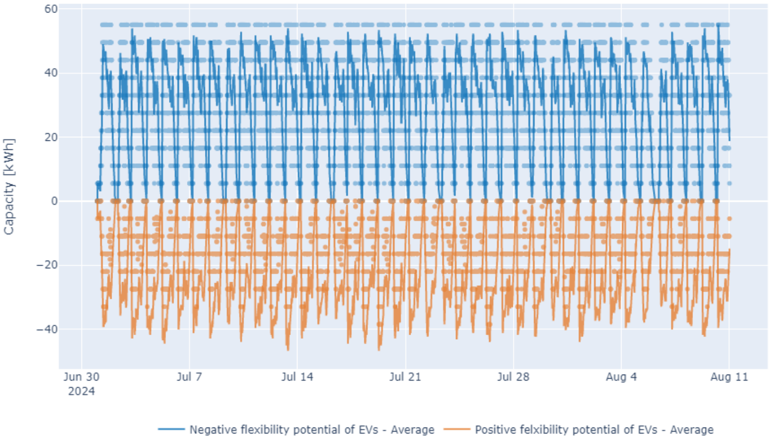

Figure 38: Assessment of the negative (blue) and positive (orange) EV flexibility potential based on the simulation results for the selected period of 1 month

Our results indicates that the selected flexibility service was activated an average of 19.2 times during the simulation period, with EVs providing 251.65 kWh of positive flexibility. Throughout the simulation period, the EVs offer on average 118 MWh of negative and 93.8 MWh of positive flexibility potential to the aggregator and thus to the DSO. For the given case, EVs could provide flexibility for 55 % of their connection time on average. A broader analysis indicates that as the share of EVs increases, so does the activated flexibility by EVs, reaching 567 kWh at a 100 % EV share and 251.64 kWh at 50 % [15]. Below are presented selected results of the simulation related with estimated quantification of the flexibility potential for Krško demonstrator.

Table 7 provides an overview of the broader context of the simulated case. It illustrates the impact of the EVs share on selected simulation outcomes. It can be concluded that both the negative and positive flexibility potential that aggregated EVs can offer to the aggregator increases with a higher share of

EVs. This is expected, as the total battery capacity of connected EVs increases accordingly, assuming the simultaneous availability of charging infrastructure.

Table 7: Impact of the EVs share on EV flexibility potential and on the activation requirements of the selected flexibility service - based on simulations for 1 month

	Share of EVs		
	10%	50%	100%
Negative flexibility potential [MWh]	104,3	118	131,5
Positive flexibility potential [MWh]	82,6	93,8	104,4
Number of successful activations	0	19,2	46
Percentage of unsuccessful activations [%]	0	1	13,9
Activated flexibility [kWh]	0	251,6	567

It can be observed that an increase in the EV share level also leads to a higher number of congestion management service activations. This is due to the growing number of EV connections to the charging infrastructure and the more frequent exceedance of the service activation threshold. This indicates that the secondary substation becomes increasingly loaded as the EV share rises. Furthermore, as the number of activations increases, Table 7 shows that a higher EV share level also results in a greater number of unsuccessful activations, due to increased secondary substation load and SoC limitations, which in the case of 100 % EV share amounts to an average of 13.9 % of all activations.

It can be concluded that the need for activated flexibility from EVs also increases. In the case of a 100 % EV share, the activated flexibility amounts to 567 kWh, whereas it reaches 251.64 kWh at a 50 % EV share. It can also be observed that at a 10 % EV share there is no need, in any case, to activate the congestion management service, as the secondary substation is never sufficiently loaded to require such activation. For the selected case, it can therefore be concluded that a 10 % EV share has no significant impact on the stability of the secondary substation or on the increased need for activations of the selected service, which is not the case for scenarios with 50 % and 100 % EV share.

Additionally, we also assessed the potential of EVs to participate in the Pure PV EV system in Slovenia, about which you can find more in the published paper [18].

The simulation results provide a foundation for the development and evaluation of the Slovenian EV4EU project demonstrator during and after the project lifetime.

7 Charging stations testing

Within the EV4EU Slovenian Demonstrator, ABB provided advanced electric vehicle charging infrastructure with bidirectional charging capabilities. ABB's V2G-capable CCS charging stations enable controlled energy flow both from the grid to the vehicle and from the vehicle back to the grid. This supports GEN-I's activities in flexibility-service testing, charging optimization, and the development of use cases relevant to the Slovenian electricity system.

Installations in Ljubljana and Krško support both research and development activities and operational validation, providing real-world environments for testing V2G integration scenarios. As the industry shifted from CHAdeMO toward CCS and ISO 15118-20-based communication, ABB adapted its charger architecture accordingly. The current 11 kW bidirectional wall box supports both group-based and private residential use cases and enables integration with home energy management systems.

From an electrical perspective, the charger accepts a three-phase AC input range from 340 to 440 V and provides a DC output voltage range from 150 to 500 V, matching typical EV battery architectures. Its bidirectional functionality supports up to ±11 kW of charging and discharging power (maximum ±36.7 A), making it suitable for V2G and energy-sharing applications. Communication is based on a modified OCPP 1.6J implementation, enabling compatibility with standard backend systems and remote management platforms.

Following the decision made in early 2024 to move toward CCS, ABB replaced several key hardware components, including the gun cable and connector, the CPI communication board, the input board and its shielding, the ceramic heat sink, and the CI board, in order to ensure compatibility with CCS requirements.

A central part of ABB's contribution is compliance with local regulatory and certification requirements. The V2G units are undergoing certification under SIST EN 50549-1 (Type A), which is a prerequisite for inclusion in the SODO list of approved equipment. Full compliance is important not only for the EV4EU demonstration itself, but also for future large-scale integration of V2G technology into Slovenian distribution networks.

From a technical development perspective, ABB is responsible for maturing the firmware required for reliable bidirectional operation. This includes implementation of control logic for V2G energy exchange, management of communication protocols, preparation of equipment for Factory Acceptance Testing (FAT), and delivery of technical documentation and installation manuals. ABB also supports GEN-I and project partners through site inspections, planning of electrical and communication infrastructure, and preparation of project documentation to ensure safe and compliant charger integration.

A V2G session was conducted using a CCS simulator, which enabled controlled manipulation of ISO 15118/DIN 70121 communication parameters and verification of bidirectional power-flow logic between the simulated EV and the charging system. This setup allowed engineers to test message sequencing, modify V2G communication frames, and validate stable initiation of a V2G session under laboratory conditions.

CCS Connector
ISO 15118-20 compliant

Main difference between CHAdeMO and CCS variant:

- Change off gun cable and connector
- Replacing CPI board (board for communication between charger and EVSE)
- Replacing Input Board and Shield
- Replacing Ceramic Heat Sink
- Replacing CI board from CHAdeMO to CCS
- Install SW compliant to ISO 15118-20 (for P, I negative values)
- Communication Protocol OCPP 1.6J

Figure 39: ABB's CCS Charging station

For development of the most suitable charging infrastructure, testing in a production environment was necessary to verify that all components, communication protocols, and system functions operate reliably under real-world conditions. Part of this process is shown in Figure 40 and Figure 41, which illustrate an important phase of technology validation before integration into the demonstrator environment.

Figure 40: CS testing in production process

To validate the communication stack and power-flow control in the absence of commercially available CCS V2G-capable vehicles, the chargers were tested using a CCS communication simulator. The simulator emulated the EV role and enabled deterministic manipulation of High-Level Communication (HLC) over PLC (HomePlug Green PHY), including SLAC association, SECC/EVCC TLS session establishment, and the ISO 15118/DIN 70121 state machine through the sequence ServiceDiscovery → ChargeParameterDiscovery → PowerDelivery.

Within these sequences, boundary and negative tests were introduced, including modified SessionID, altered EVSE status codes, and out-of-range target setpoints, in order to verify EVSE robustness, error handling, and graceful session termination.

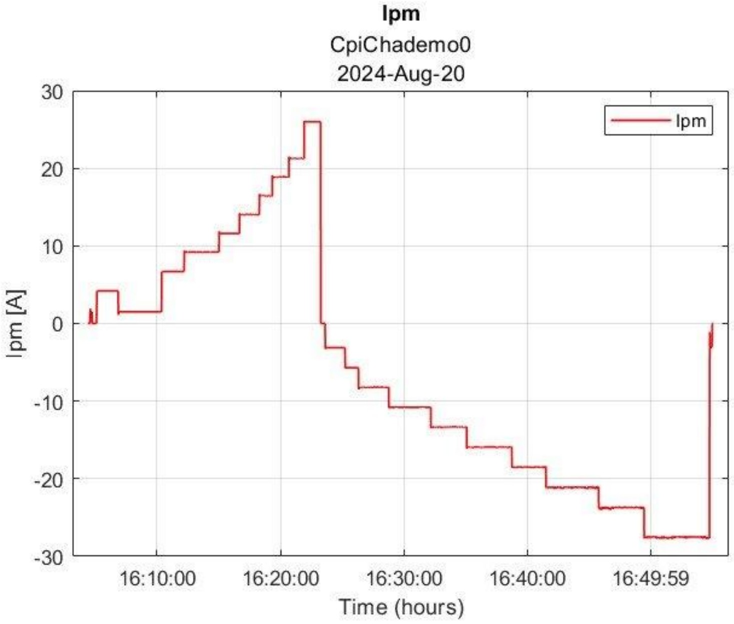

Figure 41: Results of charging and discharging the simulator

Following protocol-layer validation, bidirectional power tests were executed using an 11-kW bidirectional wall box. The following aspects were verified:

- Psetpoint tracking for both G2V (+P) and V2G (-P) at 1 s granularity, including ramp-rate limits and droop profiles.
- Coordination between HLC permissions and the EVSE power stage, including DC bus precharge and contactor logic, insulation monitoring, and anti-islanding interlocks.
- EVSE behaviour under grid events such as voltage and frequency excursions, as well as communication impairments including packet loss and re-handshake, with verification of fail-safe fallback to zero export and orderly session termination.
- End-to-end KPI logging, including communication latency, handshake success rate, setpoint-tracking MAE/RMSE, and availability, via the charger's CSMS interface (OCPP 1.6/2.0.1) for reproducibility and regression baselining.

This simulator-driven approach was necessary because currently accessible vehicles do not expose compliant CCS V2G functionality, particularly ISO 15118-20 bidirectional services, which limits reliable EV-side testing at this stage.

During testing activities, a V2G session was successfully initiated using a CCS simulator. This enabled controlled manipulation of ISO 15118/DIN 70121 communication sequences and verification of bidirectional power-flow behaviour under simulated conditions. The simulator allowed engineers to modify V2G messaging parameters and validate correct EV–EVSE interaction before field deployment.

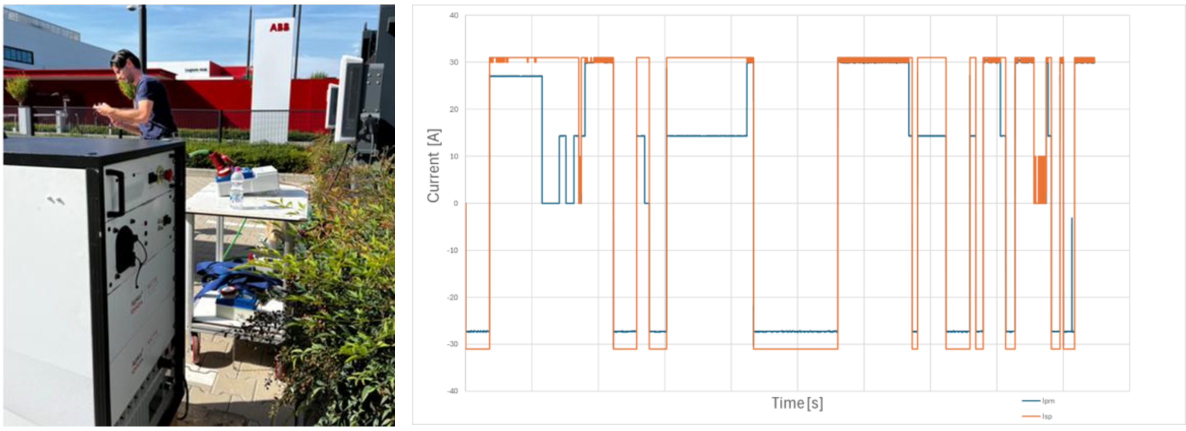

Figure 42: CS testing with car simulator

Following simulator validation, a full V2G session was performed on the Slovenian demo site using an EV connected to a bidirectional 11 kW wall box charger, where practical discharging tests confirmed stable energy export from the vehicle to the grid (Figure 44). Earlier internal tests demonstrated successful discharge profiles on several EV models at comparable power levels, supporting the feasibility of CCS-based V2G operation even in the absence of fully ISO 15118-20-compliant EVs on the market.

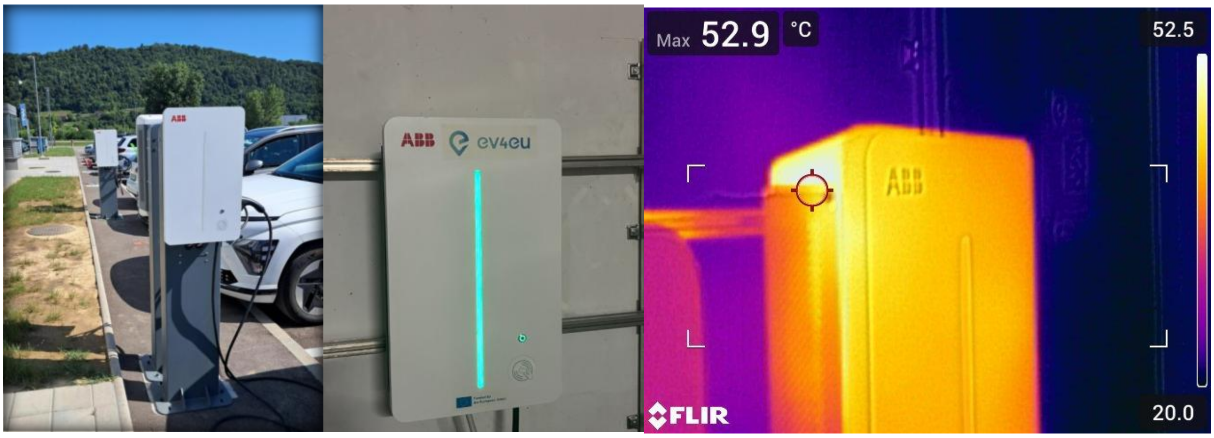

Figure 43: Slovenian demo charging stations testing

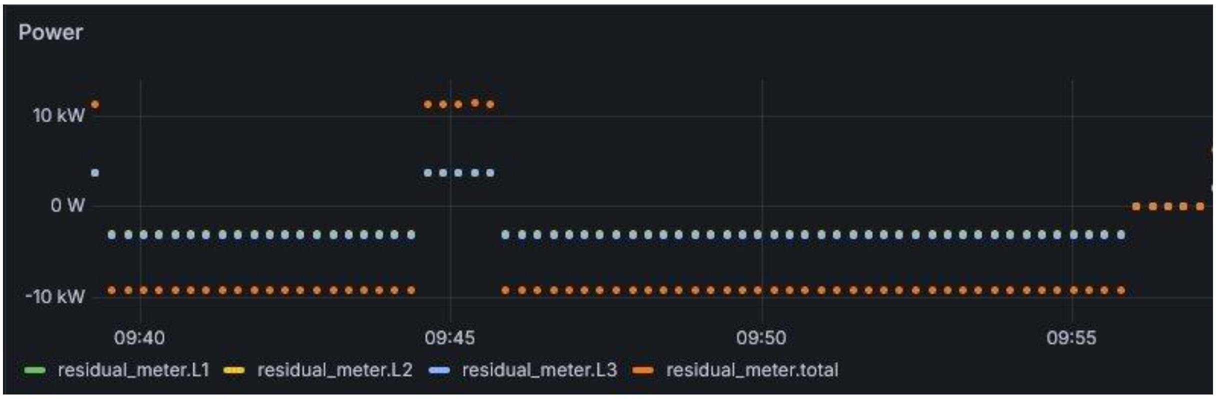

Figure 44: First results of the charging and discharging with prototype charging stations

Field measurements confirmed stable power export and reliable charger–vehicle interaction, complementing earlier tests where multiple EV models, including the Hyundai Kona, were successfully discharged at similar power levels during CCS-based V2G trials.

7.1 Transition from CHAdeMO to CCS

At the start of the EV4EU project, the planned V2G demonstrations were based on the CHAdeMO protocol, because at that time it represented the only mature and field-proven solution for bidirectional charging. CHAdeMO-compatible vehicles were available, the protocol was stable, and the ecosystem already included operational V2G deployments from which practical experience could be drawn (Figure 45). GEN-I's EV fleet included approximately 10 Nissan Leaf vehicles, all equipped with V2G-capable CHAdeMO controllers.

Figure 45: Testing discharging with CHAdeMO - Nisan Leafe

However, during project implementation, the European market increasingly shifted toward CCS. New vehicle models were more commonly introduced with CCS as the default connector, and manufacturers increasingly prioritised CCS-based roadmaps for Europe. Charging infrastructure followed the same trend, with operators investing primarily in CCS networks because this corresponded to new vehicle volumes

CHAdeMO did not become technically irrelevant; rather, it was overtaken commercially. As fewer new CHAdeMO vehicles entered the market, fewer public chargers supported the standard, and vendors had less incentive to maintain two parallel ecosystems. As a result, sourcing vehicles, planning demonstrations, and scaling beyond laboratory setups became increasingly difficult.

To avoid relying on equipment that could become obsolete during the project, the decision was made to transition fully to CCS and align development with ISO 15118-20.

ABB modified the Terra Nova 11J (CHAdeMO) charging station into the Terra Nova 11C (CCS / ISO 15118-20). This required replacement of the cable and connector, input board, shield, ceramic heat sink, and CI board, together with installation of ISO 15118-20-compliant software. Since no fully ISO 15118-20-compliant vehicles were available on the market at the time, ABB relied on the CCS simulator for testing the new V2G CS.

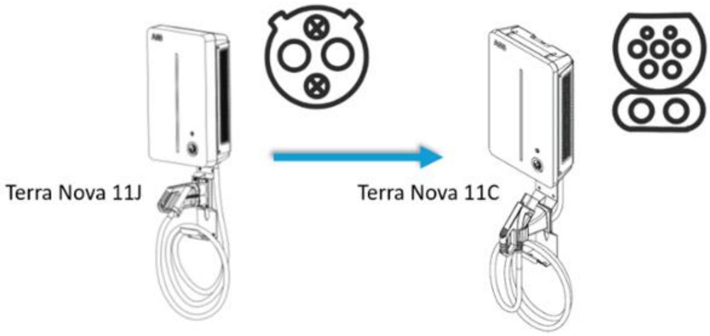

Figure 46: Transission from CHAdeMO to CCS

Testing also showed that battery discharge is possible on some EVs by initiating a DC charging session, completing insulation tests, aligning DC voltage on the charging station connector with the EV DC bus voltage, and then reversing the current once contact is made. In such cases, the BMS detects that current flows in the opposite direction, but the vehicle user interface is not designed to represent discharging operation. For example, during a 10 kW discharge, the dashboard may display 10 kW charging, while the state of charge gradually decreases and the time-to-full estimate increases (Figure 47).

Figure 47: Discharging with ABB prototype CS

7.2 Identifying interoperable EV

The next objective was to identify a vehicle capable of delivering reliable, reproducible, and technically meaningful V2G test results. To determine suitable EVs, a broad selection of vehicles available on the market was evaluated, including the VW ID.4, VW ID.7, VW ID.BUZZ, Škoda Enyaq, Tesla Model S, MG4, Tesla Model 3, and Hyundai Kona. Each model was tested for responsiveness to external power setpoints, charging-session stability, and the ability to execute both charging and discharging commands through the control chain.

The results showed significant differences between manufacturers. With the VW ID.BUZZ and the Škoda Enyaq, successful communication could not be established, which prevented further testing. Other models connected successfully, but their behaviour varied. Some showed unstable session initiation, slow reaction times, or only partial compatibility with power-profile commands. Only a small number of vehicles, most notably the Hyundai Kona and, to a certain extent, Tesla vehicles, provided the consistency required for controlled and repeatable V1G/V2G testing.

This testing campaign made it possible not only to identify technically suitable vehicles for the EV4EU demonstrator, but also to assess the current maturity of V2X implementation across manufacturers. It highlighted the importance of interoperability, standards compliance, and firmware readiness for integration of EVs into flexibility services.

The results are based exclusively on tests carried out under specific conditions, with defined vehicle models, equipment configurations, and at a particular point in time. The findings reflect the behaviour of the tested vehicles and systems during those specific sessions and may not represent general or future performance of the same models under different firmware versions, configurations, or environmental conditions. Testing was conducted using a prototype charging station, which may differ from future commercial hardware in terms of functionality, stability, and performance. Consequently, these results should not be assumed to apply to other vehicles, hardware or software versions, commercially released equipment, or later tests.

Table 8: Vehicle Interoperability Test Results

Vehicle model	Session Stability	Notes / Outcome
VW ID.4	Medium	Connected but showed inconsistent behaviour; not suitable for controlled V2G testing.
VW ID.7	Medium–Low	Communication was established, but responses were unreliable; unsuitable for meaningful tests.
VW ID.BUZZ	—	Failed to establish communication; no V2G testing possible.
Škoda Enyaq	—	No successful session initiation; fully incompatible in current firmware version.
Tesla Model S	Medium	Charging session stable, but protocol limitations prevent full V2G behaviour.*****
MG MG4	Low–Medium	Established connection, but lacked required responsiveness for controlled regulation testing.*****

Tesla Model 3	Medium	Similar to Model S: acceptable stability, but lacks full V2G capabilities.*
Hyundai Kona	High	The only vehicle providing stable, reliable, fully repeatable V2G test results.*

* Even though some vehicles did allow for discharging the battery, this was done without ISO 15118-20 communication.

7.2.1 Testing with VW ID.7

During the test conducted on 30 January 2025, the bidirectional charging capabilities of the VW ID.7 with firmware version 5.2 were evaluated. The procedure began with a standard charging session to verify baseline functionality, and this phase operated without irregularities.

The charger was first configured to deliver maximum power in order to confirm that the vehicle could accept the highest available charging rate. Several positive Tx profiles were then applied sequentially to test the vehicle's response to controlled changes in charging power. These profiles were executed and validated successfully.

In the final stage of the test, the Tx profile was set to -5000 W in order to initiate discharging. This command immediately triggered the vehicle to begin supplying power back to the system, confirming operation of its bidirectional interface. The discharge continued for approximately 70 seconds before a StopTransaction message was received, indicating automatic termination of the session. To confirm the result, the discharging process was independently verified using an external meter, which confirmed energy flow from the vehicle to the charger.

7.2.2 Testing with MG4

During the test conducted on 11 March 2025, the discharging functionality of the MG4 was assessed. After the charging cable was connected, the vehicle required several attempts before successfully initiating a charging session, indicating a delayed handshake process. Once the session was active, the first Tx_default message was sent with a setpoint of -10,000 W, which immediately initiated discharging. The MG4 maintained stable discharge for approximately five minutes without interruption (Figure 48). After this period, the power flow shifted to +10,000 W and the vehicle continued drawing power, while the charging session remained active and no StopTransaction message was issued. This behaviour suggests that the vehicle independently changed its operating mode without terminating the transaction.

After the initial five-minute discharge, another Tx_default message with a setpoint of -10 kW was sent, and the vehicle again responded correctly by resuming discharging. After four minutes, a Tx_profile command with the same -10 kW setpoint and a duration of 1000 seconds was issued. The MG4 continued discharging as expected. During this phase, the transaction was unintentionally interrupted when the vehicle was accidentally locked, causing the charging session to end.

A new test was then initiated using a Tx_profile with a duration of 900 seconds and a setpoint of -10 kW. The vehicle again began discharging and maintained this state for approximately 10 minutes before the transaction stopped automatically, returning a StopTransaction message with reason: "local". To determine whether this behaviour was repeatable, the test was repeated once more using a single Tx_profile with a duration of 15 minutes and a -10 kW setpoint. The result was the same: the MG4 terminated the transaction after approximately 10 minutes, again with reason: “local”.

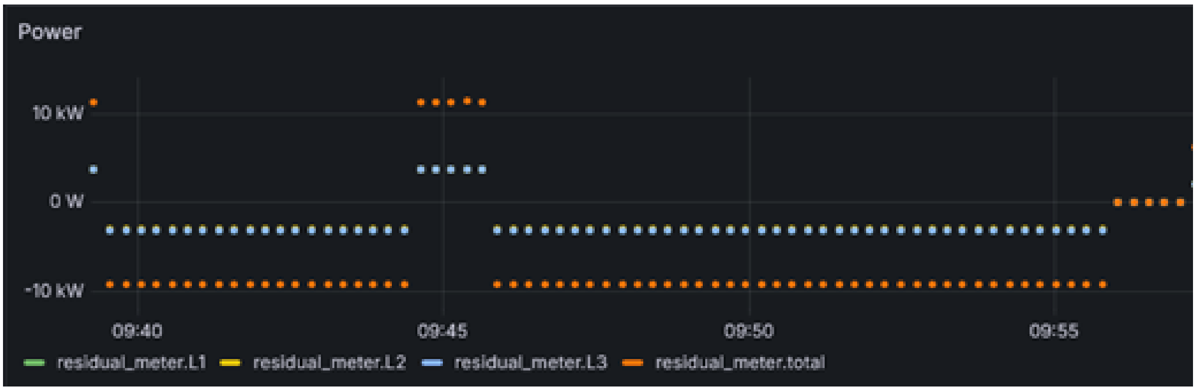

Figure 48: Testing results

7.2.3 Charging Station Failure

During another scheduled charging test with the MG4, a series of malfunctions occurred that prevented normal charger operation. At the start of the test, the vehicle was unlocked and communication with the charger appeared to initiate correctly. The charging session started, but terminated almost immediately.

On the second attempt, the session did not start at all. Instead, the charger moved unusually quickly from the Preparing state to Finishing, without delivering any power. During this phase, the charger emitted several unusual mechanical or electrical noises, indicating that an internal component might not have been operating correctly.

A third attempt resulted in the charger entering a Faulted state. To continue troubleshooting, a full reboot of the charging unit was performed. After rebooting, the charger returned to the Available state and appeared operational.

When the cable was reconnected to the MG4, the charging session initiated successfully. The initial charging power was approximately 6 kW, which was within expectations. However, after the charging profile was increased to 11 kW, a loud bang was heard from inside the charger, after which the circuit breakers tripped and power was cut off completely. This indicated a likely electrical failure inside the charging station, as shown in Figure 49.

Subsequent inspection confirmed that the failure was not systemic. According to the manufacturer, it was an isolated production error affecting only this specific unit rather than a design flaw or a wider batch issue. Although the incident disrupted testing, identification of the root cause as a one-off manufacturing issue reduced concern regarding broader reliability and allowed testing to continue on other units.

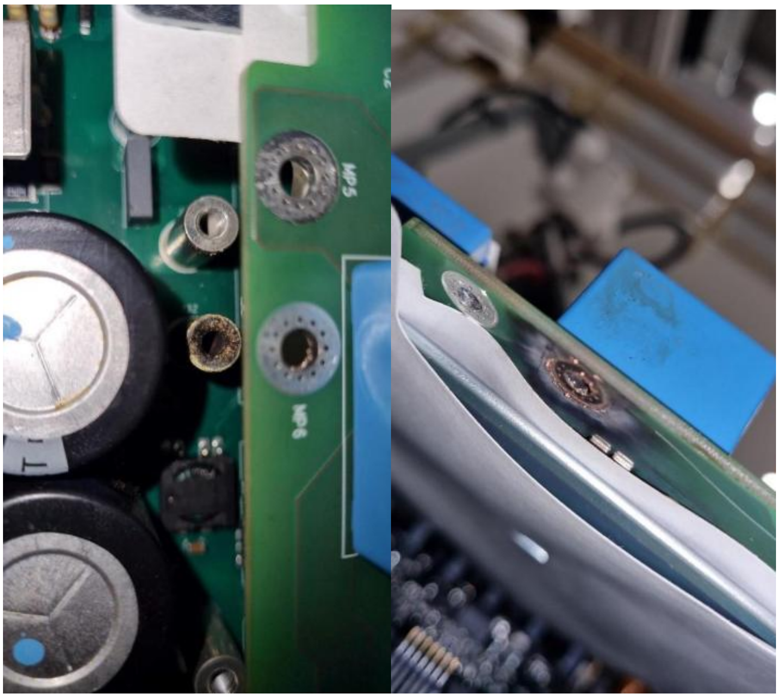

Figure 49: Charging station failure

7.2.4 Testing with Hyundai Kona - charging and analysing the thermal measurements

On 30 May 2025, a V1G-only charging test was performed using the Hyundai Kona. The vehicle was connected normally, but the charger required 33 seconds to initiate the charging session, which is longer than typical. Based on previous observations and system behaviour, this delay is most likely linked to an unsuccessful or prolonged ISO 15118-20 negotiation phase, resulting in additional time before a stable communication handshake is established.

Once charging was underway, the process remained stable until approximately 14:48 local time, when a sudden and unexplained drop in charging power to 3.18 kW was observed. This drop did not correspond to any known operational constraint, user action, or external grid event. It was therefore classified as an unexpected fluctuation without an immediately identified cause. The session then continued without further interruption.

Thermal measurements were performed at 15:00 to capture the temperature profile of both the charger and cable components under steady charging conditions. These measurements provide an important input for assessing thermal stability, long-term reliability, and safe operation in V1G charging scenarios.

Two main findings resulted from this test:

- A repeated pattern of delayed charging initiation, likely associated with communication negotiation.
- An isolated and unexplained power drop requiring further technical investigation.

The recorded power curve shows the following sequence:

- At approximately 14:43, charging power increased sharply from 0 kW to around 3.6 kW and remained stable for several minutes.
- Shortly afterward, charger output increased again to slightly above 11 kW (approximately 11.2–11.4 kW), where it remained stable for most of the charging period.
- At 14:48, a clear drop to 3.18 kW occurred. This event was abrupt, short in duration, and not correlated with temperature increase, user interaction, or grid-side changes. Its cause remains unexplained.
- The graph in Figure 50 also shows a second power disturbance near the end of the session, where both vehicle and charger ramped down almost simultaneously, confirming that the system returned to normal operation after the initial anomaly.

This power(time) profile suggests that the Kona's onboard charger behaved consistently, while the charging station experienced at least one short and isolated control or regulation irregularity.

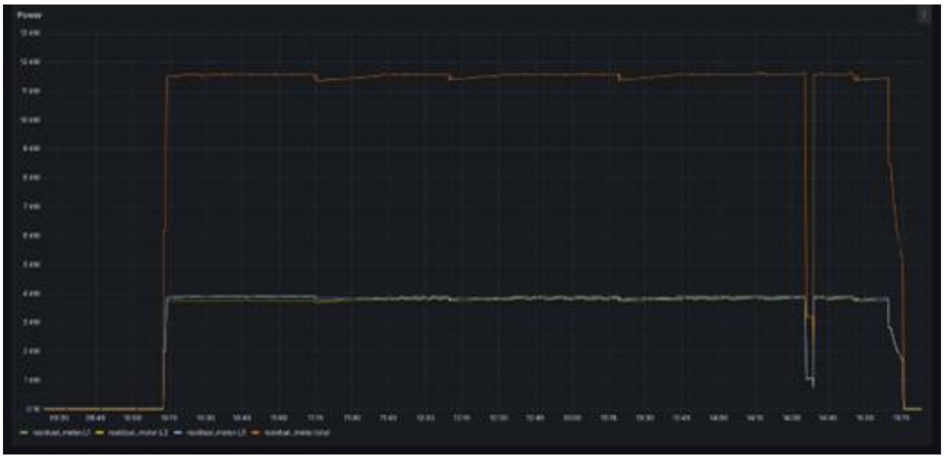

Figure 50: Results

A thermal inspection of the ABB Terra Nova 11C unit was carried out at 15:00, shortly after completion of the charging test. The FLIR measurement recorded a maximum surface temperature of 47.3 °C on the charger housing. The hottest region was located in the upper left front quadrant, consistent with the expected location of internal power electronics. The lower part of the charger and the cable-entry area remained significantly cooler, at approximately 20–25 °C.

A peak temperature of 47.3 °C is within the normal operating thermal range for ABB Terra Nova chargers under continuous 11 kW load. There was no indication of overheating, no sign of temperature-related throttling, and no evidence that thermal behaviour contributed to the earlier power drop. The results of the thermal measurements are presented in Figure 51.

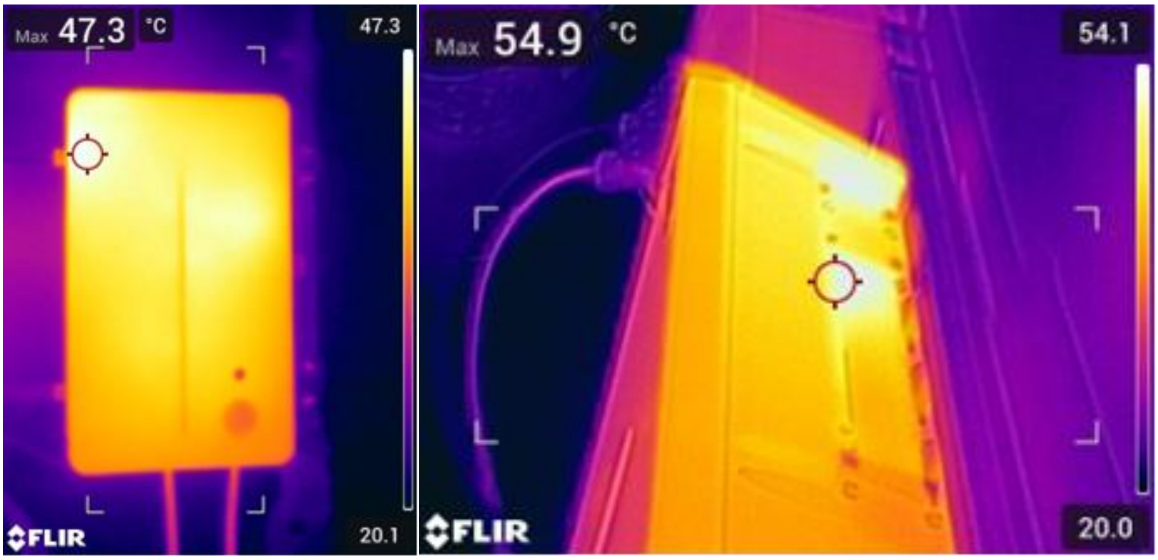

Figure 51: Results of the thermal measurements analyse

7.2.5 Testing with Tesla 3

On 1 August 2025, the first fully stable V2G discharge session with a Tesla Model 3 was achieved. Prior to the test, ABB developers implemented targeted firmware modifications on the Terra Nova 11C charger in order to improve handshake reliability, DC link control, and discharge-command behaviour. These upgrades were successful. The charger maintained a steady 10 kW discharge over an extended period, without protection trips, derating events, or unexpected communication interruptions.

Using the ABB Terra Nova 11C charger (serial TND11IT10223009), stable V2G discharge with the Tesla Model 3 was achieved after these firmware modifications. The power trace in Figure 53 shows several initial bidirectional pulses between +10 kW and -10 kW, confirming reliable control-signal negotiation, followed by sustained discharge periods at -10 kW from approximately 13:00 to 13:30, without oscillations, derating, or faults. These discharge intervals form stable rectangular plateaus, demonstrating that the charger maintained DC link regulation and that the vehicle responded correctly to backend discharge commands. The session concluded with a controlled return to 0 kW at approximately 13:45.

Figure 52: Results of the testing with Tesla Model 3

7.2.6 Testing with Hyundai Kona

On 1 September 2025, a series of V2G discharge tests was carried out using the Hyundai Kona. System operation was first verified through standard AC charging. After normal behaviour had been confirmed, the first discharge phase was initiated at 5 kW for 5 minutes. The system responded as expected, with stable power output and no interruptions.

The discharge power was then increased to 10 kW and maintained for 30 minutes. The vehicle and infrastructure operated without anomalies throughout this interval.

After completion of the first discharge sequence, charging was resumed briefly in order to re-establish baseline conditions. A second discharge test at 10 kW was then executed for 45 minutes. This phase also proceeded without issues, confirming reliable discharge performance at higher power levels over an extended period.

Overall, all discharge tests were completed successfully, and the Hyundai Kona showed stable performance across all tested scenarios (Figure 53, Figure 54).

Figure 53: Results of the testing with Hyundai Kona

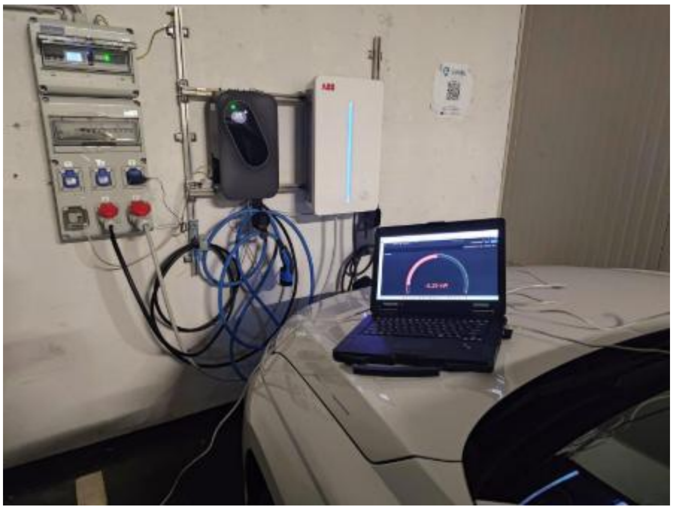

Figure 54: Testing site in Ljubljana

7.2.7 Testing in Krško demo site

At the GEN-I Krško office site (Figure 55), the demonstration environment was integrated by deploying and commissioning four V2G-capable ABB Terra Nova 11C prototype charging stations connected to the site’s dedicated electrical distribution architecture. The chargers were integrated into the local distribution box, which aggregates measurements from each EVSE, including voltage, current, power flow, and energy values.

This distribution box is electrically connected upstream to the main distribution board, which also supplies the GEN-I office building and the 100 kWp rooftop PV system, forming a unified electrical node. The entire system is connected to the medium-voltage transformer TP Inkubator Vrbina 946, owned by Elektro Celje, which links the demo site to the public distribution grid.

From the communication perspective, all four chargers were integrated with the GEN-I backend and fully connected to the Virtual Power Plant (VPP) platform. This enabled coordinated control, data acquisition, OCPP communication, and participation in flexibility activation services. The integration supports both controlled charging (V1G) and bidirectional operation (V2G), depending on project needs.

On 25 September 2025, a series of charging and discharging tests with the Hyundai Kona was performed at the Krško site. The test covered four ABB Terra Nova 11C chargers installed at the location.

Three chargers—TND11-IT1-5022-118, TND11-IT1-4722-043, and TND11-IT1-0323-001—performed as expected, with no irregularities detected during charging or discharging sequences.

However, charger TND11-IT1-0323-083 did not accept the OCPP SetChargingProfile command. This issue was reproducible across multiple attempts. Internal notes indicate that this unit had a different configuration on the ABB management portal, specifically in the “Authorization enabled” parameter, compared to the other chargers at the Krško site. ABB was informed of this discrepancy and provided with the relevant context.

All other tested functions operated normally, and the communication chain behaved consistently across the remaining chargers.

Figure 55: Demo site in Krško

7.2.8 Testing the End-to-end Communication Chain from DSO to EV

On 16 December 2025, two Hyundai Kona vehicles were transported to the Krško demonstrator site, where a complete end-to-end communication chain test was performed. Interoperability across all system layers was successfully validated. Activation signals were initiated on the FlexIS platform, forwarded to the GEN-I VPP, processed by the GEN-I V2G Charging Stations Management System (CSMS), and then sent as OCPP control commands to the ABB Terra Nova 11C charging stations on site. The chargers executed the commands correctly, and the Hyundai Kona vehicles responded as expected, confirming full operational flow across the sequence

FlexIS → GEN-I VPP → GEN-I V2G CSMS → ABB Terra Nova 11C charging station → Hyundai Kona

This test demonstrated reliable bidirectional communication and confirmed that the Krško infrastructure can support coordinated V2G activations across multiple EVSEs.

Figure 56 shows the power response of the system during a regulation activation sequence, including requested regulation power, actual operating power, and effective power. The test demonstrates that the system can follow both negative and positive power setpoints with good accuracy.

The following observations summarise system response during the activation sequence:

1. Initial Negative Activation (~ –10 kW)
    - At the beginning of the interval, the requested regulation power drops to approximately –10 kW.
    - The operating power follows this command, stabilizing around the requested level with only minor oscillations.
    - This indicates that the EVSE + vehicle combination responds reliably to downward regulation requests.
2. Transition to Positive Activation (~ +20 kW)
    - Shortly after, a strong upward activation is requested, reaching roughly +20 kW.
    - The system ramps up quickly, and both effective power and operating power reach and maintain the requested level.
    - A small dip is visible mid activation (a short drop of a few kW), but the system recovers immediately and continues tracking the requested value.
    - This demonstrates stable V2G discharging capability at higher power levels.
3. Sustained Setpoint Tracking
    - For the remainder of the activation period, the system maintains power delivery close to +20 kW, with minimal deviation.
    - This stability confirms that the complete communication chain (FlexIS → VPP → CSMS → Charger → Vehicle) correctly maintains target values over an extended interval.
4. End of Activation
    - Toward the end of the graph, the requested power returns to 0 kW.
    - The operating and effective power follow this downward ramp cleanly, returning to neutral with no overshoot.

The results in Figure 56- demonstrate successful tracking of both negative and positive regulation signals, stable performance at approximately 20 kW discharge power, and correct execution of setpoint transitions. The minor fluctuation observed during positive activation was short and self-correcting.

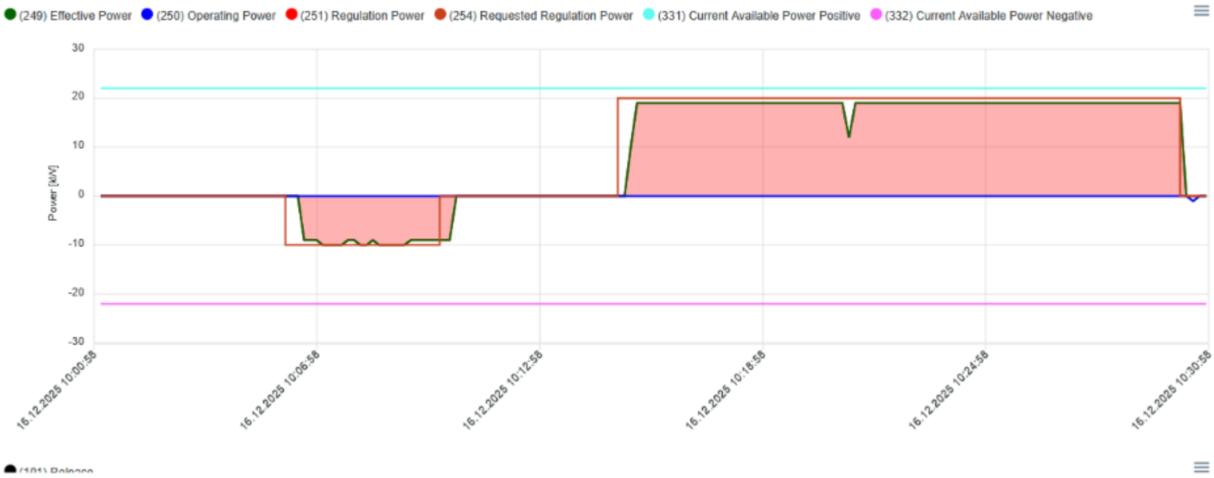

Figure 56: Results of the communication chain testing

The graph in Figure 57 shows execution of a single negative activation, where the requested regulation power dropped to approximately -18 to -20 kW. Both operating and effective power followed the command closely throughout the entire activation window. After activation began, the system reached the target negative power level almost immediately and maintained it steadily, with no visible oscillations or deviations. At the end of the activation period, the requested power returned to 0 kW, and both operating and effective power ramped back accordingly, confirming clean and controlled deactivation.

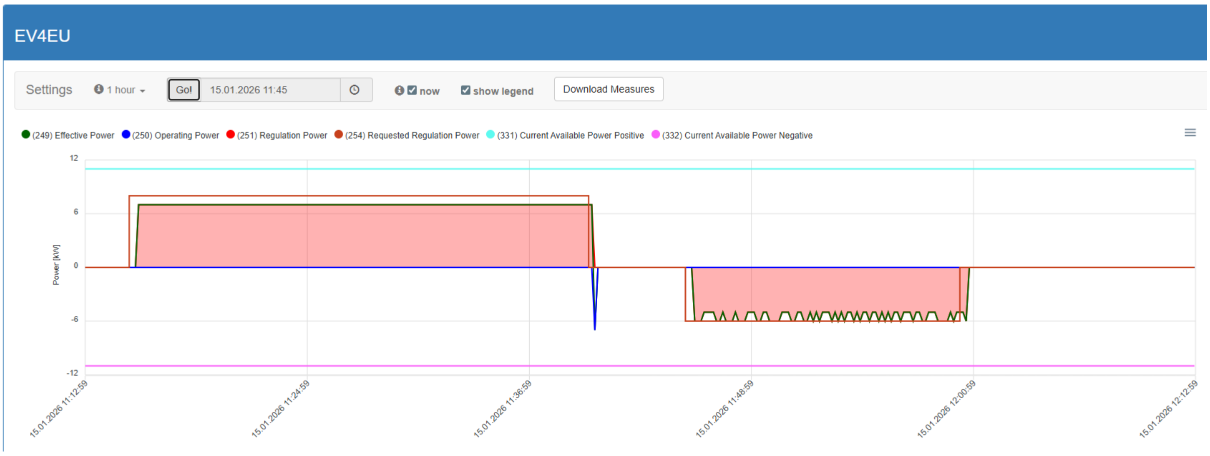

Figure 57: Results of the charging and discharging

7.2.9 V2G Control Loop Description (CSMS → CS → EV)

The purpose of this use case is to demonstrate that the GEN-I V2G CSMS can successfully control a charging station to perform bidirectional power flow with a connected EV. This is achieved by issuing charging and discharging setpoints in the form of charging profiles and verifying that the power delivered by the EV corresponds to the commanded values through independent external measurement.

The test setup involves the GEN-I CSMS sending OCPP charging profiles to an ABB Terra Nova 11C charger. Once a DC charging session is established, the charging station applies the received setpoints in real time. The EV and its Battery Management System (BMS) ultimately determine whether discharging is permitted, since V2G behaviour is governed by vehicle-side control logic.

During the demonstrations, EV–EVSE communication followed the ISO 15118 protocol. Bidirectional operation was enabled by initiating a standard DC charging session, including insulation-resistance testing and DC-voltage alignment, and then reversing current flow. Successful discharge therefore depends on EV/BMS acceptance, which in some cases may not be represented correctly in the vehicle user interface.

For successful operation, the charging station must accept negative setpoints and execute the corresponding discharging profiles. External metering must confirm energy flow from the EV back to the grid. In addition, discharging must remain stable for a sustained period and be repeatable across multiple test runs, with all stop reasons recorded accurately.

Bidirectional charging tests were performed across several EV models in order to evaluate interoperability, stability, and responsiveness to commanded discharging setpoints issued through the V2G control loop. The results reflect differences in BMS logic, firmware maturity, and V2G readiness between manufacturers.

The observed discharging behaviour can be summarised as follows:

- **VW ID.7 (FW 5.2):** discharging achieved at approximately -5 kW for around 70 seconds.
- **MG4:** successful discharging at, for example, -10 kW, but with inconsistent behaviour, including repeated session stops with the reason “local” after approximately 10 minutes.
- **Tesla Model 3:** longer stable discharge at 10 kW achieved after ABB firmware modifications.
- **Hyundai Kona:** stable and repeatable discharging demonstrated at 5 kW for 5 minutes, followed by 10 kW for 30 minutes; later tests sustained 10 kW discharge for 45 minutes without instability.

Vehicle interoperability proved to be the primary limiting factor. Acceptance and stability of discharge varied significantly between EV models and were determined largely by each vehicle’s BMS logic. A charger fault also occurred during MG4 testing, but this was later assessed as a non-systemic production issue rather than a structural problem with the setup.

7.2.10 Full-chain flexibility activation

The purpose of this use case is to demonstrate complete end-to-end orchestration of a flexibility activation request, where a flexibility signal originating from an upstream platform is translated through the GEN-I VPP and the GEN-I V2G CSMS into executable charging-station commands. This process should result in a measurable and verifiable power response at the EV connection point.

The tested activation chain includes the following sequence of systems and interfaces:

FlexIS platform → GEN-I VPP → GEN-I V2G CSMS → ABB Terra Nova 11C charging station → EV

Each link in the chain must successfully receive, interpret, and forward the control signal in order for the activation to be considered fully functional.

The test is considered successful when the control signal is propagated reliably across all elements of the chain. The charging station must accept the required OCPP commands, such as charging-profile setpoints, across the installed fleet. In addition, the delivered power response must be confirmed through external metering or telemetry, and comprehensive logging must be available for diagnosis and troubleshooting.

During the Krško site test on 25 September 2025, multiple chargers executed the required commands successfully. However, one charging station did not accept the OCPP SetProfile command, demonstrating that charger-to-charger variability may present an operational risk in end-to-end deployment.

A full communication-chain verification was performed on 16 December 2025 and resulted in a successful activation involving two Hyundai Kona vehicles. The entire sequence—from the FlexIS platform, through the GEN-I VPP and GEN-I V2G CSMS, to the ABB Terra Nova 11C charging station—operated as intended.

A live demonstration of this use case was presented during the EV4EU General Assembly on 20 January 2026, confirming the maturity and demonstrability of the full-chain concept

The behaviour of the full-chain activation inherits the limitations already observed in the CSMS → CS → EV control loop. These include dependence on ISO 15118 communication and reliance on EV/BMS logic for discharging behaviour. As a result, variability in vehicle acceptance and response remains a key constraint for reliable and repeatable flexibility activation.

7.2.11 Live demo

As part of the EV4EU project, the EV4EU platform was developed as an integrated ecosystem for management of V2G, flexibility services, and distribution-grid operations. At GEN-I, an advanced VPP was established to aggregate various flexibility assets, including energy storage systems, PV plants, and V2G charging stations, through smart controllers and IoT devices enabling real-time monitoring and remote control.

The platform includes both a commercial VPP (cVPP) for cooperation with the TSO and a technical VPP (tVPP) for activations at the DSO level. It also includes flexibility estimation, forecasting algorithms, and real-time data acquisition from measurement devices across the grid.

Development of the platform also included integration of new algorithms and methods for prediction of EV behaviour, assessment of flexibility potential, and support for automated activations required by the EV4EU demonstrators. Within the project work packages, V2G management strategies were developed together with aggregation tools, communication layers for charger integration and an open V2G platform enabling testing of different load-management and flexibility-service approaches.

During the EV4EU General Assembly on 20 January 2026, a live V2G demonstration was carried out to showcase real-time charging control and system responsiveness. The demonstration vehicle, initially at 52% state of charge, remained idle at first. A downward activation was then triggered, driving charging-point power to approximately -10 kW, where it remained stable throughout the requested interval. This was followed by a positive activation, to which the system responded immediately by increasing power to approximately +10 kW and maintaining that level consistently until the end of the sequence.

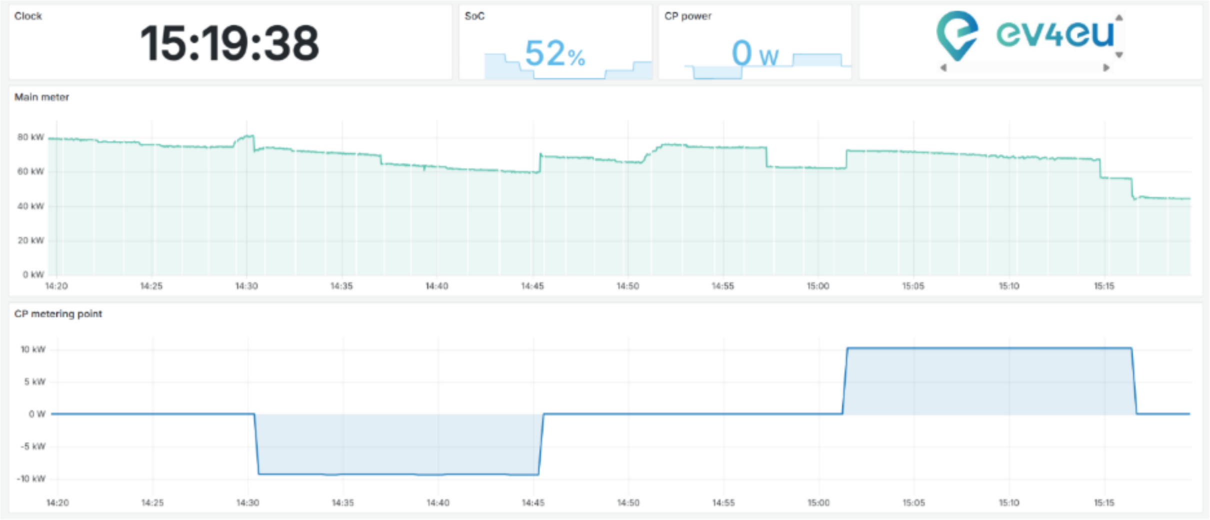

Figure 58: EV4EU platform and measurements during live demo

The main meter trace confirmed clean transitions between activation levels, with smooth power gradients and no oscillations, demonstrating reliable end-to-end control from the central platform to the charging point in a live-event setting.

The demonstration also confirmed that the activation signal was delivered through the FlexIS platform, originating directly from Elektro Celje's system, and was correctly received, interpreted, and executed by the GEN-I VPP, the V2G CSMS, and finally by the charging point and vehicle. The system responded immediately and accurately to both negative and positive power requests, maintaining stable operation throughout the activation windows. This confirms both the technical readiness of the V2X infrastructure and the successful real-time integration between the DSO (Elektro Celje) and GEN-I control platforms.

The live demonstration was completed successfully, with the system consistently following both negative and positive power activation requests without delay or instability. The charging point responded immediately to the downward activation at approximately -10 kW, maintained stable discharge throughout the interval, and then transitioned smoothly into the upward activation at approximately +10 kW, again holding the requested power level accurately. Main meter measurements confirmed clean and controlled power transitions, demonstrating that the entire control chain—from the central platform to the charging point—operated reliably and in accordance with the expected behaviour. This shows that the system is capable of delivering stable and predictable V2X services under real-time conditions.

Figure 59: Live demonstration with Kona

7.3 Evaluation of Charger Response Time and Power Error Compensation for an ABB V2G-Capable Charging Station

For evaluation of charger response time and other characteristics a dedicated experimental environment was constructed to ensure precise, time synchronized measurements of electrical parameters and charger control behaviour. To adequately quantify charger response time, more than 100 step change events were analysed. Results provide deeper insight into the dynamic performance of the charging station and its suitability for grid services and smart charging applications.

Accurate characterization of charging station behaviour is essential for effective participation in flexibility services. Applications such as demand response, frequency regulation, and V2G operations require chargers to follow power setpoints with minimal delay and high precision. Deviations in response time or steady state tracking accuracy can significantly influence system -level control strategies.

7.3.1 Experimental Setup

To evaluate the control behaviour of the charging point, a dedicated laboratory setup was constructed. Simplified system diagram is shown on Figure 60. The charging station was connected to the electrical grid through a high precision AC power meter capable of measuring voltage, current, active power, and energy with high sampling frequency. A data acquisition (DAQ) system collected these parameters continuously and transmitted them to a time series database for post-processing and analysis.

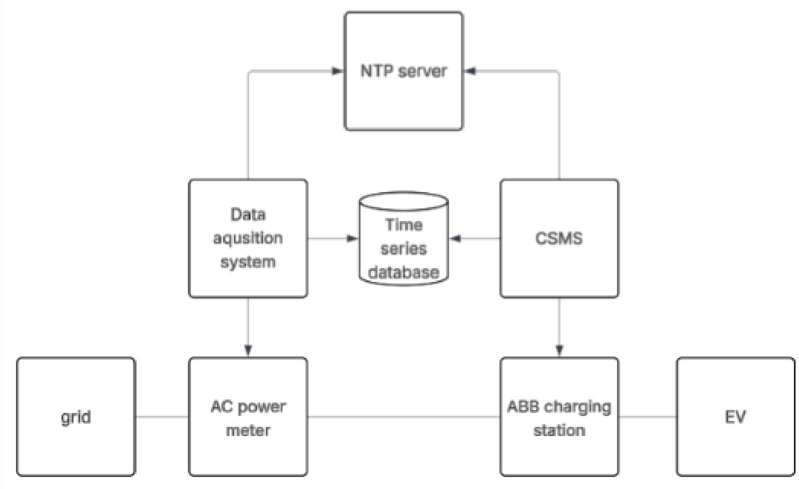

Figure 60: Laboratory system setup diagram

To ensure accurate time correlation between sent setpoints and measured power values, both the DAQ system and the CSMS were synchronized using a Network Time Protocol (NTP) server. This synchronization eliminated measurements misalignment and allowed high-fidelity calculation of the charging station's response time. A real EV was used to complete the test chain, enabling realistic charging behaviour under controlled laboratory conditions.

7.3.2 Response -Time Evaluation

A dedicated setpoint step profile was generated to analyse the charger’s dynamic response across a range of power levels and power flow directions. The profile included upward and downward step changes, ensuring a representative dataset for evaluating different operational conditions. Setpoint profile and charger response charts are shown on Figure 61.

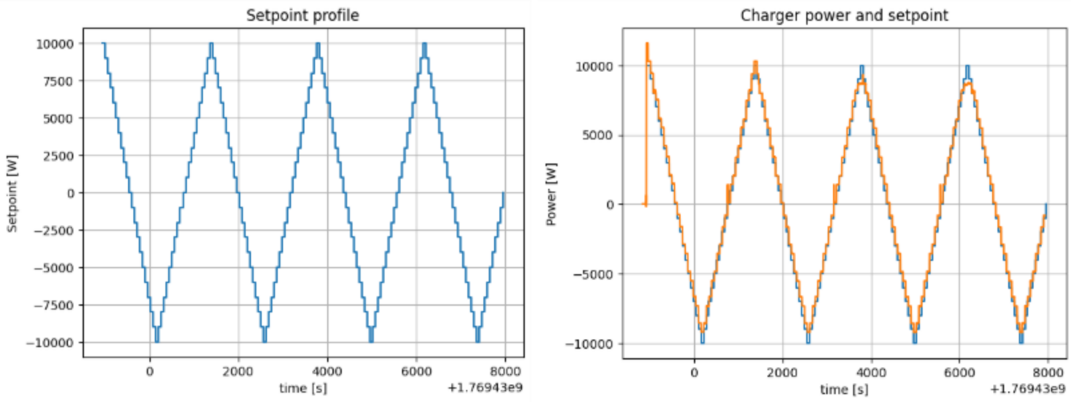

Figure 61: Setpoint profile chart and charger response power and setpoint

During testing, more than 100 step change events were recorded. The time delay between issuing a new setpoint and observing a corresponding change on the AC power meter was computed for every step. An example of a step change and histogram of measured response times are shown on Figure 62. The mean value of all measured delays was 3.2 s.

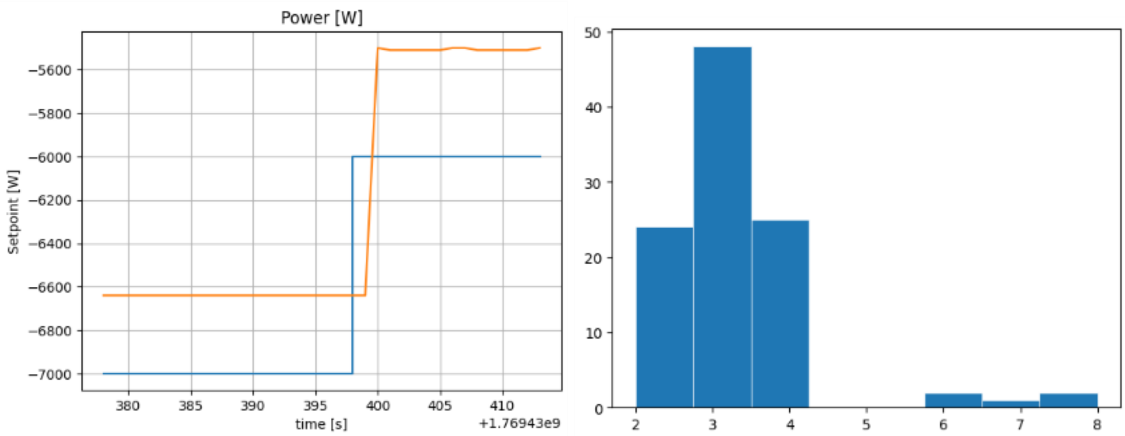

Figure 62: Single step change event and histogram of measured delays

The measured response time of 3.2 seconds makes the evaluated ABB charger applicable for most flexibility services. On the other hand, this delay may be limiting for services requiring sub second control response, such as primary frequency regulation.

The cause for difference between commanded power and measured AC side power is in charger control system design. The setpoint actually controls power delivered to EV (the power on the DC side). Measured AC power thus includes internal system losses, self-consumption- as well as AC-DC and DC--DC conversion losses. Although these losses do not affect delay calculations, they introduce a steady state tracking error that must be compensated. The development of compensation function is presented in the following chapter.

7.3.3 Power -Error Compensation

To evaluate steady state accuracy, a modified setpoint profile with smaller, more continuous power steps was applied. This approach allowed finer resolution of the relationship between the commanded setpoint and the measured AC side power. Figure 63 displays modified setpoint signal and distribution of errors which seem to be almost perfect normal distribution. Although normal distribution implies randomness of error, the closer look at profile on CP power chart, reveals that there may be some correlation between setpoint and error. We decided to conduct further analysis on which we will base our correction function.

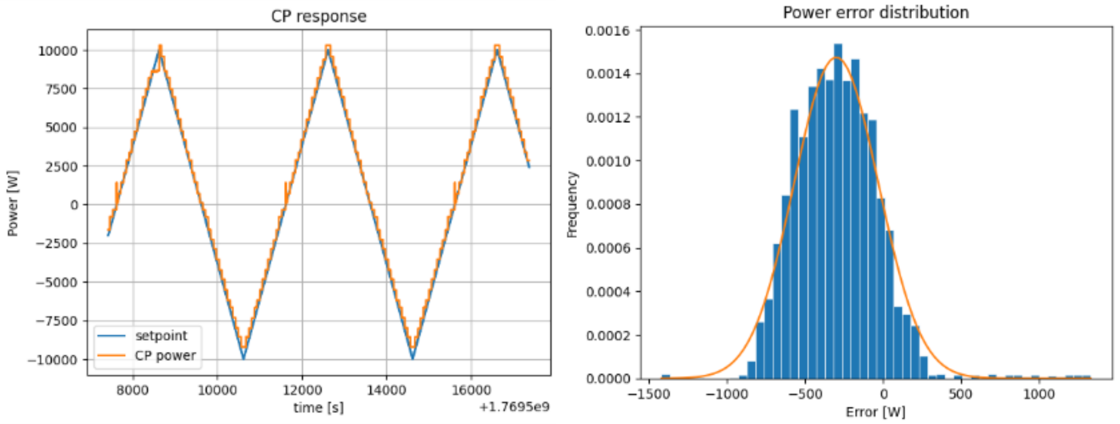

Figure 63: Modified setpoint profile and power error histogram with normal distribution function

A setpoint error scatter plot, show on Figure 64, revealed a pattern that confirmed our hypothesis, that error is correlated to setpoint. After analysis, a piecewise linear compensation function was selected and optimized to minimize average error across the entire setpoint range. Applying this compensation method significantly improved AC power accuracy. After implementation of correction function average error was less than 250 W and maximal error was 450 W. Although this is great improvement, more accurate response could be obtained using closed loop controller.

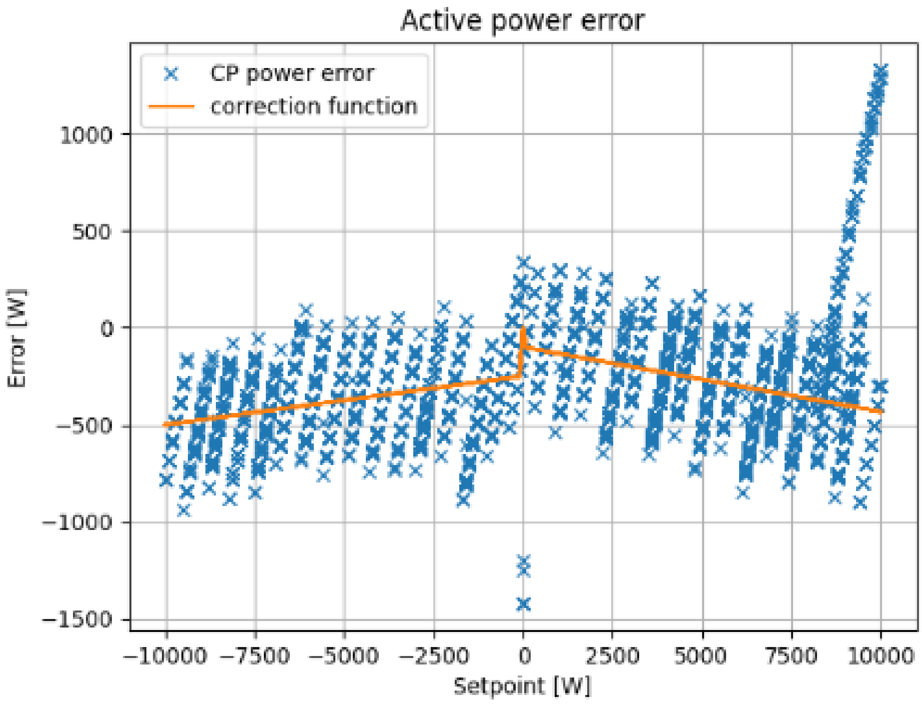

Figure 64: Scatterplot showing correlation between error and setpoint

Steady state power error is an important aspect of smart charging accuracy. Without compensation, tracking deviations caused by conversion losses can reach several hundred watts, depending on the setpoint. The piecewise linear compensation method developed here provides a practical way to reduce error without requiring any changes to charger.

7.4 Quantification of Flexibility Potential for Three Electric Vehicle Users

Flexibility potential associated with three individual EV users participating in a demonstrator project in Ljubljana was quantified using collected charging session data. Over the course of the 6-month observation period, more than 300 charging sessions were recorded across three workplace charging stations. Each charging session record included several measured parameters, such as delivered energy, charging duration, and nominal charging power. These data points provide an empirical foundation for characterizing user-specific charging behaviour and assessing the ability of EV users to contribute flexibility services.

Charging patterns among the three EV users, shown on Figure 65 exhibited clear behavioural distinctions. Histograms of delivered energy per charging session indicated three different usage profiles. User A showed a relatively narrow distribution centred between 10–30 kWh. This pattern is typical of users with consistent daily commuting habits and regular charging behaviour. In contrast, User B demonstrated a broader distribution with a noticeable shift toward higher-energy charging events in the 30–40 kWh range, suggesting more variable daily energy needs. User C displayed a bimodal distribution: a large number of very short sessions delivering less than 10 kWh, combined with occasional mid-range charging events. This dual peak structure may indicate frequent field trips or other type of exits during work and more than one charging events per day.

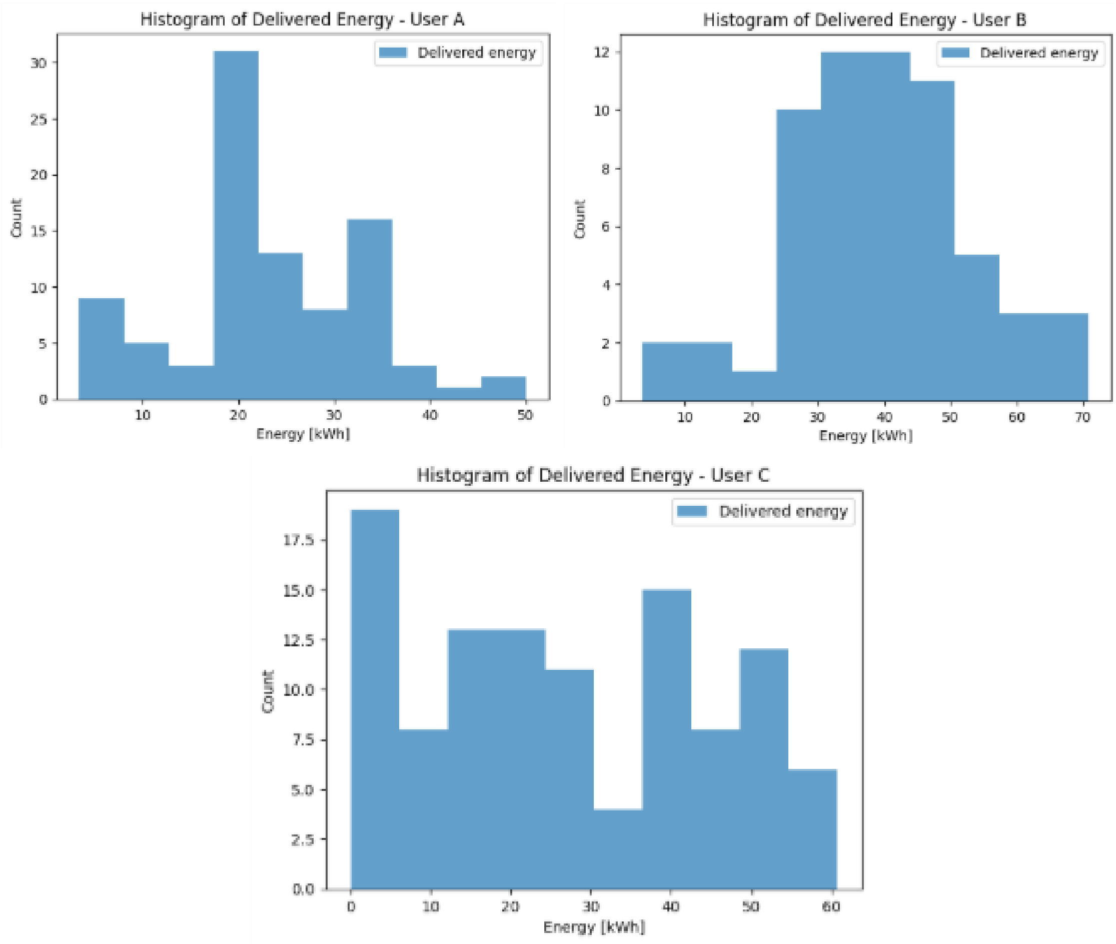

Figure 65: Distributions of delivered energy for 3 charge point users

Understanding these differences is crucial when evaluating flexibility potential. Flexibility services depend on the extent to which energy delivery can be temporally shifted without affecting quality of charging service. Users with predictable and longer charging sessions inherently have more unused time during which charging power can be adjusted.

Flexibility potential was estimated using a simple but robust model based on the difference between actual charging duration and the theoretical minimum time needed to deliver the recorded amount of energy at the charger's rated power. The available flexibility time $t_{available}$ was computed as:

$$t_{available} = \frac{E_{delivered}}{P_{charger}}$$

The corresponding available energy flexibility $E_{available}$ was calculated as:

$$E_{available} = t_{available} \cdot P_{charger}$$

It should be noted here that this model assumes constant charging power at chargers rated output power. This makes model only applicable to DC chargers with relatively low rated power, so it doesn't decrease at higher SoC.

Sessions with less than 15 minutes of potential adjustment were classified as providing no meaningful flexibility. Distribution of sessions availability potential is shown on Figure 66. We can see approximately half of sessions provide less than 15 minutes of flexibility potential.

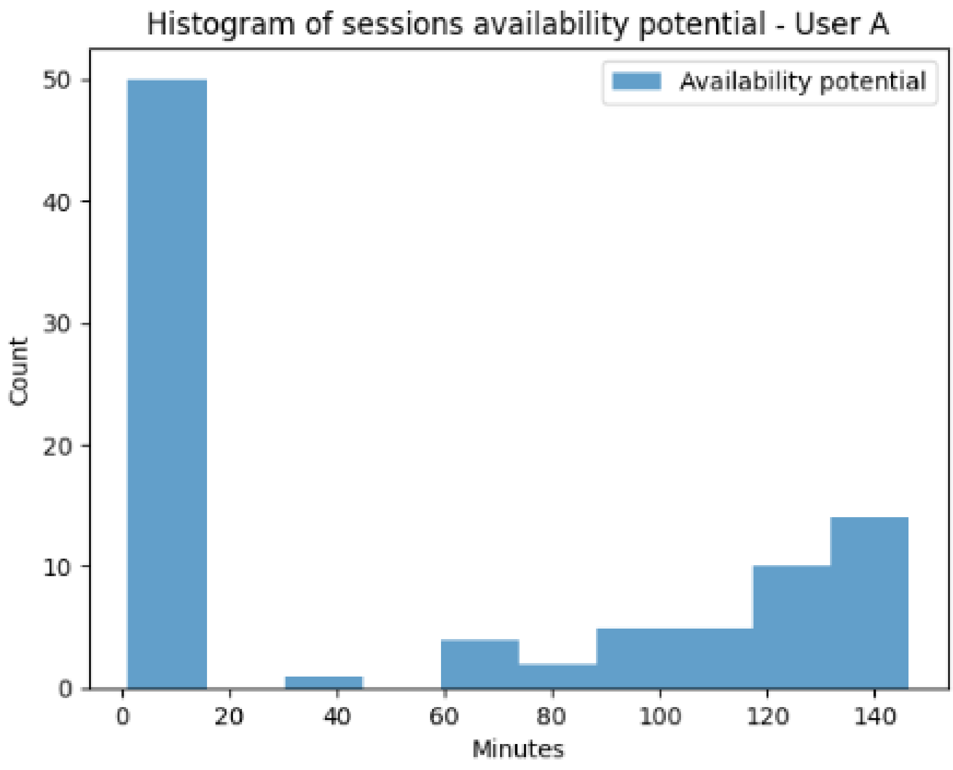

Figure 66: Histogram of session availability potential for user A

Application of this framework to charging sessions from 3 of our workplace charging stations from Ljubljan demonstrator revealed substantial user specific differences. Users B and C exhibited almost no meaningful flexibility potential. Their charging sessions were either too short, too variable, or too closely matched to the energy actually required. The lack of surplus charging time suggests that these users tend to begin charging later relative to their departure time or require a substantial portion of the session to deliver needed energy.

User A, by contrast, demonstrated a measurable flexibility potential across a significant portion of sessions. A histogram of User A's flexibility distribution showed that roughly half of the charging sessions provided no flexibility, whereas the remaining half offered between one and two hours of available time for flexibility. When analysed in the context of session duration, a clear behavioural pattern emerged. Session duration histograms showed two distinct peaks, suggesting the existence of two characteristic charging behaviours. One cluster likely reflects short, routine charging events tied to daily commuting, whereas the second cluster may represent longer sessions where the EV remains parked for extended periods, such as during full workday vehicle stays. The latter category accounts for most of the user's flexibility potential.

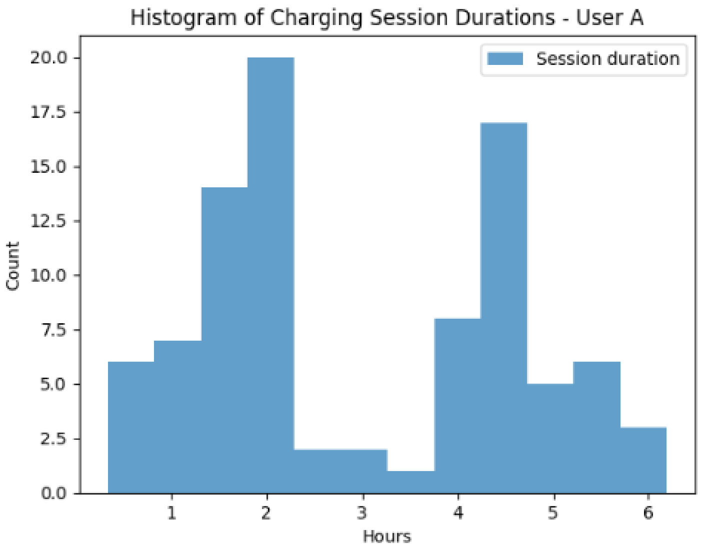

Figure 67: Histogram of Charging Session Durations for User A

The findings show that flexibility potential is not uniform and is strongly tied to individual charging behaviour. Users with predictable routines and longer parking durations, such as User A, naturally contribute more flexibility. Conversely, users whose charging behaviour is irregular or whose sessions are closely aligned with their energy needs cannot provide significant flexibility. This user dependence underscores the importance of personalized or segmented modelling approaches in smart charging system design.

From a broader perspective, the results highlight the need to integrate user behaviour analysis into flexibility forecasting for EV charging infrastructure. Aggregated models that assume homogeneity among users may considerably overestimate available flexibility. Instead, behaviour-based segmentation can improve the accuracy of flexibility predictions and support the design of user tailored incentive mechanisms.

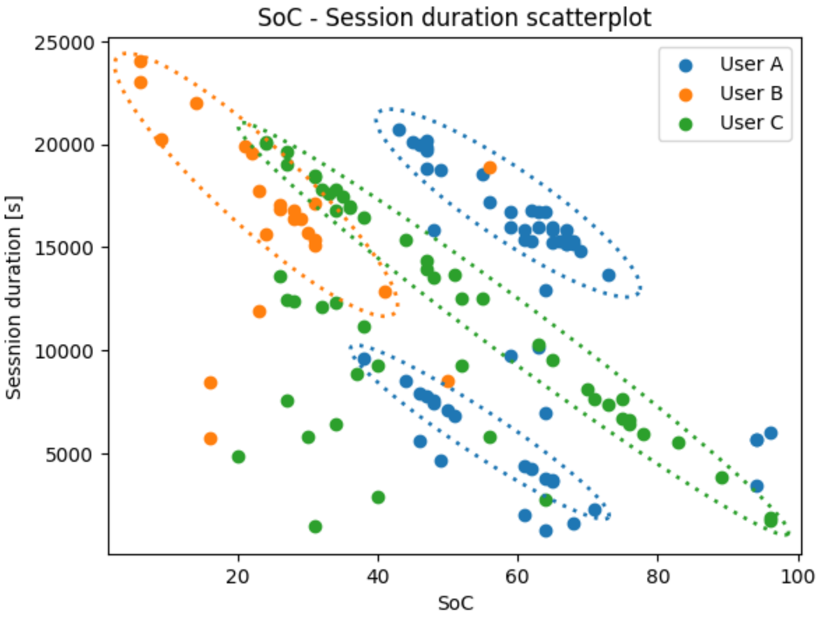

Figure 68: SoC - Session duration scatterplot

The scatterplot in Figure 68 illustrates the relationship between the initial SoC and session duration for Users A, B, and C, revealing clear user-specific behavioural clusters. Across all users, a general trend is observed: sessions initiated at lower SoC tend to last longer, reflecting the increased energy needed to reach the desired final charge level. User A demonstrates two compact clusters—one associated with short sessions and another with longer sessions—both occurring within a similar SoC range. This suggests that SoC alone may be insufficient for reliably estimating session duration at the start of a session, and that additional parameters may be required. User B exhibits a wider dispersion but forms a single dominant cluster, indicating that session duration can be more reliably inferred from initial SoC for this user. User C shows the most scattered distribution, including very short sessions at high SoC and long sessions at low SoC, suggesting heterogeneous charging behaviour such as frequent top-up events combined with occasional deep charging. Despite the wide variation in SoC values at the beginning of User C's sessions, a single primary cluster is still visible. Across all three users, approximately 80% of charging sessions fall within the identified clusters, while the remaining 20% lie outside them. This indicates that session-duration estimation based solely on initial SoC would be reasonably accurate for roughly 80% of sessions.

8 Slovenian use cases evaluation report

The Slovenian demonstrator within the EV4EU project showcases a comprehensive set of use cases designed to validate and accelerate the adoption of advanced V2X technologies. Building on Slovenia's strong energy innovation ecosystem, the demonstrator integrates EVs, smart charging infrastructure, BESS and flexibility services across key locations in Krško, Ljubljana, and Velenje.

The UCs focus on enabling bidirectional charging, optimizing grid stability, and unlocking new value streams for users and system operators. Together, they form a real-life testing environment that demonstrates how electric mobility can actively support the energy transition and contribute to a more resilient, decentralized and sustainable power system. Detailed description of UC9, UC10, UC11 and UC12 which were tested on Slovenian demonstrator are presented in section 4. For clarity and completeness, we briefly revisit the key use cases below, providing a refreshed and consolidated overview of their purpose and scope. The UCs are:

- Use-Case 9 (UC9): V2X management by a VPP. This UC aims to test the algorithms developed in task T4.4 and document in D4.4 [3], considering the aggregation of V2X flexibilities with other resources (generation, storage, etc.), taking into account the participation in multiple services and markets.
- Use-Case 10 (UC10): Participation of V2X in electricity markets. Demonstrate and evaluate the participation of V2X, aggregated with other resources, in markets at the national level such as energy market, Frequency Containment Reserve (FCR), and Fast Frequency Response (FFR) ancillary services markets (T4.4). This UC intends to understand the users' advantages of V2X participation in these markets (T4.5) and the impact that mass participation of V2X can have in these markets. The models are integrated into real tools, but participation in real markets is dependent on the market pre-qualification process that can take a long time. If participation in selected markets is not possible, the services will be validated using market emulation tools.
- Use-Case 11 (UC11): Participation of V2X in Grid Services. Demonstrate and evaluate the participation of V2X, aggregated with other resources, in markets and services at the local level (T4.4 and T4.5). In that case, the demonstration focuses on the contribution of V2X to solve problems in distribution systems, such as congestion management and voltage control. The goal of this UC is to evaluate the advantages for the users and DSO.
- Use-Case 12 (UC12): Activation of V2X services by DSOs. Before the market clearing, the DSO should be able to activate the services to be provided by V2X (T4.2). The activation is made in the Advanced Distribution Management System (ADMS) of the DSO in real time. In the first stage, integration and communication verification between VPPs and ADMS is performed, which is crucial for services activation. In this stage, V2X assets must be modelled appropriately in ADMS so that advanced functions can use V2X data. In the second stage, activation is triggered by the VPP operator (decision on the side of the aggregator). This aims to evaluate the activation of VPPs for the ADMS system, which can model EVs in different ways. In a third stage, the activation is triggered by the ADMS operator (decision on the side of DSO), considering the results of the market and the operation conditions of the distribution system [1].

These four use cases provide a comprehensive demonstration of how V2X technology can evolve from an emerging flexibility resource into a fully integrated component of both market operations and distribution system management. UC9 lays the foundation by testing advanced aggregation and control strategies within a VPP environment, ensuring that V2X can be optimally coordinated alongside other distributed resources. Building on this technical basis, UC10 assesses how such aggregated flexibility can participate in national electricity markets, exploring both the economic benefits for users and the broader system-wide effects of large-scale V2X involvement. Meanwhile, UC11 brings the focus to the distribution grid, showcasing how V2X can help DSOs address operational challenges such as congestion and voltage issues, and demonstrating the mutual advantages for system operators and end users. Finally, UC12 connects these elements by enabling DSOs to directly trigger V2X services through real-time ADMS activation, validating interoperability between aggregators and grid operators and ensuring that V2X flexibility can be deployed reliably in practice. Together, the four use cases form a unified framework that covers technical validation, market integration, grid support, and operational activation, illustrating the full potential of V2X within future energy systems.

As part of the Slovenian contribution to the project, we successfully carried out and tested a range of UCs across three demonstrator sites located in Krško, Ljubljana, and Velenje. Each demonstrator enabled the validation of specific functionalities and real-life operating conditions for advanced V2X technologies, smart charging, BESS integration, and grid-support services. Through these activities, we gained comprehensive insights into the technical, operational, and user-related aspects of implementation, confirming that the individual UCs can significantly contribute to the development of flexibility services, enhanced grid stability, and more efficient integration of EVs into the power system.

The Table 9 below provides an overview of the implementation and testing status of UCs 9 to 12 across the three Slovenian demonstrators. Demonstrator in Velenje focused primarily on validating functionalities through EV emulations with the BESS, while demonstrators in Ljubljana and in Krško executed real-life testing scenarios with CSs and EVs. The summary highlights which use cases were successfully tested in practice and which were assessed through simulation, offering a concise comparison of progress and maturity across all sites.

Table 9: Comparison of demos regarding tested UCs

	UC9	UC10	UC11	UC12
Demo in Velenje	Successfully tested with BESS	Successfully tested with BESS	Successfully tested with BESS	Successfully tested with BESS
Demo in Ljubljana	Successfully tested	Successfully tested	Successfully tested	N/A*
Demo in Krško	Successfully tested	Successfully tested	Successfully tested	Successfully tested

*- Since this demonstrator does not fall within the operational scope of Elektro Celje (EC) and does not function in this domain, Use Case 12 cannot be implemented.

8.1 UC9 – V2X Management by a Virtual Power Plant (VPP)

The activities conducted under UC9 demonstrate that V2X assets can be successfully integrated into, and controlled by, a VPP. Across all Slovenian demonstrator sites, the VPP reliably transmitted power setpoints to both BESS (Velenje) and V2X CSs (Ljubljana, Krško). The activation profiles were followed high accuracy and stability by the flexibility assets. The tests confirmed that heterogeneous flexibility assets battery storage, prototype CCS V2X chargers, and consequently compatible EVs can be aggregated and centrally managed.

While interoperability varied across EV models, the overall results validate the technical feasibility of V2X aggregation for flexibility provision. The most consistent performance was observed from the Hyundai Kona and BESS-based emulation, whereas other vehicles displayed firmware or protocol related limitations. Nevertheless, UC9 successfully demonstrated controlled bidirectional operation, reproducible power tracking, and reliable VPP–CSMS–CS communication, confirming the viability of V2X integration into real-world VPP infrastructures.

8.2 UC10 – Participation of V2X in Electricity Markets

UC10 confirmed that V2X-capable assets can participate in electricity markets such as mFRR and aFRR, either in real environments or using validated market emulation frameworks. BESS-based emulation of aggregated representative EV profiles showed that EVs can deliver both upward (positive) and downward (negative) flexibility in magnitudes relevant to ancillary services. The highest flexibility potential was observed in scenarios with predictable vehicle availability, particularly company EV fleets, which provide long plug-in durations.

Simulation studies (section 6.5) for the Krško site further quantified this potential:

- EV fleets can provide up to ~880 kWh of flexibility per day under favourable conditions.
- Under realistic charging station constraints, ~550 kWh/day remains technically achievable.
- Over a one-month simulation, aggregated EVs could provide 118 MWh of negative and 93.8 MWh of positive flexibility.

Additionally, the results (section 6.4) from the BESS demonstrator in Velenje indicate that activated emulated EV flexibility strongly depends on the connection times, user type, and service participation.Based on Velenje results we can conclude that in the mFRR service, the largest negative flexibility is achieved by weekend and workday scenarios for both home charging and company EV fleets, whereas the highest positive flexibility is provided by home charging of EVs during weekend. For aFRR, the highest negative flexibility is shared between home charging during weekends and company EV fleets (workdays and weekends), while the highest positive flexibility is delivered by company EV fleets during weekend and at home during workday.

The results demonstrate that V2X can support both slower and faster flexibility products, although continuous high-frequency activations require vehicles with sufficiently stable communication stacks and battery availability. Overall, UC10 confirms that V2X participation in electricity markets is technically feasible, scalable, and economically relevant as EV share increases.

8.3 UC11 – Participation of V2X in Grid Services

UC11 validated the use of V2X for providing distribution-level grid services, including congestion management, voltage control, and PV surplus mitigation. Technical tests and analytical work at TP Inkubator Vrbina confirmed that V2G can play a crucial role in addressing LV network issues.

Key findings include:

- Certain operating regimes of secondary substation are exceptionally well suited for V2G interventions, where approximately 120 kW of additional load is sufficient to lower voltage by 1 V.
- BESS-based EV emulations using developed aggregated representative EV profiles, successfully delivered both positive and negative flexibility services, directly reducing secondary substation loading, mitigating PV surplus, and following DSO-defined activation windows.
- For local flexibility services, the highest negative flexibility is provided by company EV fleets at work during weekends, while the highest positive flexibility is delivered by company EV fleets during workdays and weekends, following Velenje emulation results.
- High phase symmetry and consistent network behaviour indicate that aggregated V2G actions are effective at the system level, not only at individual phases.

The results confirm that V2X-enabled assets are technically capable of providing meaningful grid support, allowing DSOs to mitigate operational issues without relying solely on infrastructural reinforcement. UC11 therefore demonstrates that V2X represents a viable, scalable source of local flexibility for modern LV/MV distribution grids.

8.4 UC12 – Activation of V2X Services by DSOs

UC12 successfully demonstrated a complete, end-to-end activation chain initiated directly by the DSO. The Slovenian demonstrator validated the full workflow:

- DSO (ADMS) detects an operational constraint,
- ADMS → Lambda generates an activation request,
- FlexIS publishes flexibility tenders and activation signals,
- EVT forwards the request to the aggregator,
- GEN-I VPP processes the activation and sends power setpoints to the V2G CSMS,
- ABB V2X CSs execute the commands,
- Measurement systems confirm activation success to the DSO.

Testing at the Krško site, demonstrated reliable bidirectional activation with two Hyundai Kona vehicles, showing clean tracking of both downward (charging) and upward (discharging) power requests. The entire process from DSO detection to EV response have operated seamlessly, confirming interoperability among all system layers.

The UC12 results are significant because they prove that DSO-triggered activation of V2X flexibility is feasible in a real distribution network, using existing market and communication platforms (EVT, FlexIS) without affecting the EV user experience. This lays the groundwork for large-scale operational deployment of V2X-based grid services.

9 Conclusions

Deliverable D7.3 provides a complete overview of the Slovenian V2X demonstrator, describing the project context, partner roles, system background, and the technical setup of all three demonstration sites. It outlines how Slovenian grid characteristics, the national e-mobility landscape, and identified flexibility needs shaped the demonstrator objectives and implementation strategy. The document details the deployment of the BESS site in Velenje and the V2X charging infrastructure in Krško and Ljubljana, together with the development of aggregated representative EV profiles that enabled realistic testing of EV flexibility. It further explains the execution of all four UCs (UC9–UC12), including VPP-based V2X management, market participation, provision of grid services, and full DSO-initiated activation through ADMS, FlexIS and EVT platforms.

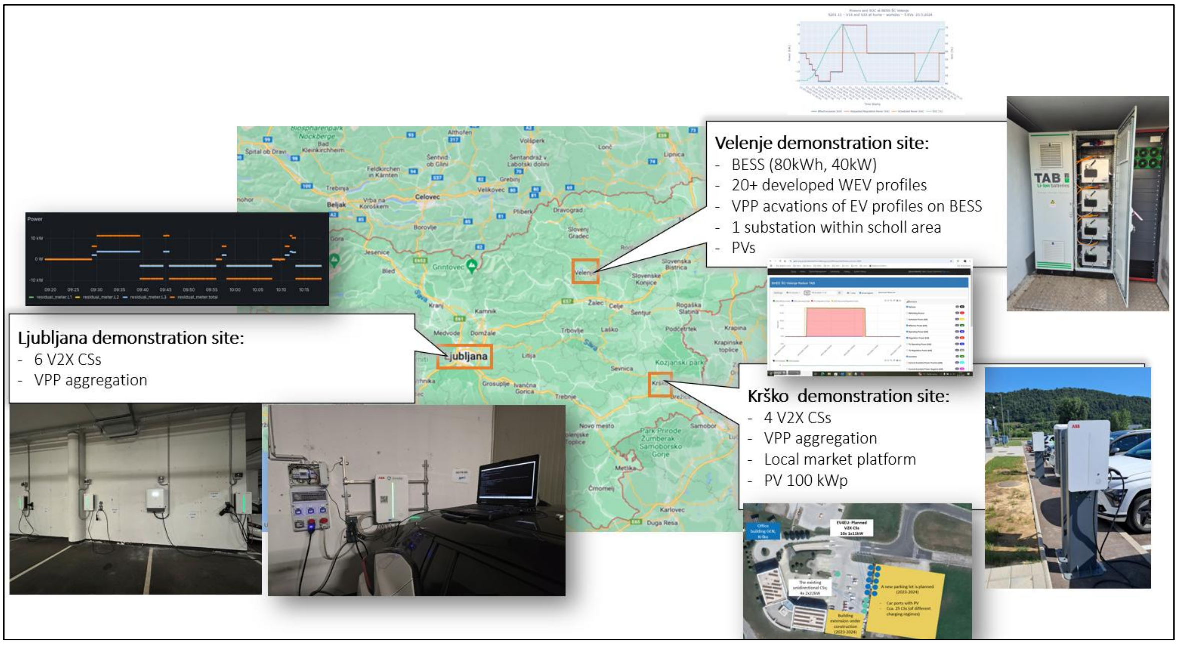

Figure 69: The Slovenian demonstrators

Extensive monitoring and analytical activities were conducted, including sensitivity modelling, day-ahead forecasting, evaluation of more than 50 VPP activations, selected KPI calculations, and quantification of EV flexibility potential across daily and monthly horizons. Charging infrastructure testing included laboratory and field validation, CHAdeMO-to-CCS transition, interoperability assessments, power-tracking accuracy evaluation, thermal profiling, response-time measurements, and verification of entire communication chain from DSO to EV.

The results confirm that V2X assets aggregated within a VPP framework can reliably provide flexibility services for both market and grid applications. The full communication from system-level detection and activation request to EV power response, was successfully validated under real and emulated conditions.

Overall, the Slovenian demonstrator provides strong evidence that V2X technologies, supported by appropriate communication, market, and control infrastructures, are ready to play a central role in future flexibility markets, grid management strategies, and largescale integration of electric mobility.

It is shown that V2X technologies can move beyond experimental pilots and become a powerful, scalable pillar of the future energy system. By successfully integrating EVs, advanced charging infrastructure, grid platforms, and market mechanisms, the demonstrator lays the groundwork for large-scale deployment of smart flexibility services across Slovenia and the wider EU. Its technical achievements ranging from automated DSO-triggered activations to reliable V2G operation and accurate forecasting prove that EVs can play an active role in stabilising the grid, supporting renewables, and participating in energy markets. As EV adoption accelerates and flexibility needs grow, the Slovenian demonstrator stands as a blueprint for future digitalised, user-friendly and clean energy ecosystems, showing how everyday EVs can collectively deliver significant value to the whole power system.

Finally, the results and insights collected in this deliverable serve as an important input for Deliverable *D7.4 Lessons learned in Slovenian Demonstrator and Services Marketability report*, contributing to the broader objective of enabling large-scale integration of EV-based flexibility into electricity markets and power system operation.

10 Bibliography

[1] T. Marentič, M. Zajc, I. Mendek, K. Anžur, M. Jug, M. Fejgelj, A. Kos, A. Smole, R. Jarc, M. Malenšek and L. Nagode, “Deliverable D7.1: Detailed definition and implementation plan of Slovenian,” Electric Vehicles Management for carbon neutrality in Europe (EV4EU) Horizon Europe funded project, Grant agreement 101056765, Online, 2025.

[2] A. Smole and e. al., “Deliverable D7.2 Slovenian demo commissioning and start-up report,” Electric Vehicles Management for carbon neutrality in Europe (EV4EU) Horizon Europe funded project, Grant agreement 101056765, Online, 2024.

[3] Marentič T. and et. all, “Deliverable D4.4: Impact of mass deployment of V2X in energy markets and services,” Electric Vehicles Management for carbon neutrality in Europe (EV4EU) Horizon Europe funded project, grant agreement 101056765, Online, 2024.

[4] M. Malenšek, R. Jarc, T. Rakar, A. Smole, T. Marentič, M. Zajc, I. Mendeš, K. Anžur, G. Papadakis and I. Nikolaos, “Deliverable D4.3: Integration of V2X in Charging Point Operators and Virtual Power Plants Aggregation,” Electric Vehicles Management for carbon neutrality in Europe (EV4EU) Horizon Europe funded project, grant agreement 101056765, Online, 2024.

[5] C. P. Guzman and e. al., “Deliverable D4.5 Demand Response Programs Design for EVs,” Electric Vehicles Management for carbon neutrality in Europe (EV4EU) Horizon Europe funded project, Grant agreement 101056765, Online, 2024.

[6] ELES, “Annual Report 2023,” [Online]. Available: https://www.eles.si/Portals/EN/ELES-Annual%20Report-2023.pdf.

[7] ELES, “Eles Slovenian transmission network,” [Online]. Available: https://www.eles.si/en/slovenias-transmission-network.

[8] A. z. Energijo, “Slovensko prenosno omrežje,” 2025. [Online]. Available: https://www.agen-rs.si/izvajalci/elektrika/prenosno-omrezje/slovensko-prenosno-omrezje.

[9] J. T. REPORT, “Local Electricity Flexibility Markets in Europe,” 2022. [Online]. Available: https://www.agen-rs.si/izvajalci/elektrika/prenosno-omrezje/slovensko-prenosno-omrezje.

[10] E. trade, “Slovenia records highest electricity demand due to severe winter,” 2026. [Online]. Available: https://www.bing.com/search?pglt=43&q=Slovenia+has+reached+a+new+record+in+electricity+demand&cvid=c166e7adabff4f7e95caeabbc0bcca68&gs_lcrp=EgRlZGdlKgYIABBFGDkyBggAEEUYOTIGCAEQRRg8MgYIAhBFGDwyBggDEEUYPDIICAQQ6QcY_FUyBwgFEOsHGEDSAQczODhqMGoxqAIAsAIA&FORM=A.

[11] EPRS, “Slovenia's climate action strategy - Roadmap to EU climate neutrality –,” [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/BRIE/2025/769559/EPRS_BRI(2025)769559_EN.pdf.

[12] PISRS, “Zakon o oskrbi z električno energijo (ZOEE),” [Online]. Available: https://pisrs.si/pregledPredpisa?id=ZAKO8141.

[13] Stat.si, “Republic of Slovenia Statistical office,” [Online]. Available: https://www.stat.si/StatWeb/en. [Accessed 15 9 2025].

[14] T. Marentič, D. Golubović, A. Kos, A. Smole, H. Morais and M. Zajc, “Demonstrating Electric Vehicle Flexibility via Stationary BESS Aggregated into a Virtual Power Plant,” *SSRN pre-print,* 2025.

[15] T. Marentič, D. Golubović, A. Kos, A. Smole and M. Zajc, “Participation of electric vehicles in local flexibility services: assessment of flexibility potential for a selected use case with V2X technologies,” in *17th Conference of Slovenian Electrical Power Engineers (CIGRE-CIRED) 2025*, Portorož, 2025.

[16] D. Golubović, “Časovno-prostorsko modeliranje dvosmernega polnjenja električnih vozil za načrtovanje prožnosti v distribucijskem omrežju,” Repozitorij Univerze v Ljubljani, Ljubljana, 2025.

[17] T. Marentič, I. Mendek, K. Anžur and M. Zajc, “Bidirectional power exchange between electric vehicles and the grid V2G for the development of flexibility services with aggregation of the EV fleet,” *Electrotechnical Review 90(5),* pp. 259-264, 2023.

[18] I. Mendek, T. Marentič, K. Anžur and M. Zajc, “A Case Study on Electric Vehicles as Nationwide Battery Storage to Meet Slovenia’s Final Energy Consumption with Solar Energy,” *Energies,* vol. 17, no. 11, p. 2733, 2024.

[19] T. Marentič, I. Mendek, A. Kos, M. Malenšek, H. Morais and M. Zajc, “Estimation of electric vehicles with V2G capabilities potential for market participation,” in *IEEE MELECON 2024*, Porto, 2024.

[20] *Electricity Supply Act (original title Zakon o oskrbi z električno energijo, ZOEE, UL RS št. 172/21),* 2021.