Living Lab

creos

Final Report

Acknowledgements

We would like to express a heartfelt thank you to our 14 participating families who accompanied us during this adventure and remained committed throughout the entire journey.

They remained patient when unexpected technical surprises arose, and most importantly, they remained curious to learn and to contribute to this project. We are grateful for having had you on our side!

A big thank you also to our over 60 colleagues from all over Creos, as well as all project partners involved. Despite many late evenings and head scratches, they supported us with their expertise and efforts.

Creos Innovation Team

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Executive Summary

The energy transition is rapidly transforming low-voltage (LV) electricity grids. Electrification of mobility and heating, combined with increasing photovoltaic (PV) generation and home storage battery systems, introduces new consumption and injection peaks that challenge traditional grid operation.

The Creos Living Lab tested, under real-life conditions, how future LV grids can integrate high shares of EVs, heat pumps, PV systems and batteries while maintaining reliability and customer comfort. Over one year, 14 households simulated the "2030 household" and enabled Creos to evaluate both customer behavior incentives and smart grid load management mechanisms.

To achieve this, households were equipped with technical installations reflecting future residential electrification:

- 16 full-electric vehicles
- 12 heat pumps
- 11 PV installations
- 4 residential battery storage systems
- 14 Home Energy Management Systems (HEMS) capable of steering EV charging and battery operation

In parallel, the project implemented key elements of the future smart grid architecture at local scale:

- Real-time LV feeder measurement devices at the transformer station
- Integration of granular measurement data into Creos' digital twin Kopr
- Forecasting algorithms for load and PV generation
- Implementation of both forecast-based and real-time load management strategies
- Interfaces enabling remote activation of smart meter relays connected to PV systems and EV chargers
- The Living Lab therefore served as a full-scale test environment for the Creos smart grid vision, delivering both operational and strategic insights for future decision making.

Smart Grid Findings

Forecast-based load management proved operationally suitable for PV injection peak reduction on sunny days, particularly in grid areas dominated by PV generation. Reliable solar irradiation forecasts combined with calendar-based relay signals enabled effective peak shaving without requiring ultra-fast communication infrastructure. This is especially relevant, as sustained sunny-day injection peaks are amongst the most critical scenarios for cable and transformer loading.

However, **limitations remain on days with intermittent cloud coverage**. Rapid PV fluctuations are difficult to predict accurately and forecast granularity can lead to missed short-lived injection peaks or temporary over-curtailment. While such days are generally less critical from a thermal cable and transformer overloading perspective, this highlights that forecast-based control is not yet fully robust under all meteorological conditions and probably cannot be in the future due to meteorological forecast limitations.

For consumption peak shaving, **forecast-based control did not prove sufficiently reliable**. The highly variable and behaviour-dependent nature of EV charging significantly limits the precision of consumption peak forecasts at a local scale. In addition to this, the frequent behaviour changes in the customer behaviour phases introduced misleading bias for the forecast algorithms. Fortunately, consumption forecast accuracy is expected to increase with a growing number of included households for statistical reasons. While valuable insights were gained, forecast-based consumption management cannot yet be considered operationally mature.

Real-time load management demonstrated technical suitability for both consumption and injection peak reduction. Winter evening peaks were significantly reduced by modulating EV charging speed, and sustained summer injection peaks were effectively curtailed. While real-time measurements enable detection of short-lived events, fully dynamic and highly precise curtailment remains challenging. The effectiveness of PV injection peak reduction on challenging days with intermittent clouds was improved compared to the forecast-based load management, but occasional short-lived peaks and unnecessary curtailment remained. Therefore, additional refinements are required to handle rapid fluctuations efficiently.

Moreover, real-time load management depends on new sensors, as well as low-latency and highly reliable communication with the customer devices, which is not yet available at scale. While PLC communication is sufficiently robust for daily smart meter data transmission, it represents a structural limitation for latency-critical real-time control. Scaling real-time load management would therefore require additional investments in measurement infrastructure and communication robustness.

Across both forecast-based and real-time approaches, the Living Lab demonstrated that nuanced and highly precise load reduction via smart meter relays is inherently difficult. In theory, load management aims to reduce exactly the amount of power required to stay within grid limits. In practice, numerous influencing factors, including forecast uncertainty, unpredictable EV connection status, real-time PV variability, relay configuration by installers, and communication constraints, make such surgical control challenging. To ensure reliable peak reduction, a conservative approach was required, meaning that more assets had to be selected for curtailment than theoretically necessary. Nevertheless, the reported impacts on customer comfort remained very low with only few households even noticing the load management phases.

The only exception was a household with two EVs needing to charge in a single night requiring the owner to complete the charge of the first car during the evening peak period in order to swap the charger to the second EV before bedtime. As load management reduced the charging speed during that particular evening, the charge of the first car was not completed and he needed to swap the charger again in the early morning.

Customer Behavior Findings

In winter, the Living Lab confirmed that combining incentives to shift EV charging outside the evening peak hours (17 to 22h), and to charge with reduced power successfully reduces low-voltage grid stress.

In summer, behavioral incentives increased local PV self-consumption and reduced overall injection levels. However, these measures were insufficient to reduce absolute injection peaks, especially when no EVs were charging and batteries were already full.

Residential batteries operating in standard self-consumption mode provided no grid support. In winter, PV generation was often insufficient to charge the batteries. In summer, batteries frequently reached full charge before the injection peak. Moreover, due to lower household consumption, batteries did not always fully discharge, which further limited their potential. Without targeted grid-oriented control strategies, batteries do not mitigate grid peaks.

Overall, participants adapted without significant comfort loss, and many adopted grid-friendly habits naturally. As a first step in the energy transition, simple solutions proved to be the most effective, as they are simple to understand and implement, and are therefore accessible to a large audience. On the other hand, complex solutions, such as complex automatization strategies in the home energy management system (HEMS) and dynamic tariffs, were less accessible and therefore less effective in the Living Lab.

An emergency simulation showed that households can reduce consumption by over 50% for short periods when motivated by solidarity and clear communication, further underlining the importance of customer behavior as a key puzzle piece in the energy transition.

An Ecosystem to Support the Energy Transition

Successful electrification and digitalization of homes requires:

- Proper planning and future-proofing during construction and renovation to facilitate electrification and reduce future installation costs
- Standardized and interoperable communication protocols
- Supporting continuous workforce upskilling, to equip professionals such as electricians and heat pump installers with the technical and digital skills needed to manage the energy transition

A resilient LV grid cannot rely on a single solution or actor to support the transformation of the energy system. The Creos Living Lab demonstrates that smart grids and active customers can significantly support the energy transition, provided that technical robustness, workforce readiness and awareness-raising evolve in parallel.

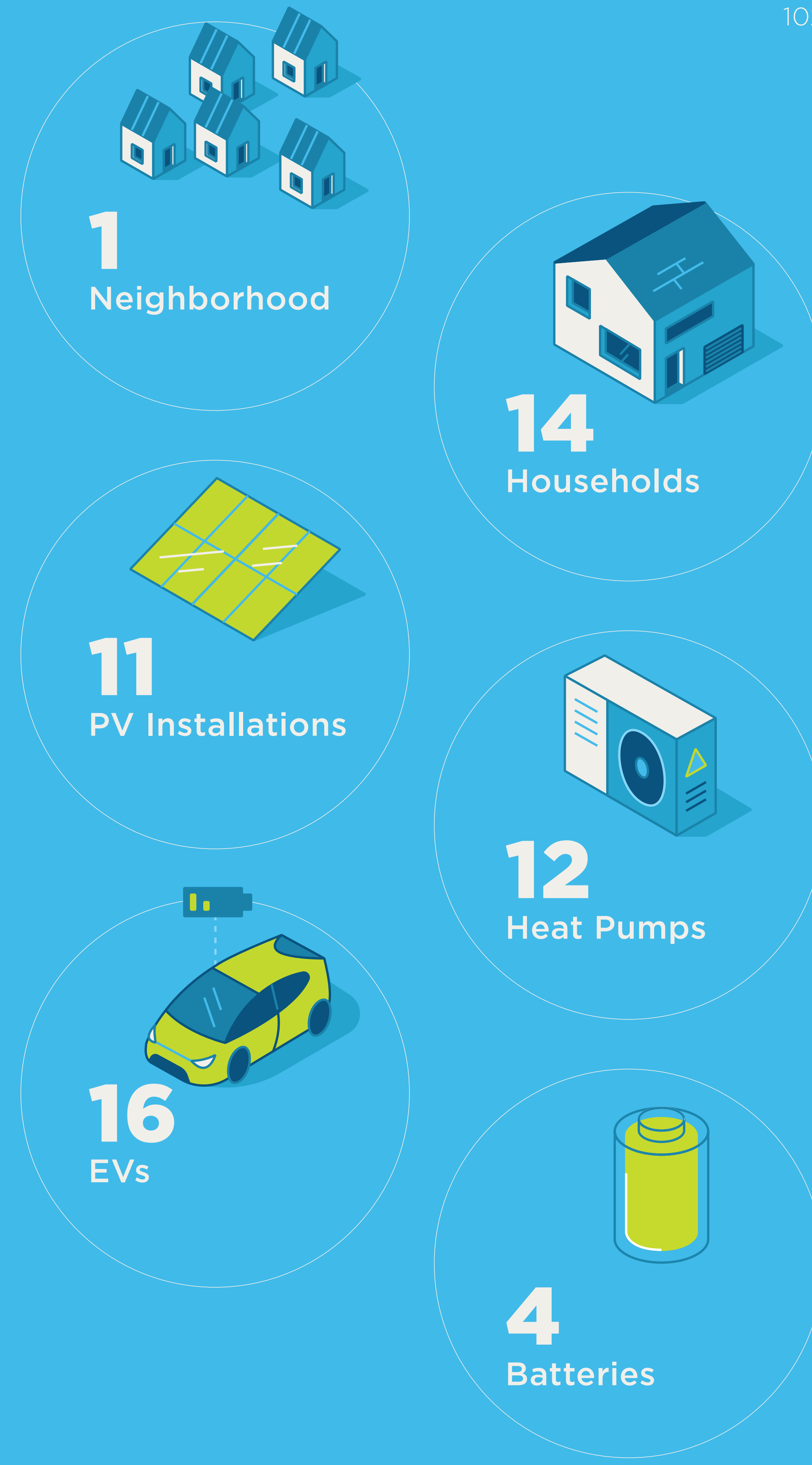
List of abbreviations

API	Application Programming Interface
EV	Electric Vehicle
HEMS	Home Energy Management System
HP	Heat Pump
ICT	Information and Communication Technology
LV	Low Voltage
MV	Medium Voltage
NECP	National Energy and Climate Plan
OCPP	Open Charge Point Protocol
PLC	Power Line Communication
PV	Photovoltaic installation
RES	Renewable Energy Sources
SoC	State of Charge
TAB	“Technische Anschlussbedingungen” or technical connection requirements
ToU	Time-of-Use
V2G	Vehicle-to-Grid

1 Project objectives

The energy transition is reshaping how we produce and consume electricity. With the rapid expansion of decentralized energy sources such as solar panels and the growing popularity of heat pumps and electric vehicles, our electricity grids are being pushed to their limits. These changes are exciting but also bring new challenges. How can we ensure our grids keep up with this transformation? How can customers with their everyday devices like EV chargers and heat pumps support the stability of the grid? And how can smart technologies help integrate these innovations without compromising the quality and reliability of electricity supply?

The Creos Living Lab is designed to find answers. Set in a real-life neighbourhood, this pilot project tests and demonstrates how the energy transition can align with Luxembourg's ambitious climate goals while preserving comfort and ensuring a reliable electricity supply.



By combining innovative technologies with active community involvement, the Creos Living Lab demonstrates how the energy transition can work in harmony with everyday life. It's not just about managing challenges—it's about turning them into opportunities for a cleaner, smarter energy future.

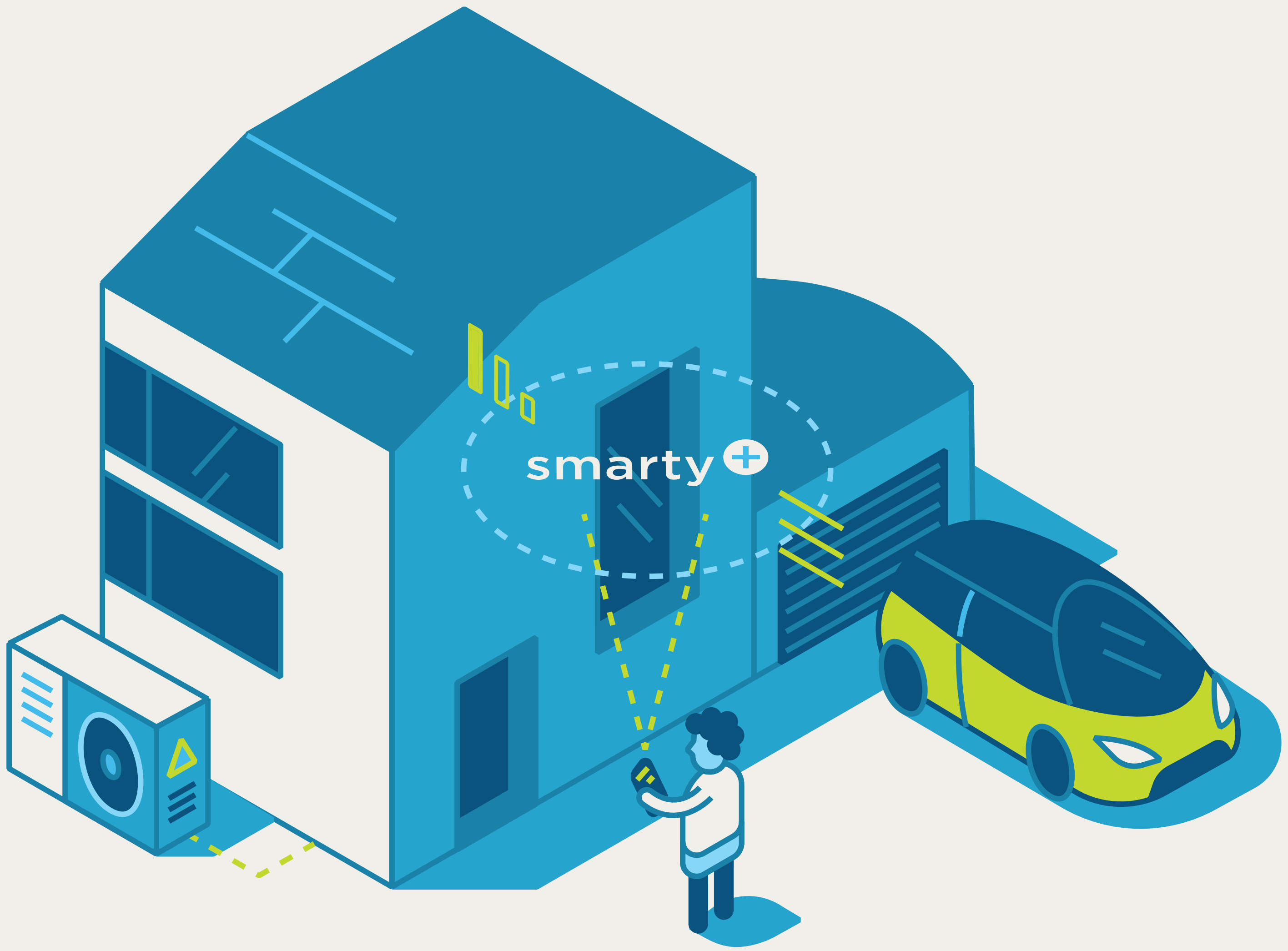


Figure 1
Future smart household

Launched in July 2024, the project brings the energy transition to life by working with residents of a local street. Over one year, 14 participating households equipped with solar panels, electric vehicles, heat pumps, and batteries helped simulate the energy landscape of 2030. Together with Creos, they explore solutions to prevent grid congestion and improve the way we manage low-voltage electricity networks. In this street, the smart grid of the future is already a reality, paving the way for valuable insights into managing tomorrow's energy needs. The Creos Living Lab focuses on two main areas:

Customer Behaviour: Participants are encouraged to change their electricity consumption behaviour to assess the impact on the grid. The project focuses on maximizing midday PV self-consumption, reducing individual peak loads, and cost optimization using various network fees and dynamic electricity tariffs.

Smart Grid Technologies: Intelligent network technologies which enable the connection of more loads to the existing grid while assuring a high-quality electricity supply are tested in practice. The goal is to identify the best implementation options for addressing future grid congestions and voltage issues, focusing on temporal dimming of EV charging speed and PV production in emergency cases.

By combining innovative technologies with active community involvement, the Creos Living Lab demonstrates how the energy transition can work in harmony with everyday life. It's not just about managing challenges, it's about turning them into opportunities for a cleaner, smarter energy future.

A good collaboration between the different actors is a key success factor for the energy transition. Therefore, Creos integrated from the start the Fédération du Génie Technique (FGT – federation of companies in the electricity, heating and information domain), House of Automobile (HoA – federation of professionals in the automotive sector) and Klima Agence (agency to support all national actors in their efforts for climate protection and a sustainable energy transition) into the project. This allowed us to fine tune the scope of the project and to share the knowledge gained in the project with other relevant actors.

The Creos Living Lab has been validated by the Luxembourgish regulator ILR (Institut Luxembourgeois de Régulation) as a "projet à caractère experimental" (c.f. Article 8septies of the Luxembourgish law on the electricity market organization). As part of this designation, Creos published both a mid-term and a final report.

2 Creos Living Lab in the context of the energy transition

The Luxembourgish National Energy and Climate Plan (NECP) has set the goals and the pathway for the country's decarbonization. To achieve these goals, the Luxembourgish government prioritizes technologies such as heat pumps and electric mobility which achieve higher energy efficiencies via electrification. These additional loads will have a major impact on the electricity grid, affecting both high voltage levels, such as the interconnection with neighbouring countries, and low voltage levels, meaning the distribution grid to which residential houses are connected.

2.1

Evolution of the loads on the low voltage grid

Historically, the loads in the low voltage levels were characterized by consumption peaks at noon and in the early evening hours, when residents were at home. The typical peaks for these historical customers are around 4 to 6 kW, which are mainly for cooking, washing and entertainment.

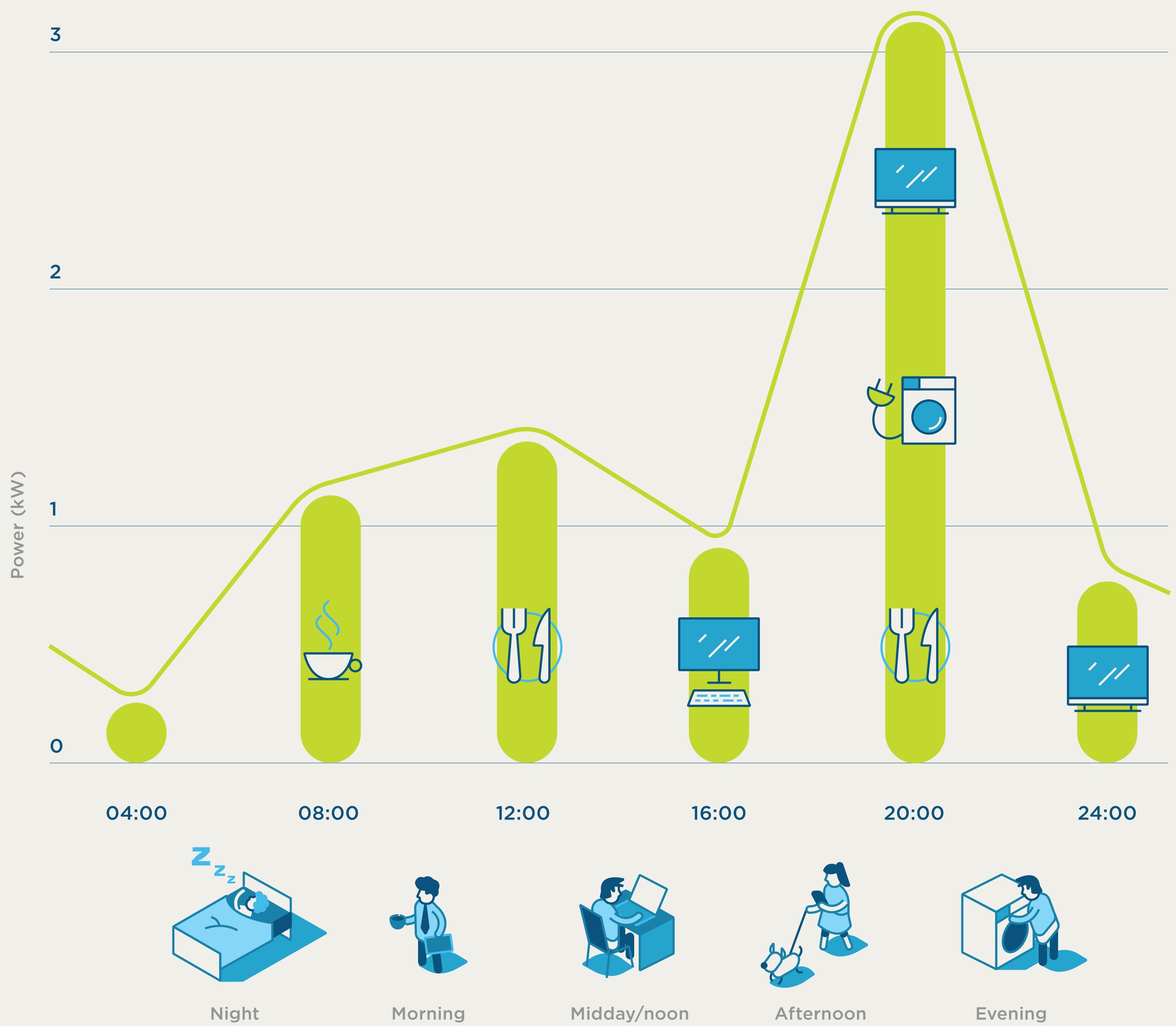
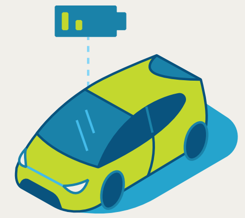


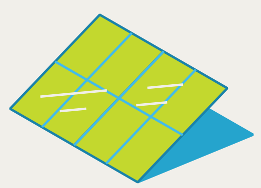
Figure 2a
Example of a load profile of a historical household consumer.
The evening consumption peak is usually between 17 and 21h.

However, this load profile will change in the future with the addition of new assets, including:

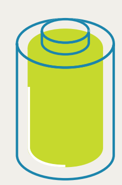


Electric Vehicles (EV): The average household in Luxembourg owns 1 to 2 vehicles. A high share of households will most probably be equipped with 11 kW wallboxes, which will thus add a considerable additional load. Currently, these chargers are mostly used during the evening peak times between 18h and 22h, when residents return home.

Heat pumps (HP): Heat pump sizes vary based on the heating needs of the house. Well-insulated houses with underfloor heating typically only need a heat pump of 2 to 3 kWel, whereas older houses with radiators need heat pumps of 5 to 8 kWel. A lot of these heat pumps have an additional heating rod of up to 8 kWel which can be used on top of the nominal load of the heat pump.



Photovoltaic (PV) installations: The number of private PV installations on the roofs is steadily increasing. New installations have an average installed capacity of 6 to 10 kWp. When the generated electricity is not consumed locally, it is injected into the grid.



Batteries: With the recent developments in the battery technology, residential customers have started combining their PV installations with batteries of 5 to 10 kWh in order to increase their self-consumption.

Home Energy Management System (HEMS): Although a HEMS does not increase the consumption of a household, it allows customers to orchestrate the consumption of their flexible assets based on their objectives. These objectives can for instance be a minimization of electricity costs and maximization of self-consumption.

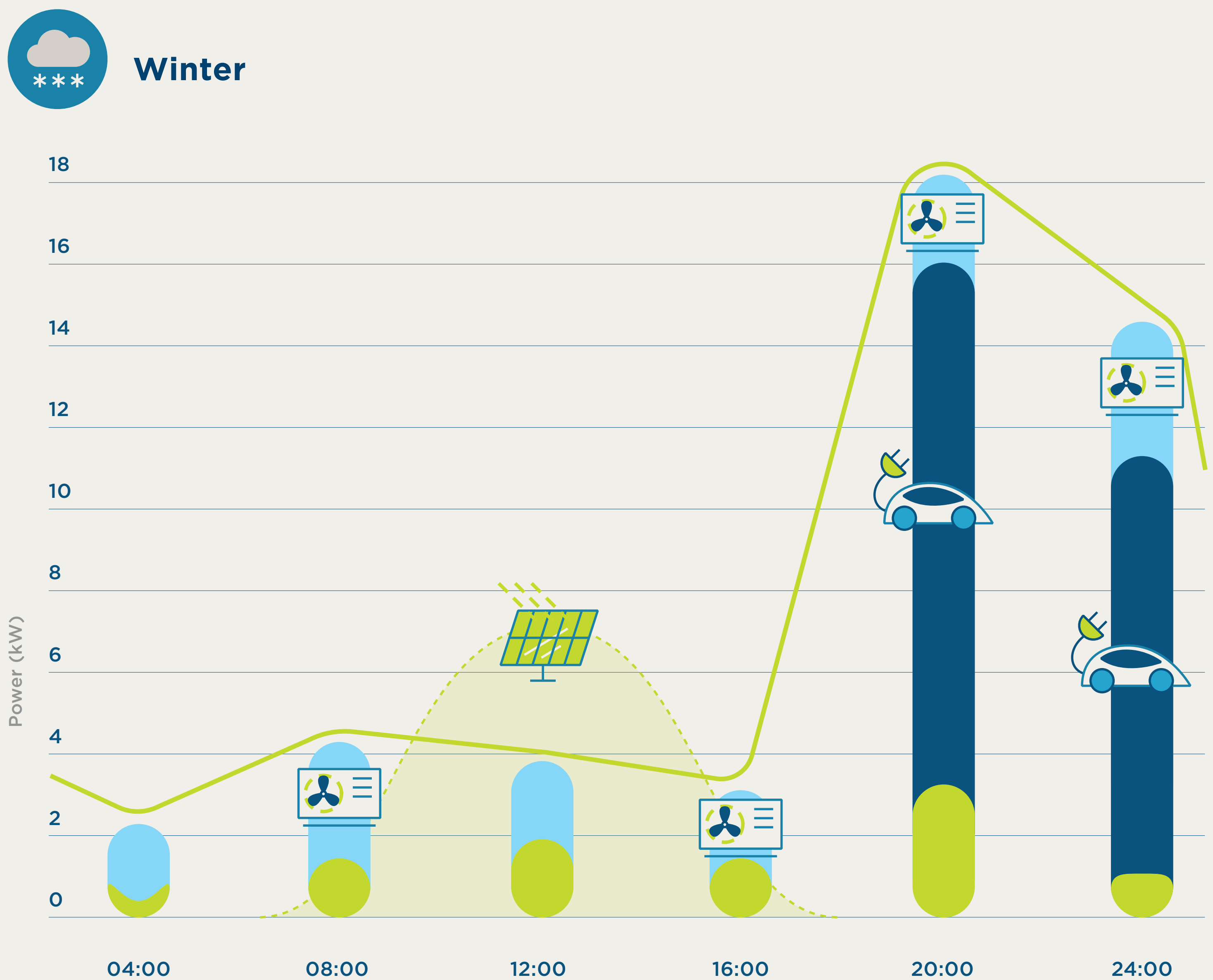


Figure 2b
Example of a load profile of a typical 2030 household prosumer
in Winter, with the household consumption and the generation profile of a PV installation.

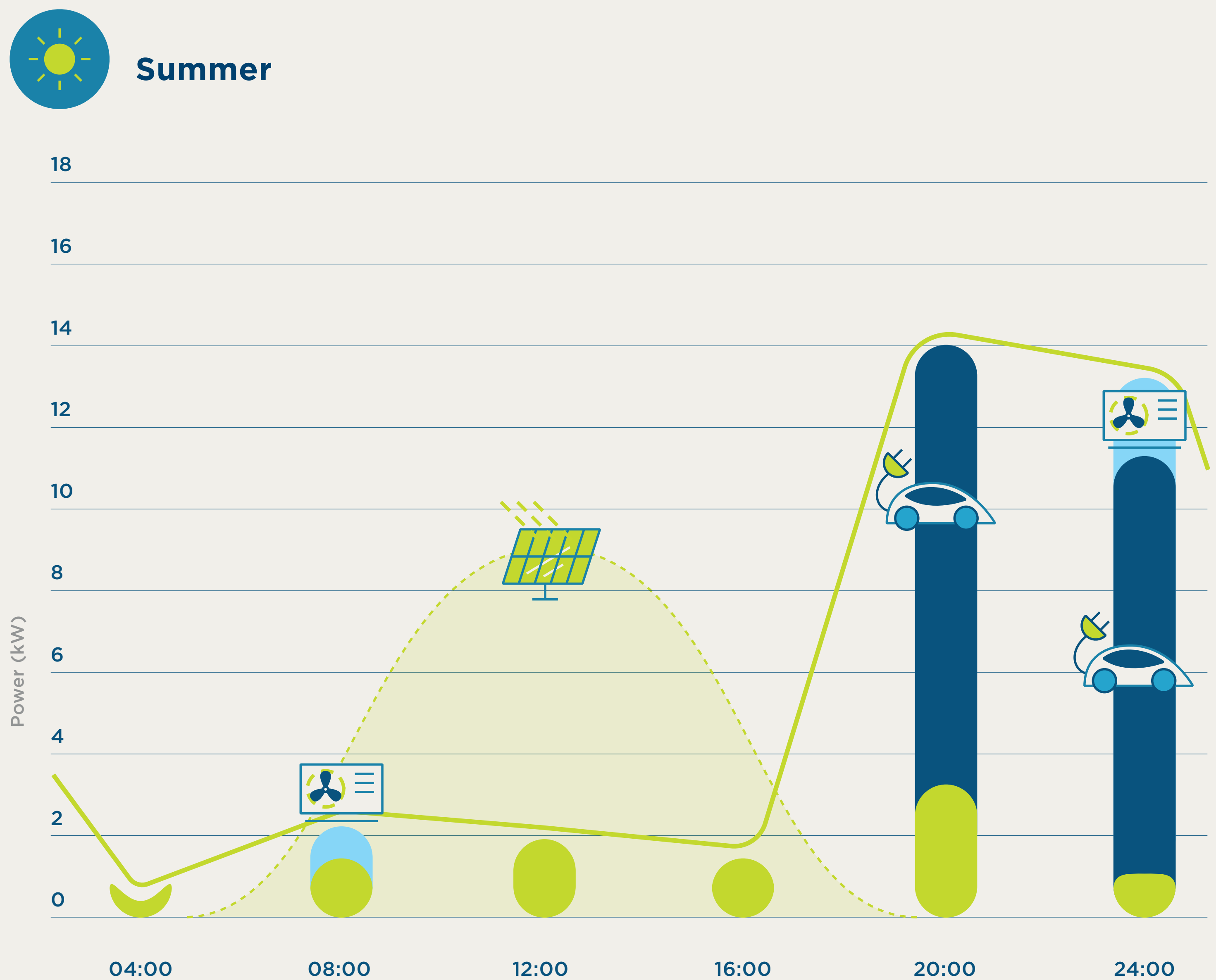


Figure 2c
Example of a load profile of a typical 2030 household prosumer
in Summer, with the household consumption and the generation profile of a PV installation.

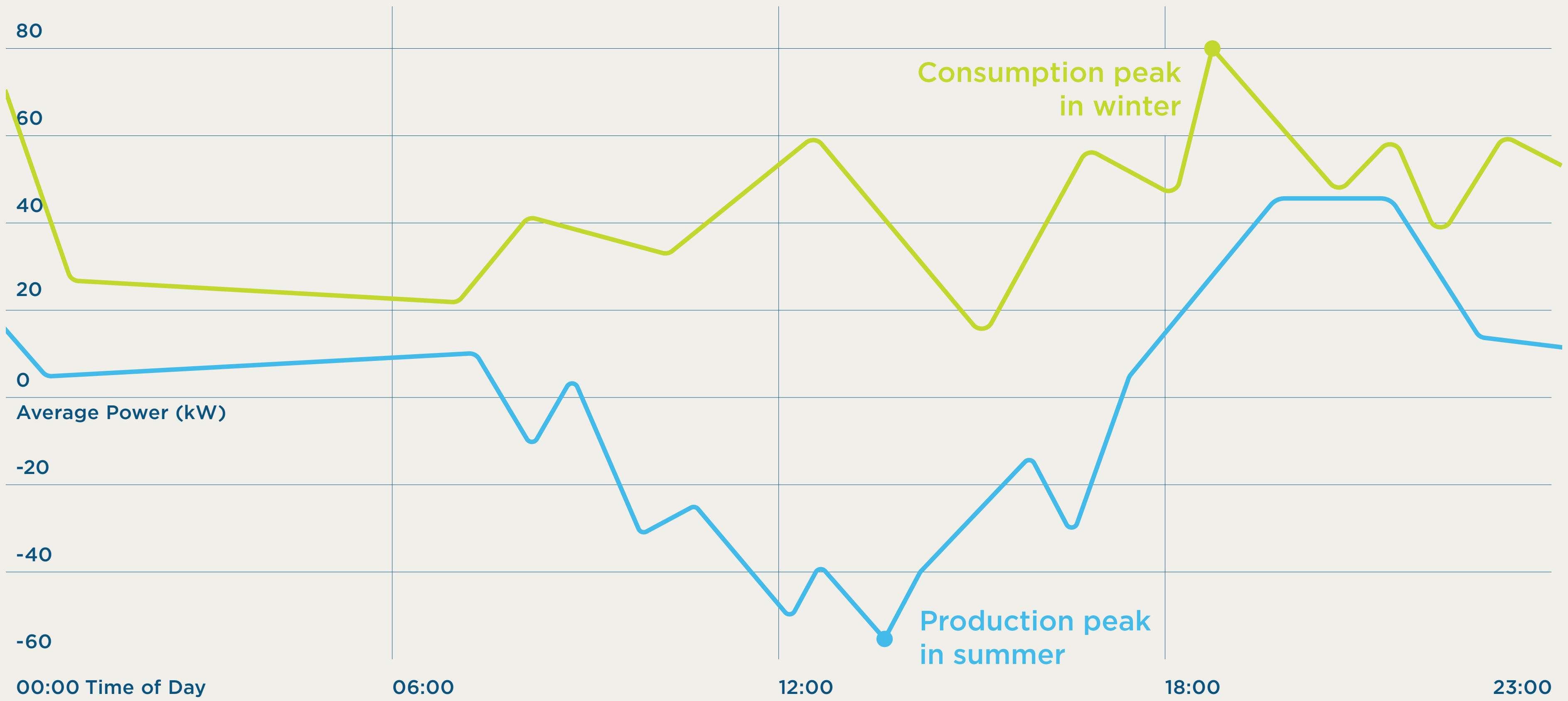
2.2

Challenges for the low voltage grid

It is important to note that the residential customer load is not simply the sum of the additional assets, as these assets do not always consume at the same time. Also, individual customers do not have their peaks at the same time, but their peak is usually spread.

Two different scenarios can put the low voltage (LV) grid under stress locally:

Figure 3
Measured active power values from the street in the Living Lab project (connection of cable to the transformer) in summer (red) and winter (blue). Net consumption is plotted as positive-, and net production as negative values.



Mid-day generation peak in summer: The Creos scenario report from 2023 foresees around 1.800 MW of PV generation in 2040 (NECP Target Scenario). PV installations generally have a similar generation profile and will inject their peak generation at noon into the grid. If this high generation peak is combined with a low local consumption, this can lead to overvoltages or congestions. The blue curve in Figure 3 shows a day in summer (07/07/2024) with a high production peak which needs to be transported from the low voltage to the medium voltage.

Evening consumption peak in winter: Heat pumps consumption is highest during cold winter days, and their simultaneity, meaning the number of HP consuming in parallel, is higher due to their higher consumption. When HP and EV loads are added to the standard household peak in the evening, this high consumption can lead to undervoltages or congestions. The green curve in Figure 3 shows a day in winter (18/01/2025) with a high consumption peak.

2.3

Solutions to manage the energy transition

The Creos Living Lab aims to better understand the impact on its grid in a future environment, with customers owning energy transition assets and reacting to outside signals, and at testing out solutions which allow the operation of the existing grid in a more efficient way.

In order to integrate all these additional loads, Creos needs to reinforce the grid. However, these reinforcements should be accompanied by other solutions to optimize the utilization of the existing grid:

Customer behaviour: HPs and EVs not only increase customers' household consumption, but they also provide a lot of flexibility to their consumption profile. Customers value their comfort levels, such as a warm home or a fully charged vehicle, but as long as their needs are met, they are generally indifferent to when the heat is produced or when the car is charged. This flexibility allows customers to shift their consumption to hours of low electricity prices, or to increase their self-consumption.

This flexibility in consumption patterns is required by an electricity system with a high penetration of volatile renewable energy sources (RES). It can be grid beneficial when it increases consumption during high PV generation or flattens the consumption curve in the evening. However, coordinated responses to external signals, such as electricity prices, can also cause new congestion issues if many customers react simultaneously. It is thus crucial for grid operators to better understand future customer behaviour patterns, and how they can incentivize a grid friendly behaviour.

Smart Grid: Grid operators need to enhance monitoring of bidirectional energy flows in the LV grid, and to be able to react in case of grid congestions or voltage issues. These capabilities, crucial to safely connect more customers to the existing grid and to be able to manage extreme situations, relies on new digital solutions like digital twins and measurement devices collecting granular data used to get advanced data insights and trigger smarter data driven decisions.

As part of this effort, Creos requires all customers to connect their EV chargers and PV installations to the relays of the smart meter to be able to reduce the consumption or injection during critical situations.

3 Selection process of participants

The selection of the location of the Creos Living Lab was a key preparatory step, as the project's success depends on participants' collaboration and motivation.

The objective was to identify a single street based on technical and motivational criteria:

Technical criteria

narrowed down a restricted set of eligible streets.

Motivational criteria

guided the final selection, including participants' openness and patience toward emerging technologies, as a pilot project entails that some technologies might not be at full maturity yet.

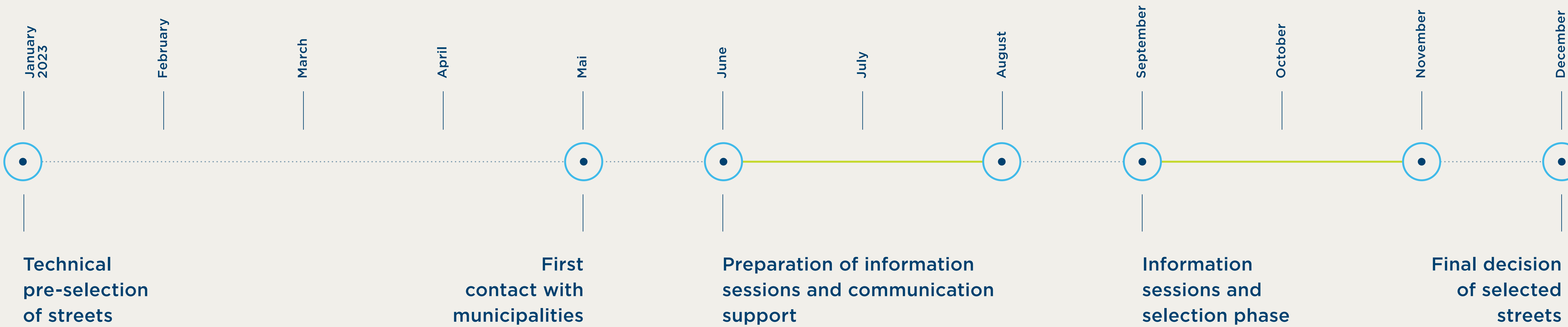


Table 1
Timeline of the selection process phases up until the project launch

Key factors contributing to the success of this selection phase included support from an external communication expert, the creation of a visual identity and engaging materials (flyers, rollouts), and collaboration with municipalities and project partners. These factors enhanced the credibility and professionalism of the initiative.

3.1

Technical pre-selection process

The aim of the technical preselection is to identify interconnected areas in the low voltage grid that are as close as possible to the targeted 2030 scenario of the NECP, all while assuring a secure provision with electricity.

At the end of this process, the four best low voltage grid areas have been selected according to the following criteria:

- Presence of a large number of heat pumps, PV systems and EVs. The latter were considered less important because they can be added in a relatively simple and cost-effective manner via a leasing contract for the project duration
- The grid area should include residential customers, ideally located on the same street, low voltage cable and transformer station
- The low voltage cable specifications should be representative of the Creos low voltage grid
- The grid area must be able to cope with the additional load encountered in the project to assure a safe electricity supply in all situations
- Grid areas with single family houses, as this was the focus of the project

In the end, no grid area could be found where all three assets had already been installed in sufficient numbers. Thus, the emphasis of the selection was laid on heat pumps and photovoltaic systems as they are the most difficult to retrofit.

3.2

Participants' selection process

The objective of this process was to select the final street for the project. The motivation of potential participants was assessed through individual interviews.

Figure 4
Initial information session for one of the identified streets

3.2.1

Information sessions and first contact

The respective municipalities were informed about the project and invitation letters for potential participants, signed by the mayors, were sent by municipalities, enhancing the credibility of the initiative. This cooperation facilitated the organization of information sessions.

From September to October 2023, the identified streets were invited to individual information session, conducted with representatives from Klima-Agence, covering:

- The project's context and objectives
- Advantages for participants
- A step-by-step guide of project milestones
- A transparent overview of test phases and estimated time commitment
- Project team expectations

3.2.2

Expectations on participants

During the project, participants are expected to:

- Be available for the installation of technical equipment, such as the wallbox and Home Energy Management Systems (HEMS)
- Participate in workshops every two months, provide feedback and complete surveys
- Adapt their behaviour as best as possible, according to the project team’s guidance

3.2.3

Individual visits

Interested participants were invited to schedule individual home visits in November 2023. These visits, conducted with an energy consultant from Klima-Agence and an external communication expert, aimed to:

- Assess motivation and technical suitability for the project
- Document existing assets and estimate the effort to install wallboxes and a HEMS

Candidates completed a survey on their motivation, willingness to adapt, and availability. The collected data was used to create an evaluation matrix, where survey responses were weighted by priority to assess the benefits and risks for each street

3.2.4

Selection criteria

All four streets demonstrated strong motivation. Ultimately, 14 households in Cruchten were selected based on:

- High interest in the energy transition and commitment to serve as role models for their communities
- Willingness to adapt behaviour for the test phases
- Diversity of household types and a strong sense of community spirit

4 Participants' technical installations

This chapter provides an overview of the technical installations implemented in the Creos Living Lab. The objective was to reach a target configuration which replicates the vision of the "2030 household" projected in the NECP.

During the first half of 2024, internal project preparations were made. This included tenders for the technical material, as well as internal IT developments.

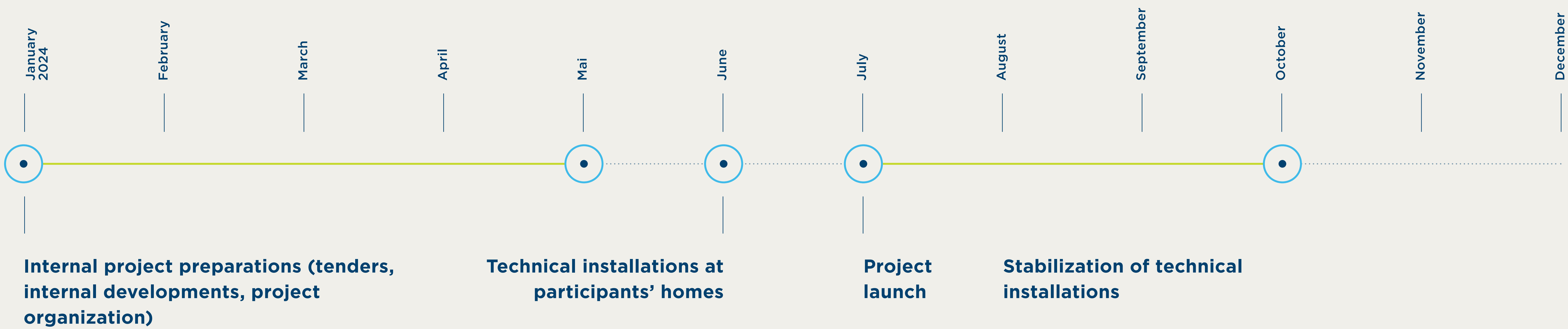


Table 2
Timeline of the phases linked to participants' technical installations

The installation of the wallboxes and batteries was made in June 2024, right before the project launched in July. From July to October, the technical installations as well as the HEMS were stabilized.

4.1

Target configuration

The target configuration of project participants is composed of the following assets (Figure 5):

- An EV with a wallbox
- A heat pump
- A PV installation
- A Home Energy Management System (HEMS)

Some installations slightly vary from the target configuration:

- Four participants are equipped with a battery
- Three participants do not have a PV installation
- Two participants do not have a heat pump

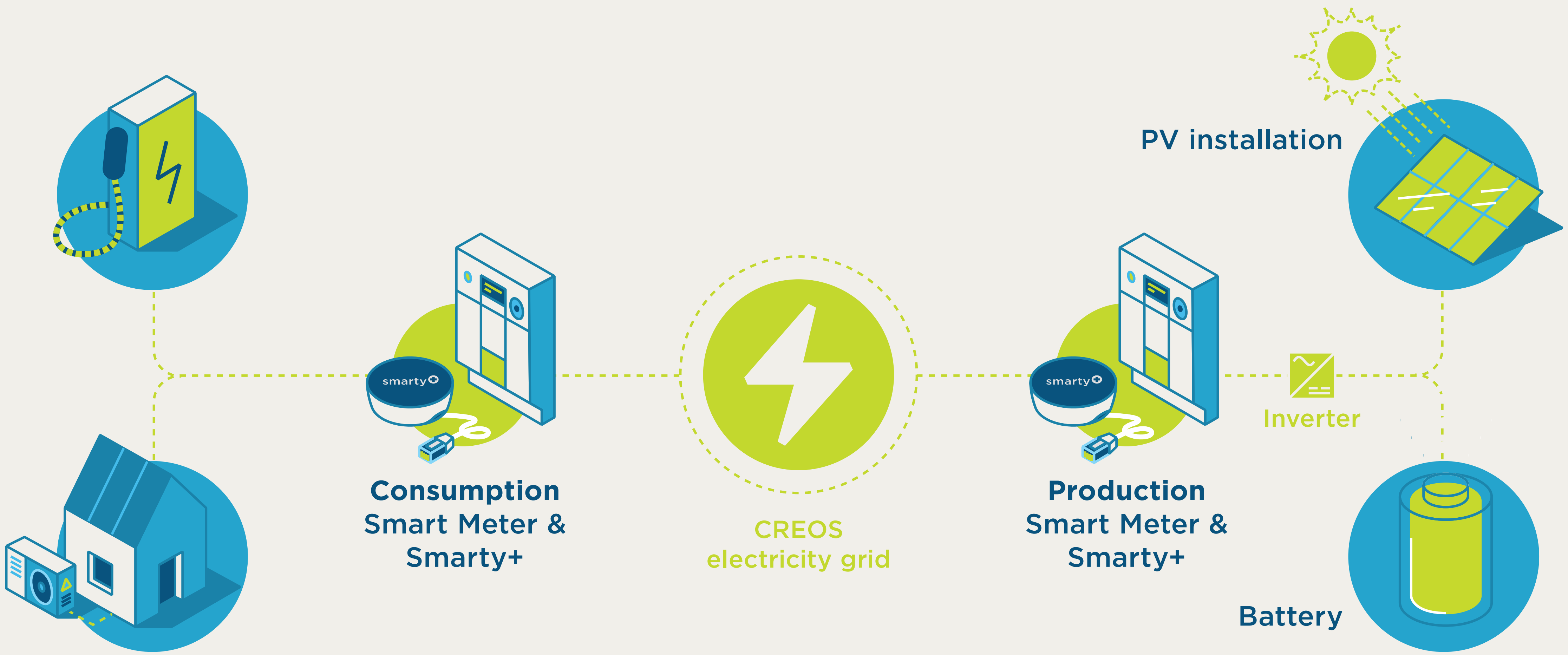
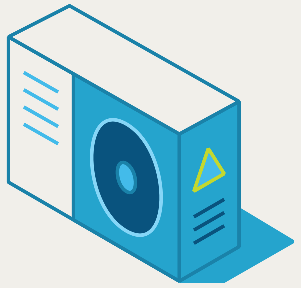


Figure 5
Visual representation of the target configuration of assets installed at participants' homes

4.2

Installed assets

This section describes the specifications of the assets present in the project.



4.2.1

Heat pumps

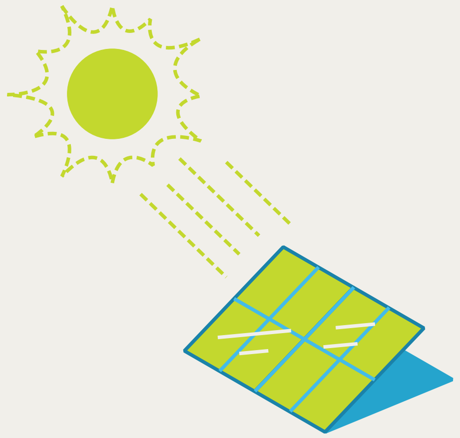
Table 3 - Key numbers: heat pumps

Total number of heat pumps	**12**
Thermal output of air-to-water heat pumps (A7/W35[1])	**5,3 kW**
Thermal output of geothermal heat pumps (W35[2])	**7,4 kW**
Capacity of heating rod	**Up to 8 kW**

[1] A7/W35 means that the incoming air has a temperature of 7°C, while the flow temperature is 35°C.

[2] W35 means a flow temperature of 35°C.

Twelve heat pumps were already installed, including nine air-to-water and three geothermal heat pumps. They cover heating, warm water and ventilation. They also dispose of heating rods to complement or replace the heat pump when the temperatures drop in winter or in case of a default.



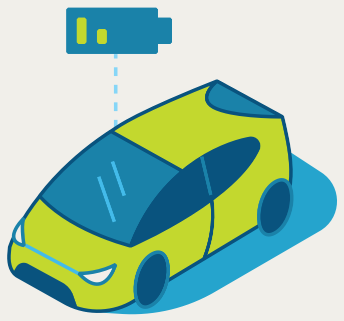
4.2.2

PV installations

Table 4 - Key numbers: PV installations

Total number of PV installationss	**11**
Range of installed capacity	**4 to 12 kW_p**
Total installed capacity	**96 kW_p**

Eleven photovoltaic installations were already installed. Ten installations have a contract with a fixed feed-in tariff and two separate smart meters, one for consumption and one for production. One installation is in self-consumption mode with one smart meter for both consumption and production.



4.2.3

Electric vehicles

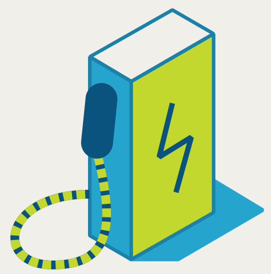
Table 5 - Key numbers: EVs

Total number of EVs	**16**
Battery capacity small model	**58 kWh**
Battery capacity large model	**77 kWh**

As there weren't yet many full electric vehicles in the neighbourhood, each participant was offered an EV for the duration of the project. The vehicles are being leased for one year.

Each participant had the possibility to indicate certain specifications and equipment which were required for their EV, such as car size category and yearly distance. This was essential to ensure that their needs were met to assure that they are used daily, which is important to see their impact on the electricity grid.

A public request for proposal was published to allow each manufacturer and dealership to participate.



4.2.4

Wallboxes

Table 6 - Key numbers of wallboxes

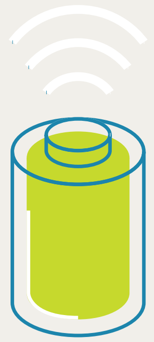
Total number of wallboxes	**14**
Communication protocol	**OCPP 1.6**
Range of power output in a three-phase configuration	**4,2 to 11 kW**

Every participant is equipped with a three-phase 11 kW wallbox. The wallboxes must be integrated into the home energy management system. To ensure a proper compatibility with the functionalities from the HEMS, the model choice was restricted with the following specifications:

- Communication with OCPP 1.6
- Connexion via Wi-Fi or Ethernet
- Possibility to modulate the power output between 4,2 and 11 kW in a three-phase-system
- Compatibility with an external load reduction signal coming from the smart meter relays. This specification is essential to ensure compliance with Creos' technical connection requirements ("Technische Anschlussbedingungen", TAB)[3].

A public request for proposal was published to allow every electrician to participate.

[3] **The Creos TAB can be found here:** https://www.creos-net.lu/en/pro-space/electricity/connection/tab



4.2.5

Battery storage systems

Table 7 / Key numbers: batteries

Total number of batteries	**4**
Communication protocol	**Modbus TCP**
Battery capacity	**9,8 kWh**

Four participants are equipped with battery storage systems. The battery is installed behind the same inverter as the PV installation and communicates with the HEMS through the hybrid inverter.

4.2.6

Energy meters and smart switches

To better monitor and understand the consumption of the heat pumps, some participants have been equipped with three-phase energy meters, which measure the electrical consumption of their heating system.

Moreover, smart switches were added into the wallboxes and for the inverters. These switches are a back-up solution for the classical relay communication via power line communication (PLC) to grant us the capability to evaluate an alternative communication channel specifically for real-time purposes.

4.3

Digital tools and communication protocols

In the project, participants dispose of several digital tools which they can use during different test phases to support them in adopting different consumption behaviours.

4.3.1

Smarty+

All households have been equipped with Smarty+[4] dongles connected to the P1 port of the smart meter (cf section 5.4.1). The dongle transmits all data available from the P1 port in real-time with an increased granularity of 10 seconds via the Wi-Fi home network.

Participants can therefore monitor their active consumption and production from both consumption and production smart meters. Moreover, the HEMS also uses the data from the Smarty+ dongles to access the consumption and production values.

However, the P1 port transmits a wider array of data. These insights are of high value for the smart grid operation, detailed in section 5.4.2.

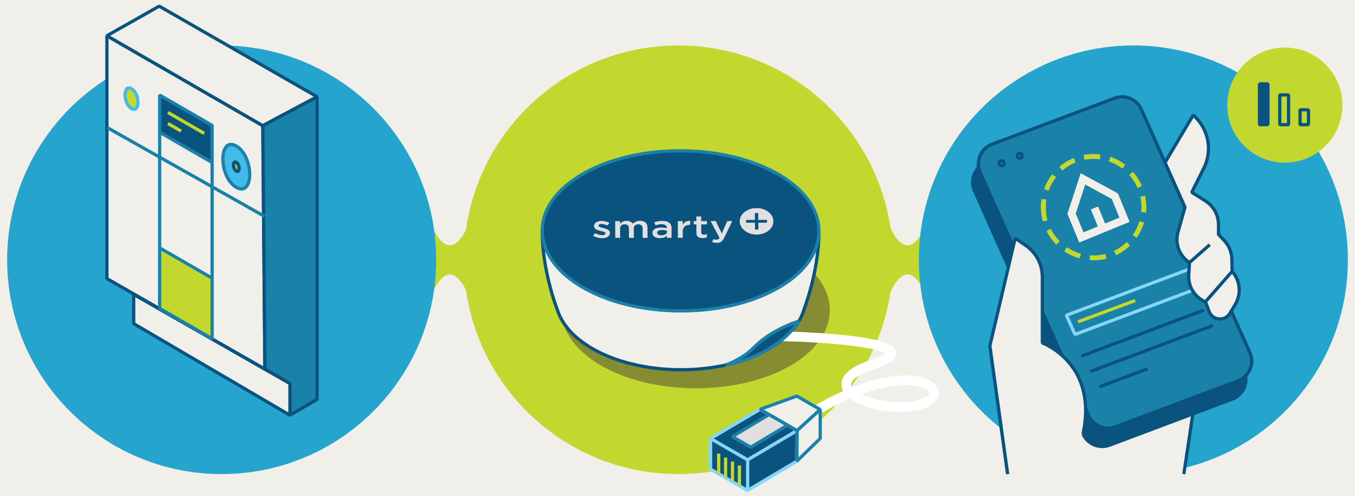


Figure 6
The Smarty+ dongle and its application for data visualization

[4] https://smartyplus.lu

4.3.2

Home Energy Management System

The objective of the HEMS is to optimize the usage of electricity by visualizing the participants' data and by automizing the use of certain devices.

The HEMS gathers data from different appliances to show the user which devices are consuming or producing in their household. This helps to raise awareness on their consumption habits. Moreover, it can steer the wallbox and the battery.

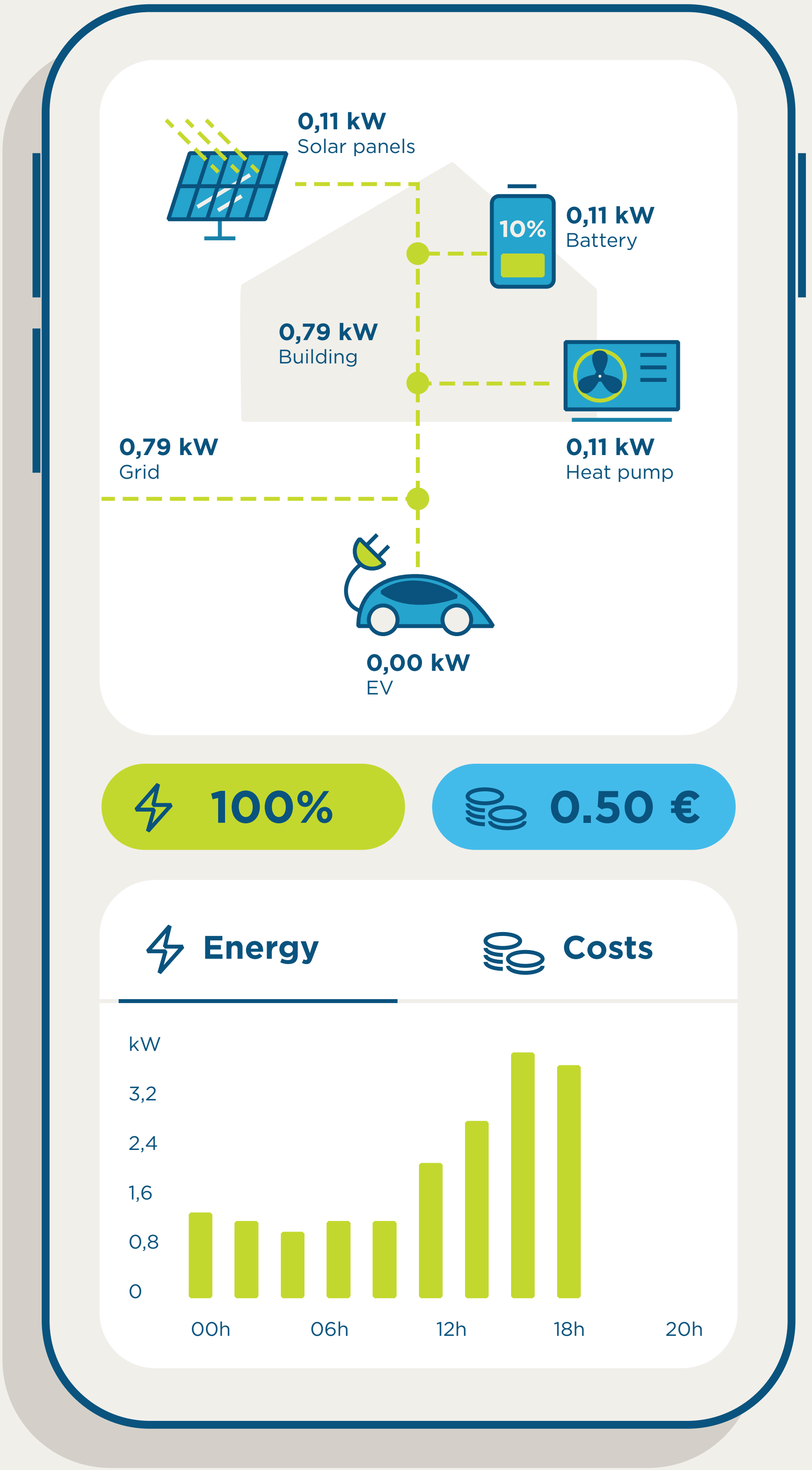


Figure 7
Example of the HEMS application showing the electricity consumption and production

The HEMS provides different strategies for EV charging:

- Charge at full power with 11 kW
- Charge with reduced power according to a capacity limit set by the user. In this case, the HEMS will monitor household’s consumption and production to adapt the power of the wallbox to reduce peak consumption from the grid
- Charge in a preferred self-consumption mode to follow available excess PV electricity
- On top of these strategies, the user can specify additional conditions, like charging targets (define autonomy and duration of charge), or optimize the EV charge based on dynamic supplier tariffs

The charge and discharge of the battery is set to maximise self-consumption. The battery will therefore charge as soon as excess electricity is available from the PV installation and discharges as soon as the PV does not cover the user’s needs anymore.

The HEMS is connected to the local network via Ethernet and retrieves the following data:

Table 8
Description of different data sources in participants’ homes, their use and communication protocols

Device	Use	Communication via
Smarty+	To measure the consumption and production of the household via the P1 ports of the smart meters	Smarty+ API
Wallbox	To retrieve the data from the charging sessions and steer the charging sessions (duration, power, start)	OCPP 1.6
Hybrid inverters	To retrieve the data from the production installation and steer the battery charge/discharge	Modbus TCP
Non-hybrid inverters	To retrieve the data from the production installation	No direct communication. Data is retrieved via the Smarty+ dongle
Energy meters	To measure the consumption of heat pumps	Shelly API

Since some equipment was already present in participants’ homes, the selection of the HEMS was done based on the flexibility of the system to integrate different types and models of equipment with open protocols. For this project, the HEMS “Smartmaster Home” by Nexxtlab SA was used, which was an existing system in the market. The communication protocols used in the project are not linked to any proprietary licences and their use does not require any additional charges.

4.3.3

Visual representation of communication flows with the HEMS

The figure below shows the communication flows between the different devices connected to the HEMS.

Some devices, such as the Smarty+ and the energy meter, communicate via a wireless connection, while other devices, such as the wallbox and the inverter, communicate via Ethernet. The data is transmitted, either directly or indirectly through the HEMS to the cloud from the HEMS provider. The application then accesses the stored data.

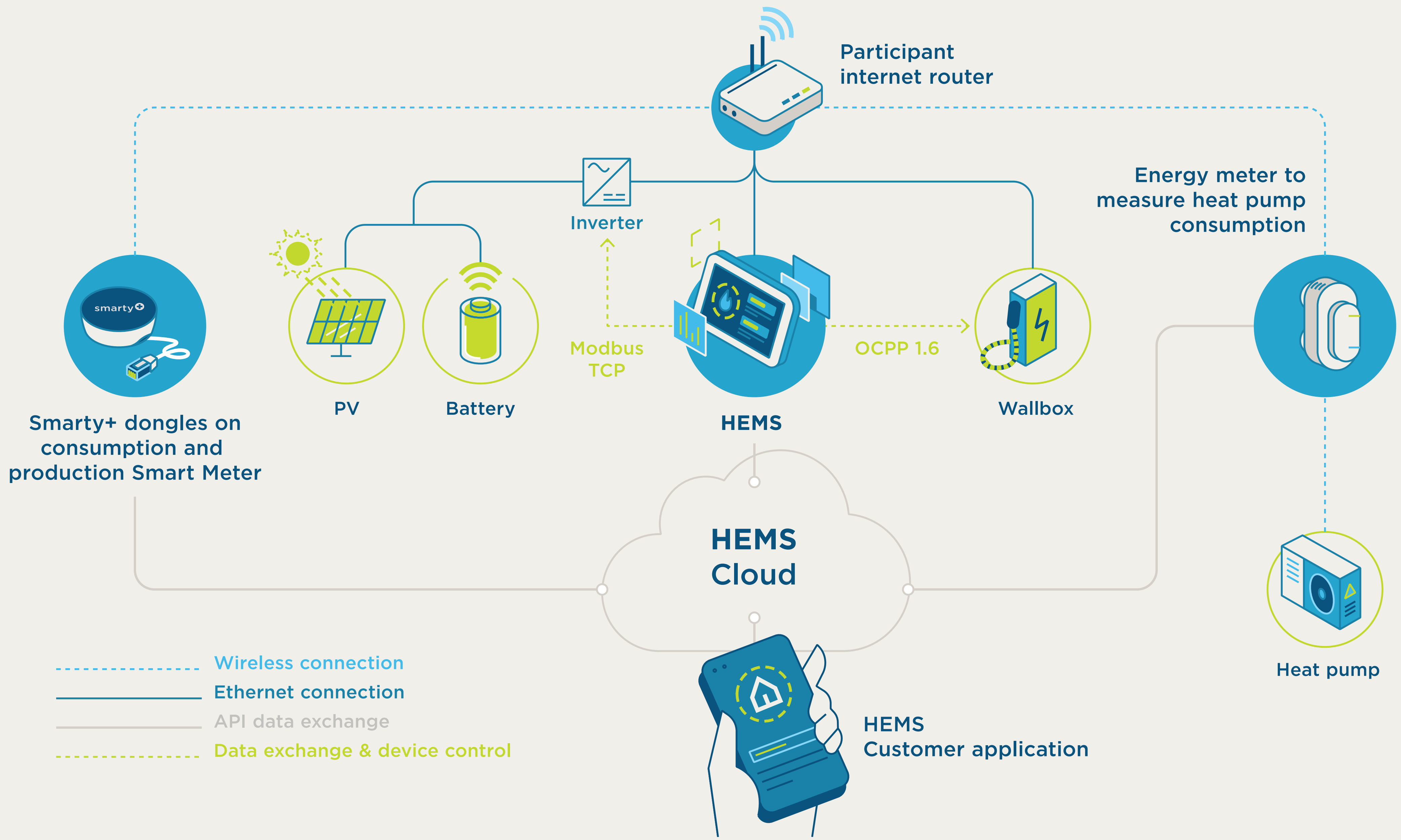


Figure 8
Communication flows on configuration with wallbox, PV installation and battery.

4.3.4

EV application

The EVs offer an own application with several parameters. For instance, users can program charging schedules and adapt the power when charging through the application.

4.4

Lessons learned and challenges in electrifying and digitalizing homes

The lessons learned from the installation process underline the complexity of electrifying and digitalizing homes. Addressing physical and digital challenges requires thoughtful planning, workforce upskilling, and collaboration between stakeholders. As the market for smart home solutions evolves, greater standardization of communication protocols and cross-compatibility will be essential for simplifying installations and enhancing user experience.

4.4.1.

Physical constraints in existing installations

To comply with the Luxembourgish grid connection requirements, wallboxes and PV inverters must be connected to the smart meter relays via a communication cable. In this project, the smart meter and the location of the wallbox were on different floors most of the time. Often, there were no available or empty conduits to easily connect the devices, resulting in important additional work and cost to drill through the concrete and insulation.

These challenges are common and may discourage customers from adopting energy transition technologies due to high upfront costs. High installation costs may deter customers from electrifying their homes or lead to improperly connected devices to save on expenses.

4.4.2

Digitalization of homes requires proper installation and maintenance

The installation of a HEMS with controllable devices, such as a wallbox or battery, requires proper connectivity in participants' homes as well as compatible communication between the HEMS and the different devices.

Different initiatives are emerging to standardize the communication and data exchange for devices implemented in a "smart home". However, at this stage, there is no universal standardization yet.

When navigating through the market, there are mainly two approaches, each with its advantages and challenges:

- **Proprietary systems:** Some manufacturers offer closed, integrated systems with wallboxes, inverters, heat pumps and HEMS. These systems are often easier to install initially, as the compatibility of the devices is guaranteed. However, they are also proprietary and therefore limit the integration of existing assets or devices from other manufacturers. Moreover, this results in strong dependencies on a single manufacturer, which can compromise long-term maintenance of the system and upgrades.
- **Open protocols:** The alternative is to use systems based on open protocols, which allows a wider range of manufacturers, devices and assets to be integrated. However, the initial implementation of the system requires a greater effort and expertise to ensure the compatibility of the devices.

A universal "plug and play" solution is often unrealistic due to the variability of customers' installations. For example, in this project, an existing wallbox with OCPP 1.6 connectivity could not communicate with the HEMS because its system is restricted to specific partners. Overall, the proper configuration and integration of the wallboxes was more challenging than expected. A broad skillset is required to understand their role in the ecosystem which includes the smart meter, the customers' internet network and the HEMS.

Moreover, due to a lack of standardization, inconsistencies in the implementation of communication protocols across manufacturers complicate the integration of devices. Different interpretations of the protocol can result in inconsistent behaviours, making the communication between devices with the HEMS unreliable. In the project, different versions of the same wallbox reacted differently to the control signals of the HEMS, as they interpreted the messages differently.

Proper installation is critical, but successfully digitalizing a home goes beyond the initial installation process. The system must be regularly maintained and kept up to date. For instance, in the project, different software versions on the newly installed wallboxes temporarily disrupted communication with the HEMS. Similarly, hybrid inverters and batteries from the same manufacturer failed to communicate due to incompatible software versions. The issue had to be manually resolved by an intervention from the manufacturer.

4.4.3

Preparing the workforce for the energy transition

The challenges described above highlight the importance of planning the energy transition: during construction or major renovations, future-proofing homes, by adding electrical conduits for a wallbox, PV or connectivity for a HEMS, can greatly facilitate electrification in the future and reduce future installation costs. Customers rely heavily on professionals, such as their electricians, installers and architects, to guide them in preparing their homes for the energy transition.

The transition introduces new challenges for professionals like electricians and heat pump installers, whose roles are increasingly multidisciplinary.
For instance, electricians no longer only connect devices electrically, but they are also required to integrate systems like wallboxes into customers' internet networks. This blending of electrical and IT expertise has greatly increased the skillset expected of these professionals, making their roles more complex and demanding.

To fully support the energy transition, the workforce must adapt and expand its knowledge base.
Training and upskilling are essential to equip professionals with the technical and digital skills needed to manage a harmonious integration of these new assets linked to the energy transition. This evolution is not just beneficial but necessary to ensure the transition is seamless and effective.

5 Smart Grid

5.1

Evolution of the Electricity Network

The low-voltage distribution grid has faced continuously evolving challenges in its operation. Historically, grid operators had limited insights into peak instantaneous loads due to the lack of granular measurement data, as meters were traditionally only read once per year. As detailed in section 2.1 however, the historic average loads in the low voltage grid were also relatively low compared to the new assets (EV and heat pumps). Additionally, not a lot of production units had already been connected to the low voltage grid.

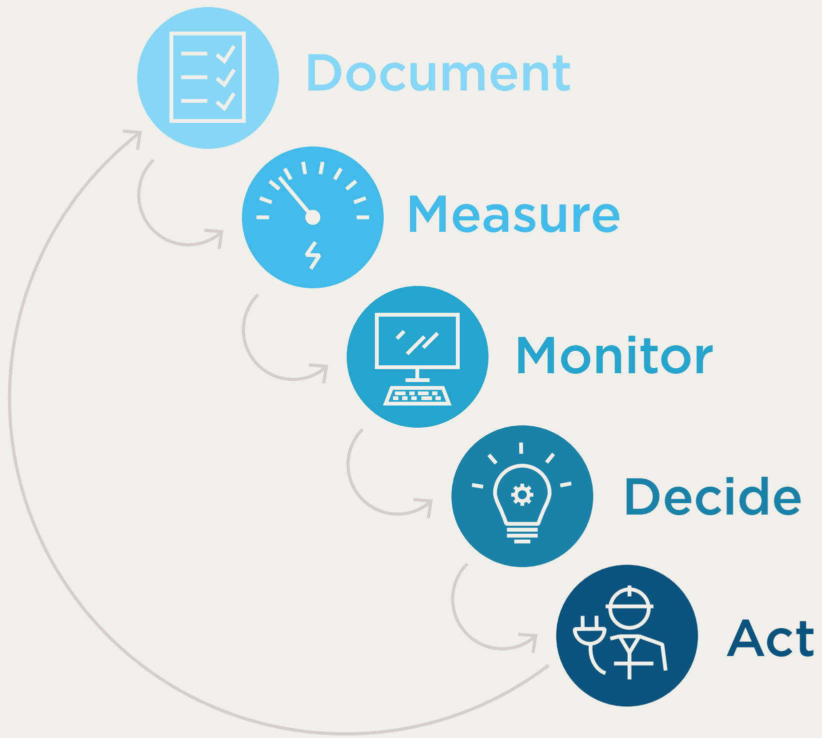
Today, the energy landscape has undergone significant transformation. The energy transition is accelerating, marked by the electrification of heating and mobility, but also by the development of PV installations resulting into bidirectional electricity flows. To enhance visibility into grid loads, Creos has equipped all households with smart meters capable of transmitting 15-minute granular consumption data daily. This advancement provides Creos with comprehensive insights into the actual grid load with the limitation that the data is only available the day after.

Looking ahead, the rapid progression of the energy transition is anticipated to place higher demands on the low-voltage grid. To address these challenges, Creos is advancing towards real-time[6] load measurement and active system management. These systems will enable proactive interventions during extreme scenarios, ensuring the secure and reliable delivery of electricity under all conditions.

[6] To simplify readability, the word real-time was used in this chapter even though near real-time would technically be more precise.

5.2

Creos Smart Grid Vision



To ensure the low-voltage grid is equipped to meet future demands, Creos has developed its Smart Grid Vision, structured around five key pillars:

- **Document:** Accurate and comprehensive digital documentation of the grid infrastructure is essential for calculating electricity flows and ensuring a clear understanding of the network's operational dynamics.
- **Measure:** Sensors strategically installed throughout the grid provide a detailed view of its current state, enabling precise measurement of key parameters.
- **Monitor:** Monitoring the measurement data allows for the detection of alarms and faults, highlighting vulnerable areas of the network. Monitoring encompasses various timescales, from analysing historical data for load forecasting across different horizons to real-time observations.
- **Decide:** When vulnerabilities are identified, data-driven analysis facilitates the evaluation of potential solutions, leading to informed decisions on preventive actions.
- **Act:** Once a decision is made, the chosen solution must be implemented, ideally through remote control mechanisms.

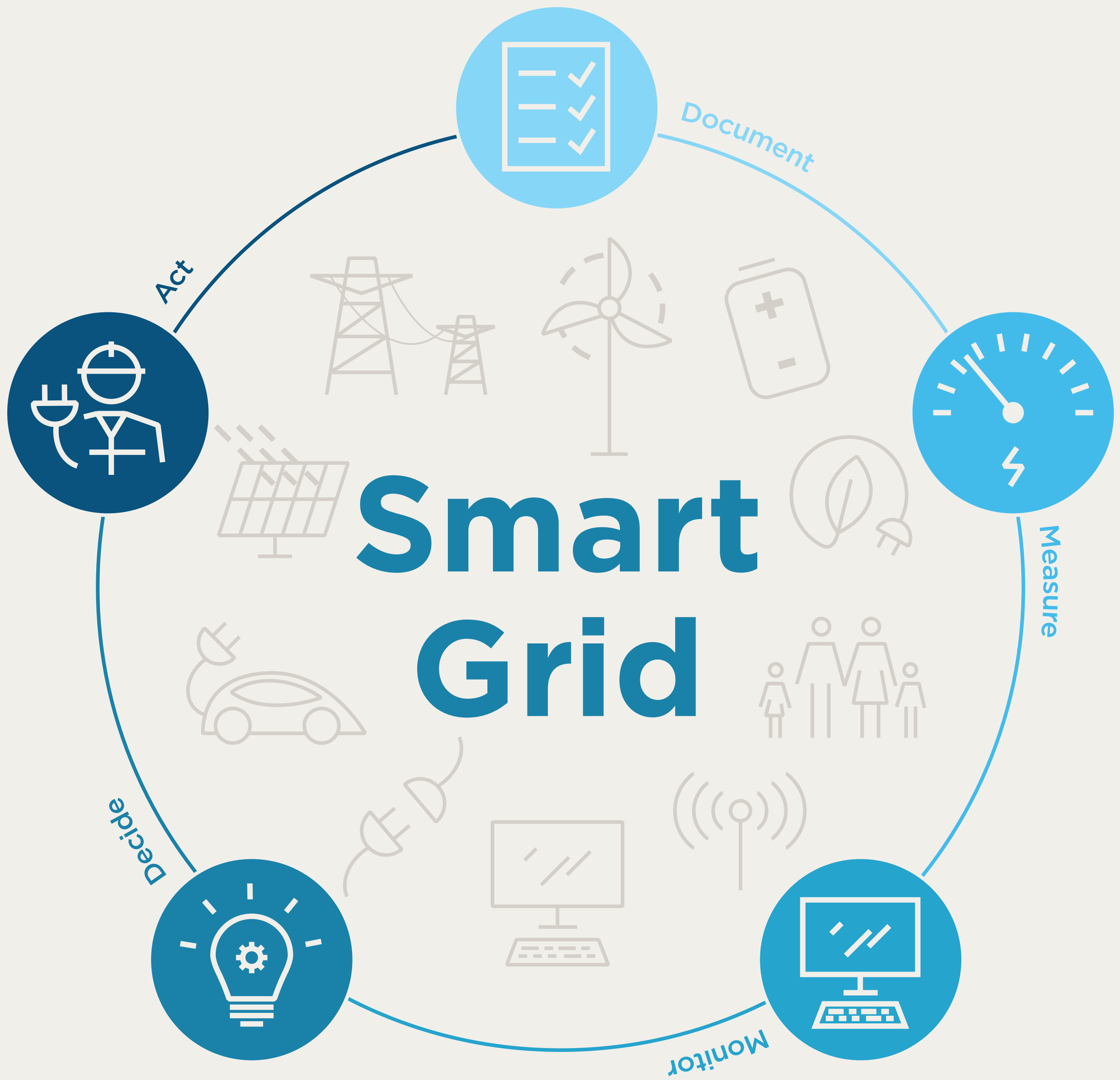


Figure 9
Creos Smart Grid Vision

In the scope of the Creos Living Lab, the smart grid of the future has been implemented at a local scale as explained further in section 5.4 below. The pilot project serves as a platform to test and validate the complete value chain of the Smart Grid Vision. As a foundational element, precise documentation of all grid assets including cables, transformer stations, and connection points as well as the installed wallboxes is essential. Additionally, real-time measurement devices have been installed at the local transformer station, as well as in participating households via the Smarty+ Dongle.

This comprehensive data is integrated into the digital twin, *Kopr*, enabling real-time and forecast-based monitoring of grid loads. Leveraging this data, advanced algorithms have been developed within *Kopr* to detect critical grid conditions and determine proactive actions to manage loads on the low-voltage grid during extreme scenarios. These actions are explained in more detail in section 5.3 followed by a detailed explanation of the individual developments done in the scope of the Living Lab in section 5.4.

5.3

Smart Grid tests in the Living Lab

The focus of the smart grid tests in the Creos Living Lab is to gain first operational experience with actions for grid load optimization based on smart meter relays. To be compliant with the TAB guidelines, the photovoltaic systems and the electric vehicle charging wallboxes need to be connected to the smart meter relays. This enables Creos to temporarily reduce the consumption or generation of both assets when necessary, as detailed in section 5.4.4. That way the load on the grid can be reduced in emergency situations like grid bottlenecks. Of course, these bottlenecks are only simulated in this project using lower thresholds to always assure a secure provision with electricity. Two main strategies are tested in the Creos Living Lab:

Real-Time Data-Based Load Management

Based on real-time measurements, dimming signals are sent out as soon as grid load thresholds are exceeded.

Forecast-Based Load Management

Based on consumption and production forecasts, planning signals are sent to implement load reduction measures at predicted grid bottlenecks.

Real-time data-based load management has the advantage of eliminating inaccuracies caused by forecasts and only initiating dimming when necessary. However, the downside is that communication with the dimmable device must occur extremely quickly. This communication is carried out via the existing smart meters using Power Line Communication (PLC), which can be prone to interference. As a result, costs for improving the communication infrastructure and installing real-time measurement devices must be carefully weighed.

In contrast, forecast-based load management identifies and addresses grid overloads early through predictions. Planning signals have more time to reach the smart meters and trigger dimming. This approach requires highly precise forecasts however, which can be prone to errors. During the pilot project, various forecasting models are being compared, with forecasts based on smart meter data already available nationwide using Creos' existing infrastructure.

For the Creos Living Lab, both strategies have been integrated into *Kopr* with adjustable parameters to identify an optimal, practical solution over the course of the year. Resident feedback is a crucial component of this approach, as the ultimate goal is to ensure the long-term comfort and reliability for grid users.

More details on the interferences of the PLC signal and its suitability for load management can be found in subsection 5.6.4.

5.4

Smart Grid developments for the Living Lab

To enable the tests mentioned in section 5.3, the smart grid of the future was developed and set up on a local scale. The installed devices and necessary developments are detailed in this section.

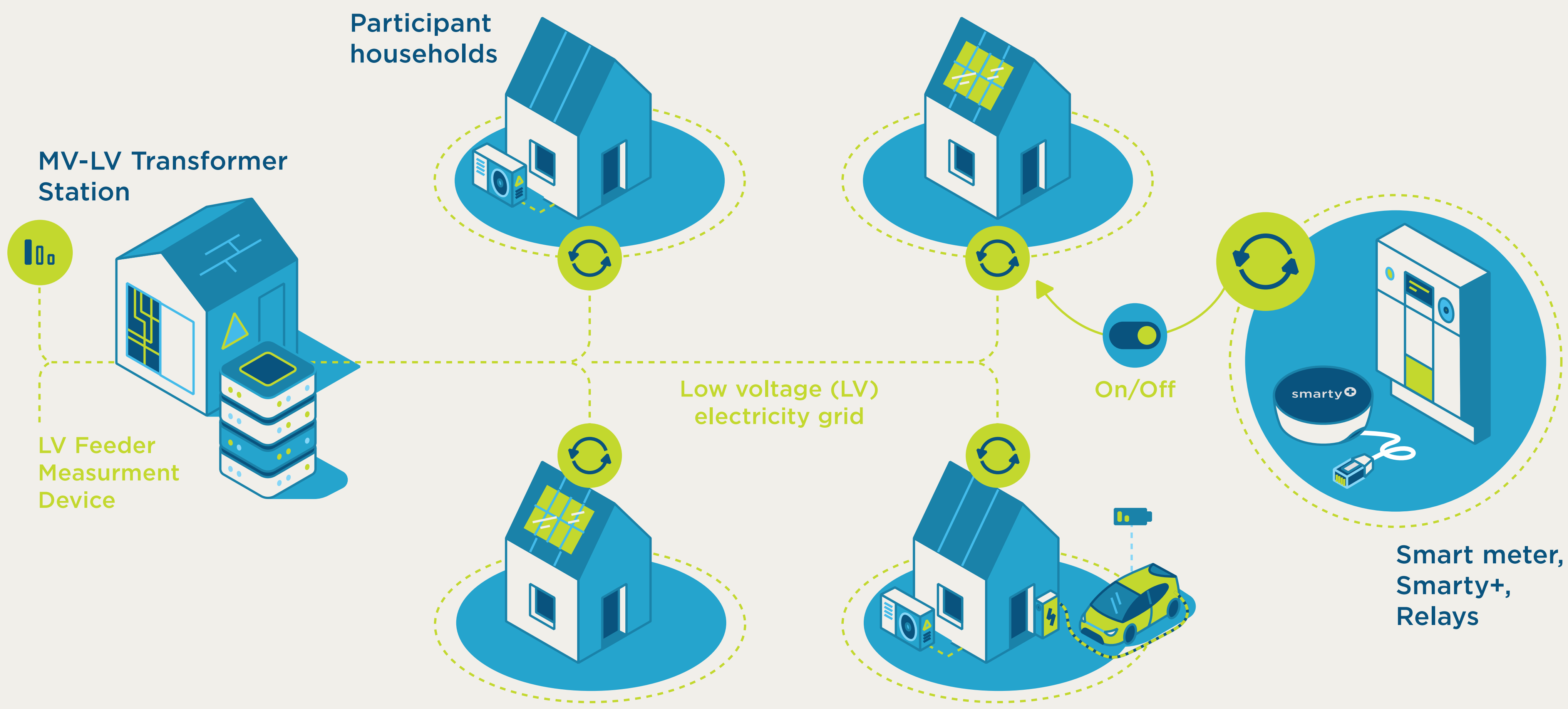


Figure 10
Placement of measuring devices in the LV grid

5.4.1

Smart Meter Data

The smart meter is not particularly installed for the Living Lab, but its data is nevertheless an essential part of the project. Practically all households connected to the Creos grid are equipped with a smart energy meter named Smarty[7] in Luxembourg. This energy meter is situated at a customer's connection point and regularly measures the consumption and production of the household. The data is collected by the related data concentrator via PLC (Power Line Communication) and transmitted to Creos once per day. Extensive data is available from the P1 port as mentioned in section 5.4.2 but due to the limited transmission bandwidth of the PLC signal, only the average power data is transmitted to Creos once per day with a granularity of 15 minutes.

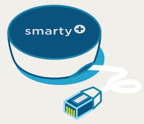
[7] https://www.creos-net.lu/particuliers/infos-pratiques/smarty

Measured Data	Unit
Active power consumption	kW
Active power production	kW
Reactive power consumption	kVAr
Reactive power production	kVAr

Table 9
Data transmitted by the smart meter via PLC (15 minutes average values)

5.4.2

Real-time Smarty+ Data



In the scope of the Living Lab, Smarty+ devices have been installed, a dongle that can be connected to the P1 port of the smart meter. Due to the connection to the household's Wi-Fi network, it is capable to transmit all data available from the P1 port (specified in Table 10) in real-time with an increased granularity of 10 seconds. These insights are of high value for the smart grid operation as the data also includes valuable insights into the voltage values at the delivery points and delivers a view for each phase individually.

In addition to the increased visibility of the grid load in real-time for Creos, parts of this data are visualized and made available to the participants via the Smarty+ smartphone application as mentioned in section 4.3.1.

Available Data from P1 Port	Unit
Current date-time	-
Total imported energy register (P+)	kWh
Total exported energy register (P-)	kWh
Total imported energy register (Q+)	kVArh
Total exported energy register (Q-)	kVArh
Instantaneous imported active power (P+)	kW
Instantaneous exported active power (P-)	kW
Instantaneous imported reactive power (Q+)	kVAr
Instantaneous exported reactive power (Q-)	kVAr
Active threshold (SMAX)	kVA
Threshold for max. imported/exported current	A
Instantaneous imported apparent power (S+)	kVA
Instantaneous exported apparent power (S-)	kVA
Relay 1 control state	-
Relay 2 control state	-
Number of power failures	-
Number of voltage sags per Phase	-
Number of voltage swells per Phase	-
Instantaneous voltage per Phase	V
Instantaneous current per Phase	A
Instantaneous active power (P+) per Phase	kW
Instantaneous active power (P-) per Phase	kW
Instantaneous reactive power (Q+) per Phase	kVAr
Instantaneous reactive power (Q-) per Phase	kVAr
Last Index gas channel x	m^3
Last Index water channel x	m^3
Last Index heat channel x	GJ

5.4.3

Real-time Transformer Station Measuring Device

To enable real-time monitoring of the load on each low-voltage feeder, advanced measurement devices have been installed at the transformer station. These devices capture key parameters such as current, voltage, and frequency for each individual phase of the feeders connected to the station, with a high measurement frequency of 200 milliseconds. The devices are configured to aggregate these measurements at the grid edge, transmitting the maximum, minimum, and average values every minute. This granular and timely data forms a critical component of the monitoring infrastructure, ensuring precise oversight of the grid capacity.

Value	Unit
Active Power	kW
Reactive Power	kVAr
Apparent Power	kVA
Active Energy	kWh
Reactive Energy	kVArh
Apparent Energy	kVAh
Frequency	Hz
Current	A
Measured Neutral Current	A
Calculated Neutral Current	A
Voltage (Phase to Neutral)	V
Power Factor	-
Flicker	-
Voltage Dips	-
Voltage Swells	-
Transient Overvoltages	-
Voltage Interruptions	-
Bridge Diagonal Voltage	V
Voltage THD	-
Residual Voltage THD	-
Mains Signal Voltage	V

Table 11
Data measured by the LV Feeder Measurement Device

5.4.4

Load Management Mechanism via Relays

As part of the Living Lab, the use of the relays of the smart meter for load management is being tested. The smart meter is equipped with two relays, R1 and R2, which are required to be connected to the EV charging wallbox (R2) and the PV inverter (R1) according to Creos TAB guidelines. This temporary action requires the wallbox to reduce its charging speed to 50% (typically 5.5 kW) and reduce the feed-in of the PV system to 30% of the installed inverter power. Each relay operates a dry contact with the following functionality:

- **Closed position:** Load management is active
- **Open position:** Load management is not active

The position of the relays can be controlled through two types of messages:

- **Direct Actioning:** A command specifying the relay position is sent and executed immediately upon receipt
- **Calendar upload:** A schedule defining when the relay should switch to closed or open positions is uploaded. This schedule can cover an entire year, including specific adjustments for holidays or other exceptions

Relay messages are transmitted from Creos to Luxmetering and then forwarded to data concentrators via fiber optic cables and/or cellular connectivity. The data concentrators, typically located in MV-LV transformer stations, use PLC signals to transmit the message to the smart meters.

Since PLC communication is susceptible to interferences, which may compromise the reliability of the real-time direct actioning messages, additional real-time capable relay modules have been installed. These modules leverage participants' internet connections and integrate with Creos systems via APIs, enabling low-latency communication for enhanced reliability.

5.4.5

Digital Twin of the grid – Kopr

Developed together with Datathings, *Kopr* serves as the digital twin of the Creos Smart Grid. It maps Creos' entire network topology and uses advanced machine learning algorithms to generate customer-specific load curve forecasts. Based on this, *Kopr* calculates resulting power flows and voltages within the network enabling the monitoring of the grid status. It can also be used for grid planning, simulating alternative switching positions, new connections, and future grid loads as the energy transition progresses.

Kopr is already deployed across the entire Creos grid, utilizing smart meter load curve data for its forecasts. For the Creos Living Lab, the platform has been enhanced with several additional features to meet the specific demands of the project:

- Integration of real-time data streams from the Smarty+ devices and transformer station measurement systems
- Development of an interface to activate load management mechanisms via the relays
- Introduction of a new interface for monitoring and controlling grid loads and associated load management actions
- Creation of automation algorithms to detect and manage grid constraints in real-time and based on forecasted conditions
- Addition of new forecasting algorithms tailored for testing within the Living Lab

These enhancements ensure that *Kopr* not only supports current grid operations but also provides the tools and intelligence necessary to address future challenges in an increasingly dynamic energy landscape.

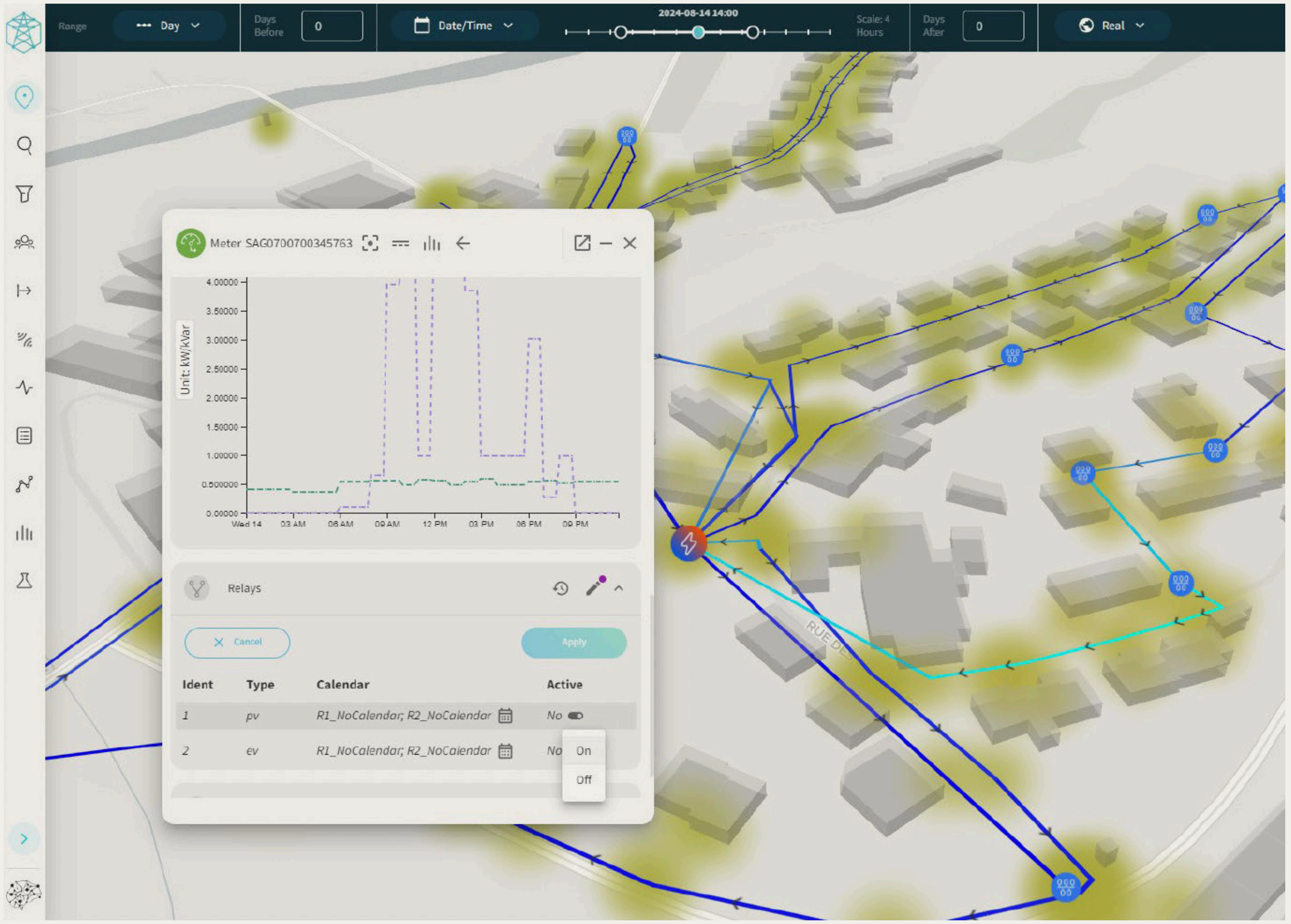


Figure 11
Kopr – The digital twin of the electricity grid

5.4.6

Smart Grid Data Flows

Figure 12 illustrates the data flows implemented to connect various measurement devices to Creos' digital twin, *Kopr*. It provides a high-level overview of how the different measuring devices and relays are integrated with Kopr, as described on the next page.

These interconnected data flows ensure that *Kopr* receives comprehensive and timely information to monitor, forecast, and operate the load management, providing a foundation for managing the challenges of the energy transition.

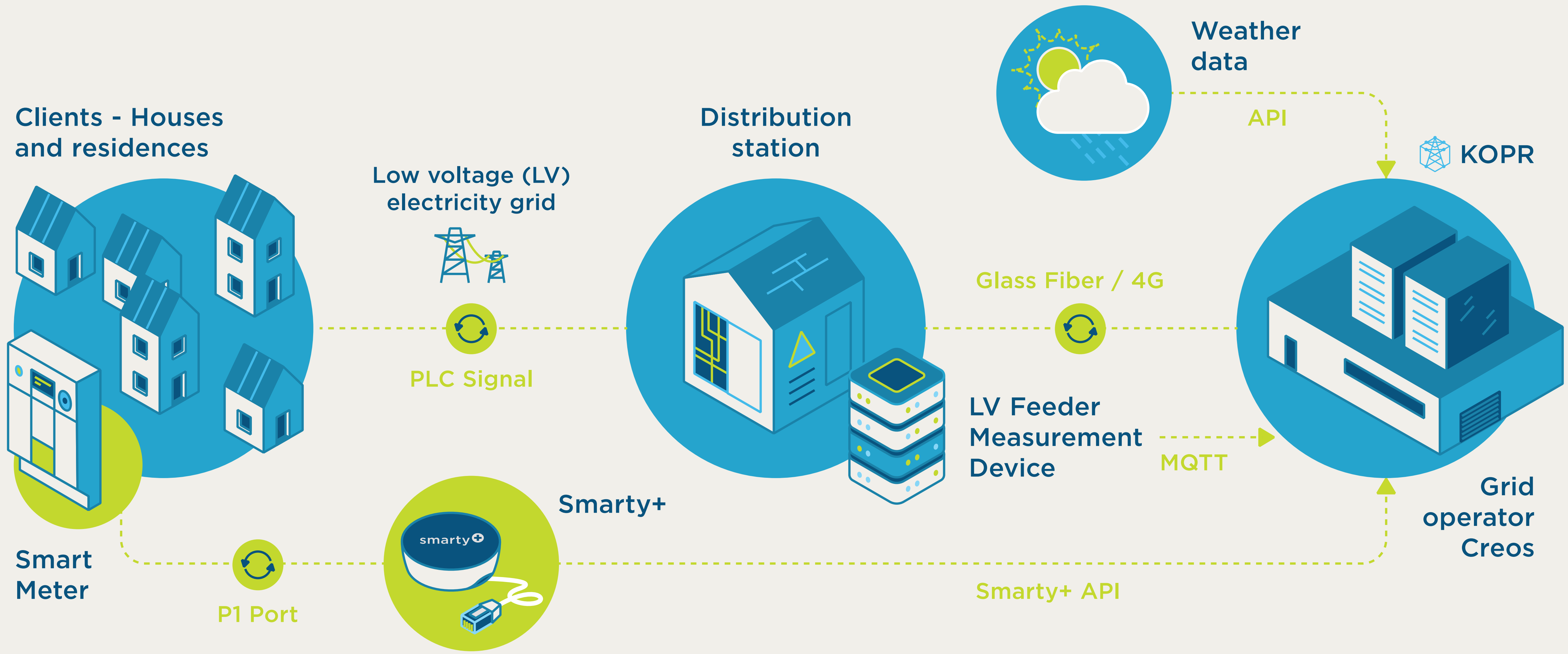
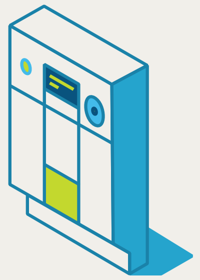


Figure 12
Data Flow Graph



Smart Meter Integration: The smart meter communicates with Creos systems via Power Line Communication (PLC) using the low-voltage distribution grid cables to connect to the data concentrator at the transformer station. The data concentrator aggregates information from all connected smart meters and transmits it to Creos systems via fiber optic cables and/or 4G cellular connectivity. Smart meter measurement data is transmitted to Creos once per day, while relay requests are sent on demand. Depending on available PLC bandwidth, multiple relay requests can be sent daily, although this communication method can be prone to interference.

Smarty+ Dongle Integration: The Smarty+ dongle collects measurement data from the smart meter via its P1 port and transmits this data to Creos systems using the household's Wi-Fi connection and the Smarty+ API.

Low-Voltage Feeder Measurement Device: Installed at the transformer station, this device transmits real-time data to Creos systems via MQTT requests. It shares the same fiber optic cables and/or 4G cellular modem used by the data concentrator, ensuring efficient communication.

Additional Data Sources: External data sources, such as weather information, are integrated into Creos systems via API calls to support forecasting algorithms and enhance grid management capabilities.

5.5

Outcomes from forecast-based load management

Forecast-based load management aims to anticipate grid bottlenecks before they occur by using forecasts of household consumption and PV generation to trigger relay actions early.

In the Creos Living Lab, multiple forecasting approaches were tested and evaluated to determine their suitability for managing future low-voltage grids with high shares of flexible loads such as EV chargers and heat pumps, and high PV penetration.

This section summarizes the performance of the tested forecasting approaches, highlights the operational outcomes, and identifies the key lessons learned for the deployment of forecast-based load management in real electricity grids. To keep testing conditions consistent throughout the smart grid tests, the participants were asked to adopt the consumption behaviour described in Section 6.1.2 during these periods.

5.5.1

Summary: Suitability of Forecast-Based Load Management

The Living Lab enabled Creos to gather valuable in-field experience in which circumstances the forecast-based load management works well. Overall, precise load management control via relays - where only as much load reduction is achieved as strictly necessary - is very difficult. There are many influencing parameters, including uncertainties of connected EV chargers, relay signal implementation by the installer or actual PV output at the moment of the reduction for example. Therefore, a higher number of assets needs to be selected to assure a secure load reduction.

Injection peaks — well suited

For injection peak shaving the results proved that forecast-based load management is well suited on sunny days in grid areas dominated by PV injection peaks, thanks to reliable PV forecasts and the suitability of the calendar-based relay function.

This outcome is highly satisfying, because it is the most relevant circumstance for injection peak related grid congestions. Challenges remain for days with intermittent clouds, but these are also less critical from a grid congestion perspective. More detailed results can be found in section 5.5.4 and 5.5.5.

Consumption peaks — complex

For consumption peak shaving, the experiences of the Living Lab showed additional complexities and the field study did not provide sufficient results to prove forecast-based consumption load management as a viable option at the current stage.

Nevertheless, valuable lessons-learned on the limitations of household-level peak forecasting models and the unpredictable nature of EV charging can be drawn and included in future developments. For more insights, please refer to section 5.5.2 and 5.5.3.

5.5.2

Quality of Consumption Forecasts

The forecasting models used for consumption in the Living Lab are based on historic smart meter data and Gaussian Mixture Models (GMM). These models perform well for households with stable and repetitive consumption patterns, especially when no significant changes in the installed devices occur over extended periods.

However, the Living Lab introduced substantial variability that challenged the accuracy of traditional household-level forecasting:

- **Impact of newly introduced large loads:** The addition of 13 EVs—each representing up to 11 kW of flexible but irregular consumption—significantly reduced model accuracy. Since these charging events did not exist in the historical dataset, the model lacked comparable reference patterns and thus was not able to accurately estimate both the timing and magnitude of evening peaks related to EV charging.
- **Frequent behaviour changes:** Throughout the year of the Living Lab execution, the participants were asked to frequently adopt new consumption behaviour schemes for testing purposes. This further reduced the accuracy of the GMM consumption forecast model because the historic learning data that was at its disposal was no longer valid with each change of behaviour. This impact also needs to be expected at a lower rate outside of the Living Lab, because charging sessions depend heavily on daily routines, such as sport activities, social visits, or unexpected trips. Irregularities in this routine are difficult to capture with statistical models trained on historic averages.
- **Aggregation effect:** Based on statistical theory, forecasting becomes more accurate when more customers are aggregated because uncertainties of individual behaviour are reduced at an aggregated level. While individual household-level forecasts are highly uncertain, the aggregated load of a large number of consumers such as for a whole transformer station or town is expected to be easier to predict. Nevertheless, even small deviations at household level impact the forecast precision in a street with only a few customers such as the street selected for the Living Lab.

Conclusion: As a conclusion, the consumption forecasting related to EV charging in the Living Lab represented a worst-case scenario for GMM-based models and does not allow to conclusively validate the use of forecasts for consumption load management. Nevertheless, the project delivered important insights into the specificities of different forecast models and impacting parameters to assure a reliable output. This underlines that forecasts need to be tailored to specific circumstances and use cases.

There is no silver bullet forecast model that fits all needs and, in the end, different approaches may be chosen depending on the consumer types and the aim of the forecast. A forecast with high accuracy for daily energy consumption forecasts is likely not optimal for forecasting peak periods and vice versa. On a similar manner, forecasts optimized for short-term predictions (days or weeks) are not optimal for long-term predictions (years).

5.5.3

Outcomes of Forecast-Based Load Management for EV Chargers

During forecast-based consumption peak shaving tests, relay messages commanded EV chargers to temporarily reduce their charging speed during predicted evening peak periods.

Key findings include:

Consumption peaks were dominated by EV charging: Consumption peaks in the field study were dominated by EV chargers, although EVs are not constantly connected. With 11 kW power consumption it is the defining element of the individual household's consumption peaks. This makes EV charging speed modulation very suitable for peak reductions. At the flipside, it also brings challenges because EVs are not charged every day and their charging depends heavily on the daily routine of the household which is subject to large changes (e.g. irregular visits of friends or family).

Difficulties to predict the charging cycles of individual EVs: To reduce impacts on customer comfort to a minimum, the load management algorithm aims to select the minimum necessary number of EV chargers to achieve the required peak reduction. Unfortunately, the before-mentioned uncertainty which EV will be charging in the peak period makes this very challenging. To alleviate the risk of not achieving enough load reduction, more EV chargers needed to be included in the load reduction action than ultimately necessary to confidently flatten the evening peak. This risk must be carefully balanced with the impact it may have on customer comfort.

Minimal comfort impact for most households: In practice, participants reported little to no disruption, because charging speed modulation primarily occurred in the evening and charging could continue later at night allowing enough time for a full charge by the morning.

Only Households with two EVs signalled an impact on comfort: For participants sharing a single wallbox for two EVs, comfort impacts occurred when both cars needed to be charged on the same night. This requires the first car to complete charging in the evening to allow the owner to swap the charging to the second car overnight. In this instance, one occurrence was signalled where the charge of the first car was not finished before bedtime blocking the owner from plugging in the second car overnight. This risk could have been alleviated by installing a wallbox which is capable to plug in two cars simultaneously and to swap the charge automatically after the completion of the first charging session.

5.5.4

Quality of Production Forecasts

The Living Lab also evaluated PV forecasting approaches. Initially, PV production was predicted using the same GMM models used for consumption based on temperature and historic production patterns, but these performed poorly for PV injection. To improve accuracy, a new PV generation forecast approach was introduced during Living Lab which relied on a physical PV generation modelling and reliable solar irradiation forecasts from a new weather data source.

The improved PV generation forecast model delivered:

- **Highly accurate predictions on sunny days,** enabling precise timing of peak injection periods. Figure 13 shows the measured PV generation in green and the forecasted generation in blue on a sunny day with a very high generation peak.

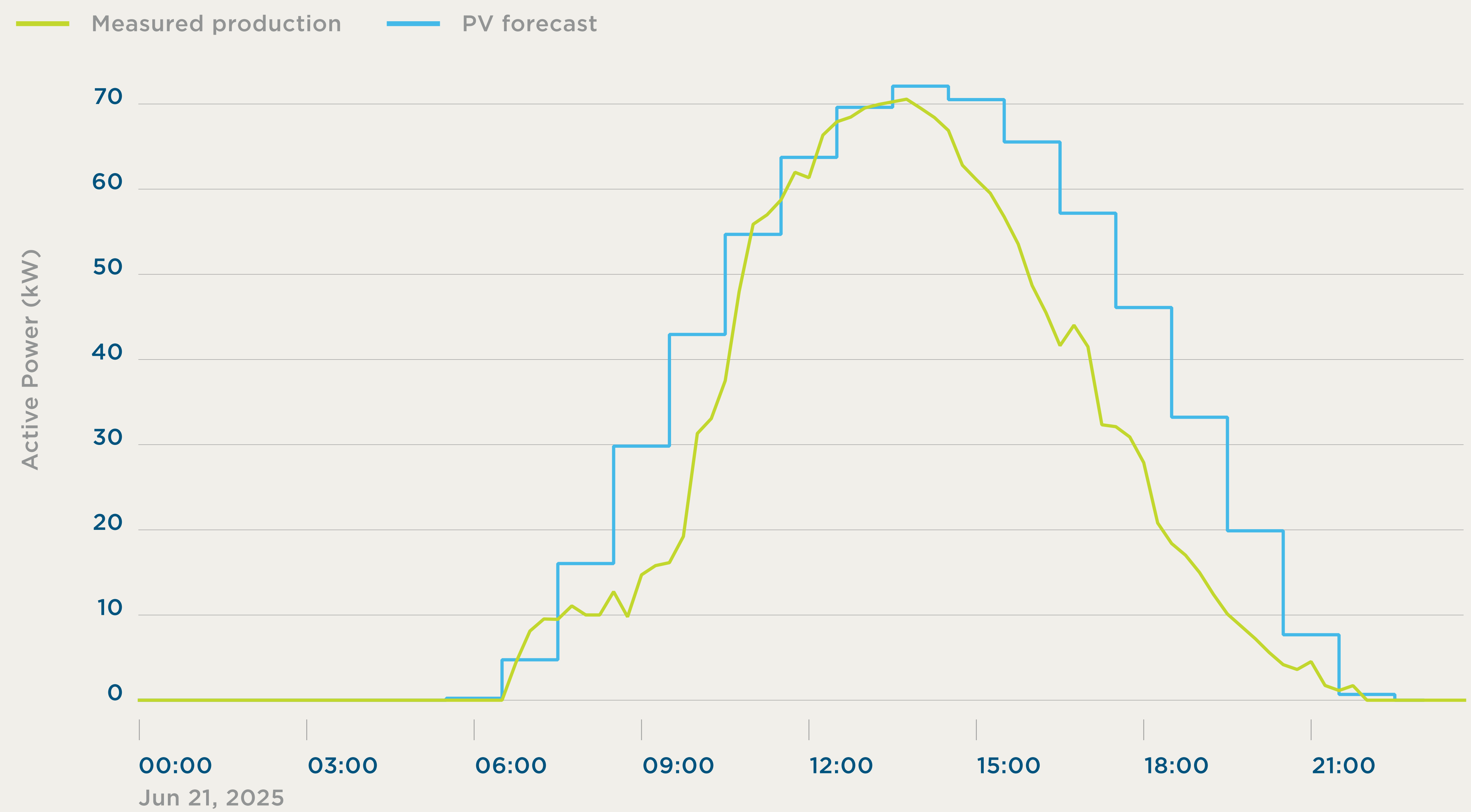


Figure 13
PV Forecast accuracy on completely sunny days

- **Reduced accuracy under intermittent cloud coverage**, which is related to the flattening effect of the reduced 1h granularity of the underlying weather forecast data source compared to the measured data. Figure 14 illustrates that substantial short-term peaks are not visible in the current forecast. A more granular weather forecast would thus be beneficial to accurately predict generation peaks on days with intermittent clouds. Nevertheless, such days are expected to remain challenging because of the difficulties to accurately predict the timing of the cloud coverage for all locations.

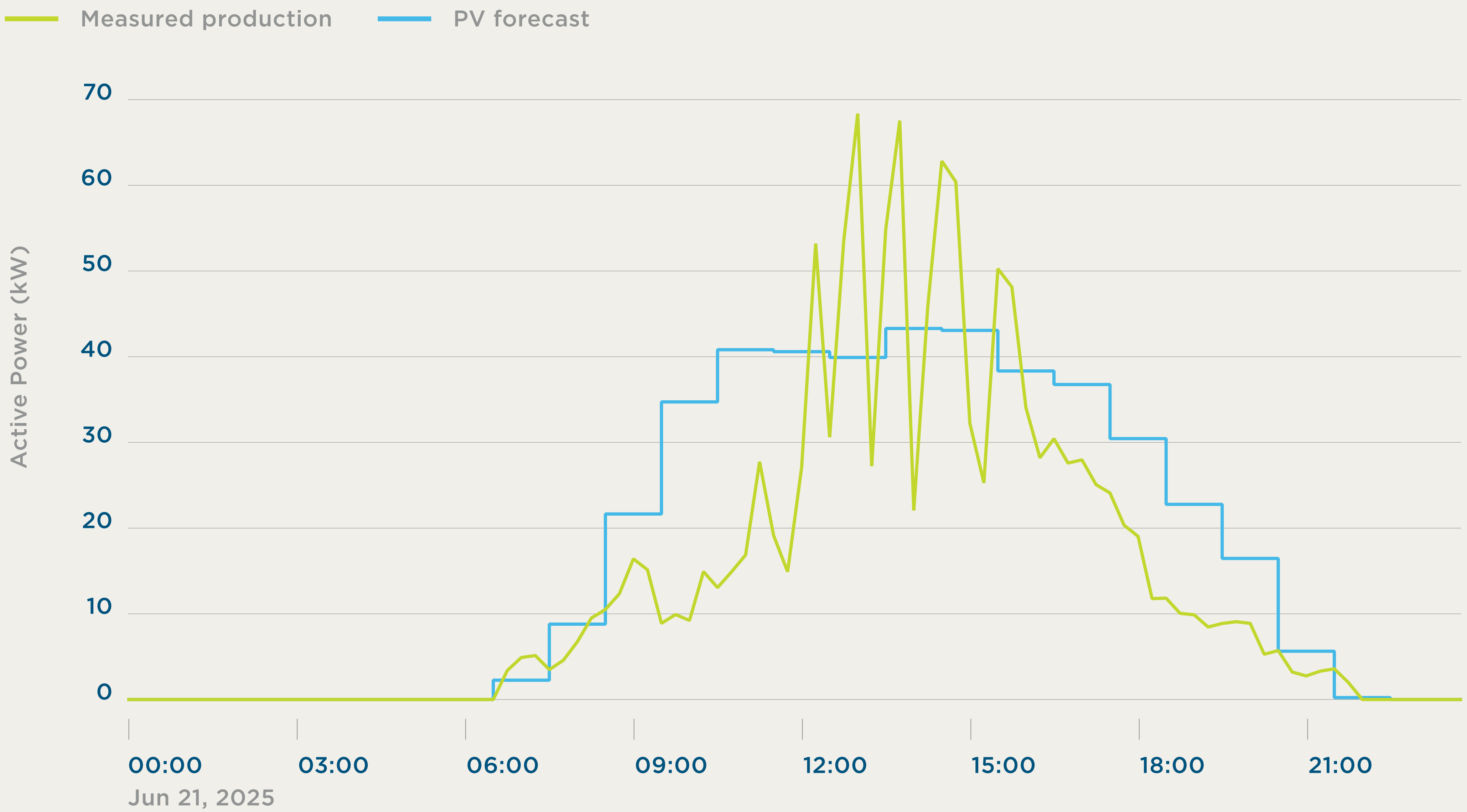


Figure 14
PV Forecast accuracy on days with intermittent clouds

- **The accuracy is sufficient for LV grid operations**, because transformer and cable overloads occur only after prolonged high injection periods rather than short-lived fluctuations. As these elements require extended peak periods to overheat, it is not strictly necessary to predict short-term peaks on days with intermittent clouds.

Conclusion: PV production forecasts were robust enough for safe injection peak shaving, particularly in grid areas dominated by PV generation like the feeder selected for this project. The final forecast is however always a combination of the generation and consumption forecasts and may thus be impacted by uncertainties in the consumption prediction. Especially, PV battery systems may lead to deviations from the forecasted injection because the state of charge of the battery and the charging schedule is unknown.

5.5.5

Outcomes of Forecast-Based Injection Load Management

During forecast-based injection peak shaving tests, relay messages commanded PV inverters to temporarily reduce their injection power during predicted peak periods around noon.

Key findings include:

Compatible with existing communication infrastructure: The communication of relay instructions is reliable enough to enable forecast-based load management. The smart meter relay calendar messages are significantly less prone for interferences as they allow for longer transmission durations compared to the direct relay messages used for real-time load management. These interferences are explained in more detail in section 5.7. As forecast-based dimming allowed sufficient time to deliver relay messages via PLC, there is **no dependence on ultra-fast and costly communication infrastructures**.

Effective on sunny days: Peak reduction was very effective on completely sunny days. This is directly linked to the accuracy of the forecasts on these days as stated in section 5.5.4

Lower accuracy on days with intermittent clouds: The accuracy of the reduction was lower on days with intermittent clouds. On the one hand, this is caused by uncertainties to forecast when intermittent clouds will impact PV injection. Additionally, the weather forecast source delivered one hour average solar irradiation flattening periods of high irradiance within the hour. Due to this, the forecast missed significant intermittent forecasts completely failing to reduce brief injection peaks on these days as illustrated already in Figure 14 of the previous section.

Self-consumption and batteries influence the accuracy: In areas with high PV self-consumption or battery charging, inaccuracies in consumption forecasts may occasionally lead to unnecessary PV curtailment.

Conclusion: Forecast-based injection load management is feasible using todays PLC communication infrastructure especially on very sunny days in PV dominated grid areas where cable and transformer loading is the most important. Margin of improvement remains on days with intermittent clouds and grid areas with high self-consumption where both injection and consumption forecasts could profit from improvement. However, this is less important than the before mentioned usage scenario because self-consumption and intermittent clouds result in lower cable and transformer loading.

This reinforces the advantage of controlling household-level injection rather than PV inverter output alone, especially when households use batteries or self-consumption to automatically smooth their injection peaks.

5.6

Outcomes from real-time data-based load management

Real-time load management aims to detect and mitigate grid overloads using real-time or near-real-time measurement data.

In the Living Lab, this approach was tested using measurement data streams from the new LV feeder measurement devices at the transformer station and the Smarty+ dongles as explained in section 5.4. Although highly granular data was available, the control algorithm for real-time load management was purposely based on **15-minute running average values** for threshold evaluation. The control algorithms and data used for real-time load management are further detailed in section 5.6.2. Section 5.6.3 and 5.6.4 summarize the operational results and provide insights into the suitability of real-time load management for future LV grid operation for both consumption and injection. The results focus on the case where the following precursors of reliable data and instruction communication are met. To keep testing conditions consistent throughout the smart grid tests, the participants were asked to adopt the consumption behaviour described in Section 6.1.2 during these periods.

Although the impact of eventual forecast inaccuracies is avoided in this case, there is a strong reliance on very low latency communication of the load management instructions and high fidelity of real-time measurements. Real-time measurement availability proved to be very reliable throughout the project, but real-time communication of load management instructions can be prone to interferences as explained in section 5.7. These instructions must be executed briefly in order to effectively mitigate emerging grid constraints.

During the Living Lab, **frequent perturbations of the Power Line Communication (PLC) channel** were observed, particularly during periods of high PV generation. These disturbances significantly limited the reliability of real-time relay actuation via the standard smart meter communication path. To enable testing of real-time control strategies, additional real-time capable relay modules were therefore installed, using the participants' internet connections as an alternative communication channel. The following results are therefore only valid in case a reliable real-time communication has been established.

5.6.1

Summary: Suitability of Real-time Based Load Management

Real-time data-based load management was tested for both consumption and injection use cases in the Creos Living Lab to evaluate its effectiveness in mitigating critical grid situations under real operating conditions. For both use cases, **additional real-time data and relay communication improvements beyond the status quo on the Creos LV grid are a pre-requisite**. The following results are thus only valid in case a real-time capable communication towards the relays and real-time data have been set up.

Overall, precise load management control via relays — where only as much load reduction is achieved as strictly necessary — is very difficult. There are many influencing parameters, including uncertainties of connected EV chargers, relay signal implementation by the installer or actual PV output at the moment of the reduction for example. Therefore, a higher number of assets needs to be selected to assure a secure load reduction.

For consumption: Real-time load management proved capable of reducing evening peak loads when consumption is dominated by EV charging. However, due to uncertainties regarding which EVs are charging at a given moment and the presence of other significant consumers, precise control at asset level remains complex.

To reliably achieve the targeted load reduction and remain within grid constraints, **conservative strategies were therefore required**, involving the selection of comparatively large number of EV chargers for load management. This approach ensured reliable load reduction during peak periods by increasing the probability that actively charging EVs were included in the load management, at the expense of potentially involving more chargers than strictly required.

For injection: Real-time load management demonstrated high effectiveness in reducing sustained PV injection peaks, which are most relevant for preventing cable and transformer overloading. Nevertheless, the fast dynamics of PV generation under intermittent cloud coverage revealed limitations of the applied control logic, particularly when relying on 15-minute averaged values.

While real-time measurements enable the detection of short-lived peaks, **additional refinements are required** to handle rapid fluctuations efficiently.

> **Note:** Neither the high-resolution real-time measurement devices installed at the transformer station nor the additional real-time capable relay modules are part of the country-wide rollout in the Creos grid. Consequently, enabling real-time load management on a larger scale would require substantial additional investments in both measurement and communication infrastructure. This challenge is particularly pronounced for **PV injection load management**, as PV inverters are prone to introducing interference on the PLC communication bandwidth, further reducing the reliability of the current PLC-based relay control.

The following subsections provide a detailed analysis of the results, limitations, and improvement potential for both consumption and injection load management.

5.6.2

Control Algorithms and Data used for Real-time Load Management

Different sources of real-time data are available in the scope of the Creos Living Lab, differing in granularity and measurement location. As described in Sections 5.4.2 and 5.4.3, real-time measurements were available at both the transformer station level (via the SGIM device) and at the individual household level (via Smarty+ dongles). In principle, real-time load management can rely on various levels of observability, ranging from aggregated measurements at the transformer station, to individual feeder-level monitoring, and further down to household-level measurements. In addition, **hybrid approaches are conceivable**, in which forecast-based load management is augmented with real-time measurements to improve accuracy and robustness, particularly under rapidly changing grid conditions.

For the real-time load management tests conducted in the Living Lab, the focus of the control algorithms was placed on load measurements of a single low-voltage feeder at the transformer station via the SGIM sensor. This choice reflects operational relevance, as cable loading is typically highest at the beginning of the feeder, where the aggregated current of all connected households flows. As only one feeder was included in the field study, all real-time control actions were therefore based exclusively on the loading of this feeder. Nevertheless, the applied concepts and findings can be directly transferred to transformer-level load management.

In terms of granularity, control thresholds were evaluated using 15-minute average values derived from the real-time measurements. This design choice reflects the physical behaviour of grid assets such as cables and transformers, which do not overload due to short, instantaneous peaks but rather as a result of sustained high loading over extended periods. At the same time, this design also helps to avoid frequent activation by preventing oscillation between ON/OFF states which could occur if thresholds were only exceeded for very short periods instead of the 15-min periods.

Voltage quality monitoring: Besides cable and transformer loading, voltage quality has also been closely monitored throughout the project. Voltage variations require different monitoring strategies because the highest voltage deviation is expected to arise at the end of the feeder due to voltage swell or sag. To achieve this, Smarty+ data from the end of the feeder was integrated into the monitoring controls as well as alternative simulated voltage based on cable loading and transformer level voltage measurements.

Voltage regulation additionally requires more granular monitoring, as **even brief deviations from permissible voltage limits are not allowed under DIN EN 50160**.

However, **no load management actions have been triggered based on voltage control**, because voltage quality in the selected street remained largely unaffected by the applied load management actions and was primarily driven by effects originating from higher voltage grids. This behaviour can be explained by the relatively short feeder length of the tested area and its limited load compared to the higher voltage grid. On top of this, voltage quality remained within acceptable limits throughout the entire project duration. Therefore, voltage regulation was deliberately excluded in the following results.

5.6.3

Results of Real-Time Consumption Load Management

Real-time consumption load management was tested in winter where the highest consumption peaks occur. Due to the uncertainties which EVs are charging during a given peak consumption period and the fact that EVs are not the only consumers, load management relying solely on regulating the EV charging speed is complex. This makes the accurate prediction how many and which EV chargers should be reduced to achieve a planned consumption reduction difficult. At the same time, choosing the wrong chargers is prone to risks because it could result in insufficient load reduction to remain within grid constraints. Therefore, two strategies with differing risk affinity were tested as explained in Table 12.

Dynamic Default: On	Dynamic Default: Off
Full speed charging is allowed by default in the typical peak periods.	Charging is done at reduced speed by default during typical peak hours.
Reduction only occurs when high thresholds are exceeded.	Full speed charging is allowed only during off-peak hours when lower thresholds are reached again.
Shorter intervention periods.	Longer intervention periods.
Higher risk of critical peaks.	Lower risk of critical peaks.

Table 12
Real-time consumption load management strategies

Dynamic Default On aims to allow fast charging as much as possible and only reduce the charging speed when strictly necessary. This is achieved by setting a high threshold for load management activation resulting in later activation and faster deactivation. Dynamic Default Off follows a more conservative approach where charging at reduced speed is requested in the typical peak times (typically during evening hours) and full speed charging is allowed only in off-peak periods (typically throughout the whole night and at daytime). This is achieved by setting a lower threshold for load management activation resulting in earlier activation and longer deactivation periods.

In the end, **both strategies effectively reduced the peak load** compared to the baseline scenario. This is illustrated well by Figure 15, showing consecutive periods of the Dynamic Default On and Dynamic Default Off test phases, with a worst-case reference day in between, without any load management. As external factors like weather did not change significantly throughout this short period, it serves as a highly representative example. It is apparent that the peak loads in both load management strategies were significantly lower than the reference day in-between. The 15-minute average measurements of the feeder apparent power peaked at **72.6 kVA** for dynamic default on and **69 kVA** for dynamic default off, compared to **90.6 kVA** for the worst-case reference. More notably, both load management strategies managed to significantly reduce prolonged peak periods: 60 kVA were exceeded for a maximum of 30 consecutive minutes in both load management phases, compared to 210 minutes in the worst-case reference.

Default On peak
72.6 kVA

Default Off peak
69.0 kVA

Reference peak
90.6 kVA

> **Note:** The current asset level consumption control using only EV chargers limits its effectiveness, because high consumption peaks caused by other consumer devices cannot be addressed.

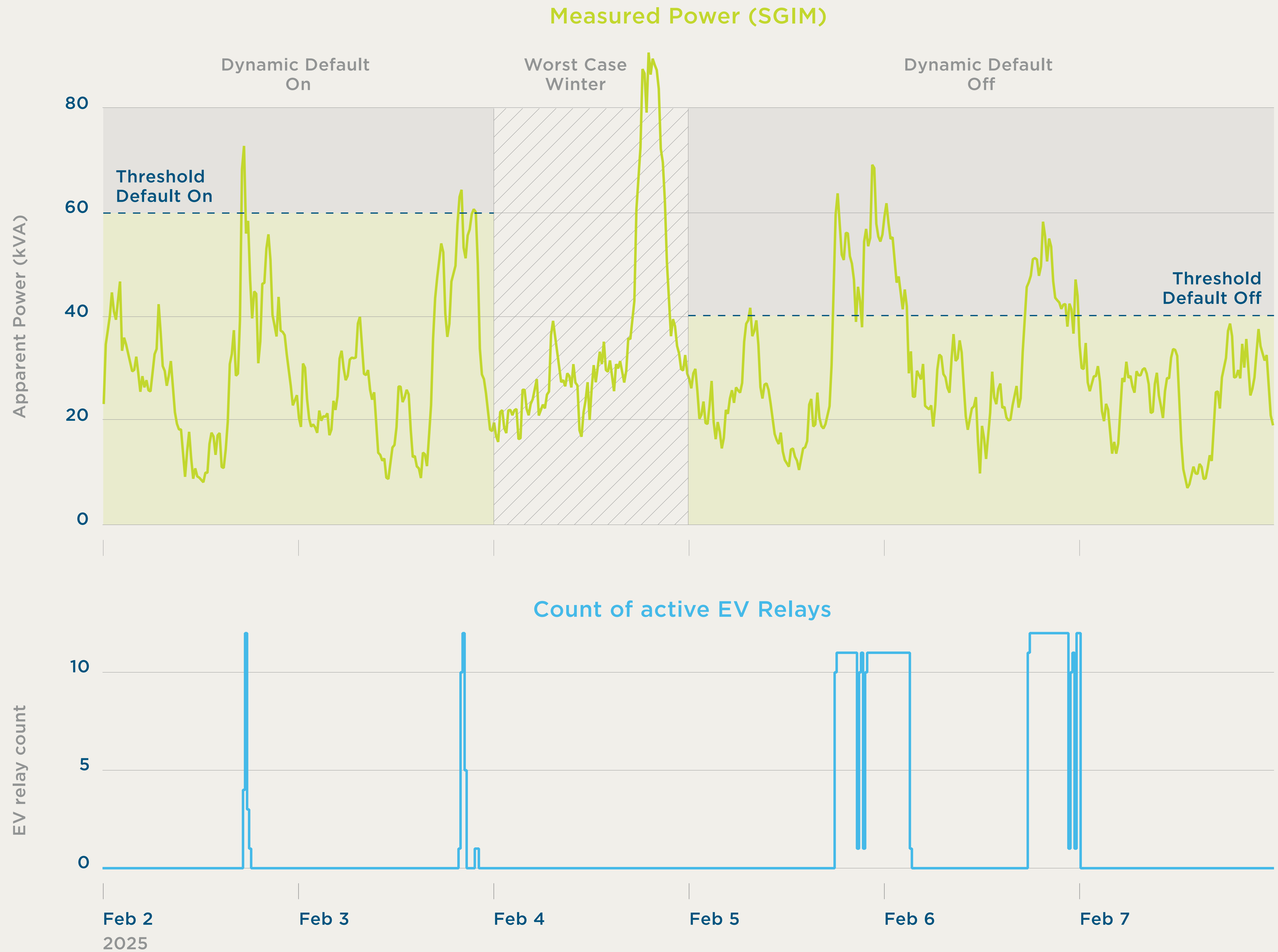


Figure 15
Impact of load management activation on the feeder power profile

5.6.4

Results of Real-Time Injection Load Management

The challenges for injection peak load management differ substantially from the consumption use case with EV charging speed modulation. The before mentioned uncertainties in the selection of the right EV wallboxes are not relevant for injection because - unlike the EV - the PV system is constantly connected, and the solar irradiation is practically identical for all systems in a street.

Added to this, the effective reduction of the injection is further simplified because injection in the LV grid is currently dominated by PV systems. This allows for reliable injection peak reductions, even in tests where only a small selection of PV system was used for load management.

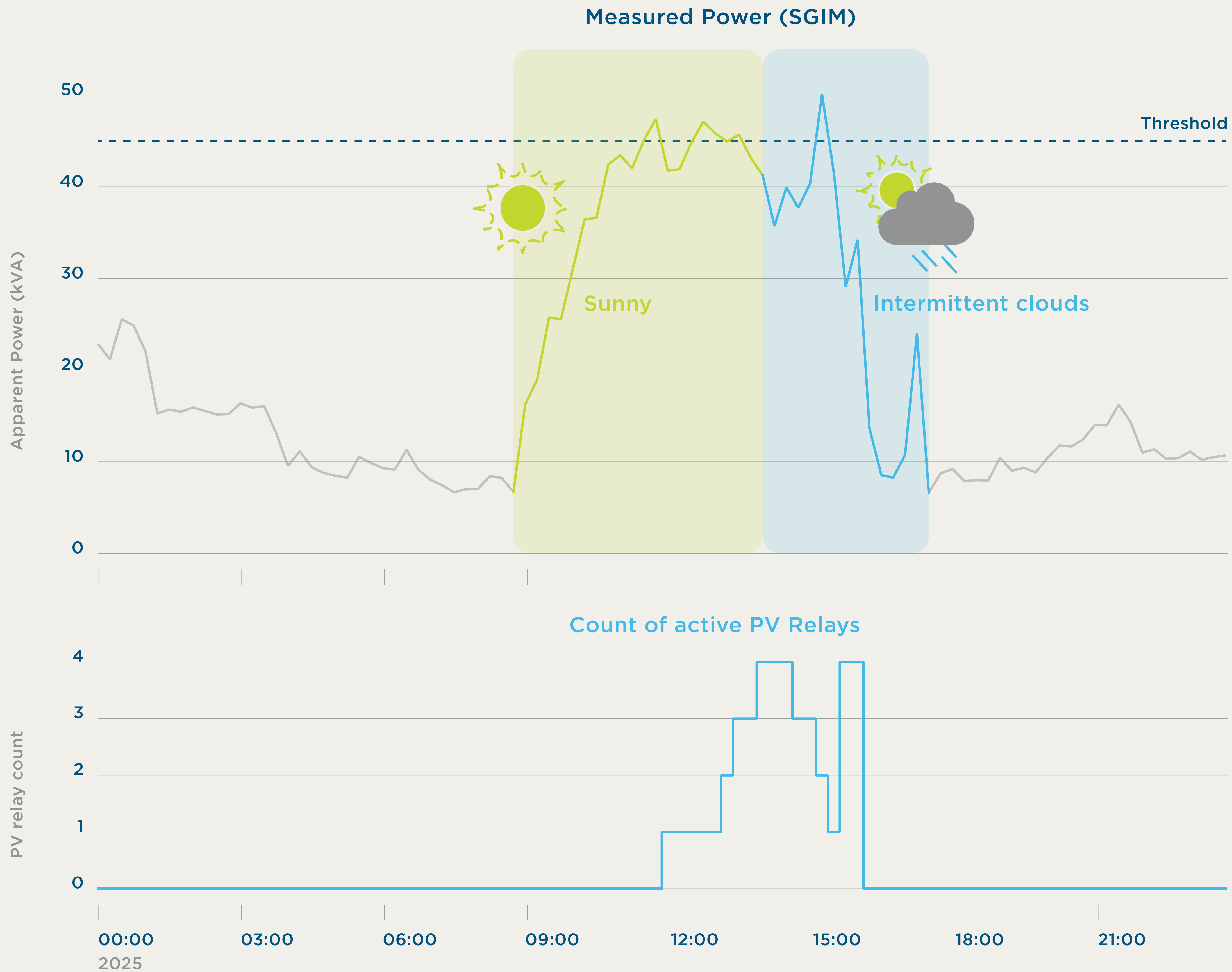


Figure 16
Injection load management in sunny vs cloudy conditions

On the flipside, the fast dynamics of PV output poses new challenges to the control algorithms of PV load management, particularly under conditions with intermittent clouds. The exemplary day in Figure 16 above illustrates this phenomenon well. It shows the active power of the feeder alongside the number of activated PV curtailments of a sunny morning with intermittent clouds appearing in the afternoon.

Sunny period — well handled: On a typical sunny morning, the feeder power follows the characteristic Gaussian-shaped profile of PV injection. As the injection increases towards midday, an increasing number of inverters are curtailed as soon as the defined threshold of 45 kVA is overstepped, reaching a maximum of four out of twelve PV systems being curtailed at the peak injection around 14:00. As a result, the injection peak is effectively reduced, underlining that the load management algorithm is able to handle the sunny period very effectively.

Intermittent clouds — algorithmic limits: At approximately 14:30 on the analysed day, intermittent cloud coverage leads to temporary reduction in PV generation, causing the feeder load to fall below the threshold and resulting in the deactivation of some curtailment. At 15:15, clouds disperse again and full solar irradiation resumes, producing a short injection peak of around 20 minutes. Although brief, this peak is sufficient for the 15-minute average power to exceed the threshold and trigger additional PV curtailment. Due to the averaging window, the curtailment only becomes effective at around 15:30, at which point cloud coverage has already increased again. This leads to an **excessive curtailment being applied for approximately 15 minutes, despite the absence of a sustained injection peak**. This showcases that some limitations of the control algorithm remain for periods with intermittent clouds.

Conclusion: The results confirm that real-time injection load management is an effective means of mitigating sustained PV injection peaks, which are the most critical for preventing cable and transformer overloading, while limiting the number of curtailed PV inverters to the minimum required. Consequently, injection load management performs particularly well under stable, sunny conditions. However, potential for improvement remains on days with intermittent cloud coverage.

While the real-time algorithm proved capable of detecting short-lived injection peaks — an advantage compared to forecast-based approaches — the use of 15-minute averaged values was not well suited to mitigate these fast dynamics effectively. **Further improvements could be achieved by increasing the algorithm's sensitivity to rapid injection fluctuations** and by introducing a hybrid approach that combines forecasts with real-time measurements. This would enable a more effective handling of brief injection peaks while avoiding unnecessary curtailment.

Regarding the comfort of the participants, no impacts have been signalled from PV curtailment.

5.7

Insights on Power Line Communication for Load Management

Creos is at the forefront of smart meter deployment in Europe and has completed its nationwide rollout with the primary objective of collecting 15-minute granular active and reactive power data from all customers. Beyond metering, smart meters also provide additional functionalities, most notably the integrated relays connected to EV chargers and PV inverters, which enable the activation of load management measures in case of grid congestions.

Communication with the smart meters is based on Power Line Communication (PLC), a data transmission technology that uses the existing low-voltage cable infrastructure. PLC operates by superimposing a higher-frequency signal onto the 50 Hz power signal, allowing smart meter data to be transmitted to data concentrators. These concentrators bundle the data and forward it to Creos systems via cellular or fiber-optic connections. According to the Technical Connection Requirements, no other devices connected to the grid are permitted to emit disturbances in the CENELEC and FCC frequency bands (9–500 kHz), ensuring reliable smart meter communication.

Summary

Although not representative of the entire low-voltage grid, the Living Lab offers early insights into challenges that may arise in grid areas with a high penetration of energy transition technologies. It demonstrated that while PLC communication is sufficiently robust for its primary use case — daily transmission of smart meter load curves — it represents a critical limitation for real-time load management applications.

In grid areas with a high penetration of inverter-based technologies, such as PV systems, batteries, EV onboard chargers, and modern heat pumps, PLC communication becomes increasingly vulnerable to interference. These interferences can significantly reduce transmission reliability and increase latency precisely during periods when real-time control actions are most needed. In addition to this, faulty devices may also emit interferences among which certain types of power supplies have been identified.

As a result, **PLC latency and reliability were identified as the main limiting factors for real-time load management** using smart meter relays. In contrast, forecast-based load management allows control signals to be transmitted in advance, providing sufficient time for delivery and thereby making this approach feasible with the existing PLC infrastructure.

Details

The selected grid area for the Creos Living Lab represents an extreme but realistic future scenario, with a high concentration of inverter-based devices. While PLC communication was sufficiently reliable for smart meter data collection prior to the project, the additional use case of transmitting load management signals exposed several challenges. Multiple interventions were required to improve latency and reliability. Certain interference sources, including a specific PV inverter model, were successfully mitigated through the installation of low-pass filters and an additional data concentrator. However, new interferences repeatedly emerged, necessitating detailed investigations to identify their origin.

In one case, a faulty LED driver was identified as a significant interference source, highlighting the **difficulty of locating individual devices emitting disturbances** on the PLC frequency bands. Through the expertise of metering specialists, the interference sources were eventually identified and mitigated. Following these interventions, PLC communication performance improved to a level where near real-time load management signals could be transmitted with latencies below two minutes. Nevertheless, maintaining this level of performance requires continuous monitoring and potential corrective actions.

A deeper analysis revealed that PV and battery inverters are particularly prone to emitting high-frequency harmonics within the frequency range used by PLC. Figure 17 illustrates this effect by showing the PLC transmission success rate at the selected transformer station over time prior to the installation of batteries. Periods of nighttime operation are highlighted in blue. During daytime hours, when PV inverters are active, the transmission success rate is noticeably lower compared to nighttime periods. While this behaviour does not pose a significant issue for the transmission of daily smart meter load curves — since missing data can be recovered during periods of lower interference — it becomes critical for load management applications.

For real-time load management, high transmission reliability and low latency are required exactly during periods of high PV injection, when PLC interference is most pronounced. The presence of **battery storage systems further exacerbates this effect** by extending inverter activity into nighttime hours, thereby increasing the duration of interference. These findings underline the importance of ensuring strict compliance of inverter-based devices with international standards limiting emissions in the CENELEC and FCC frequency bands.

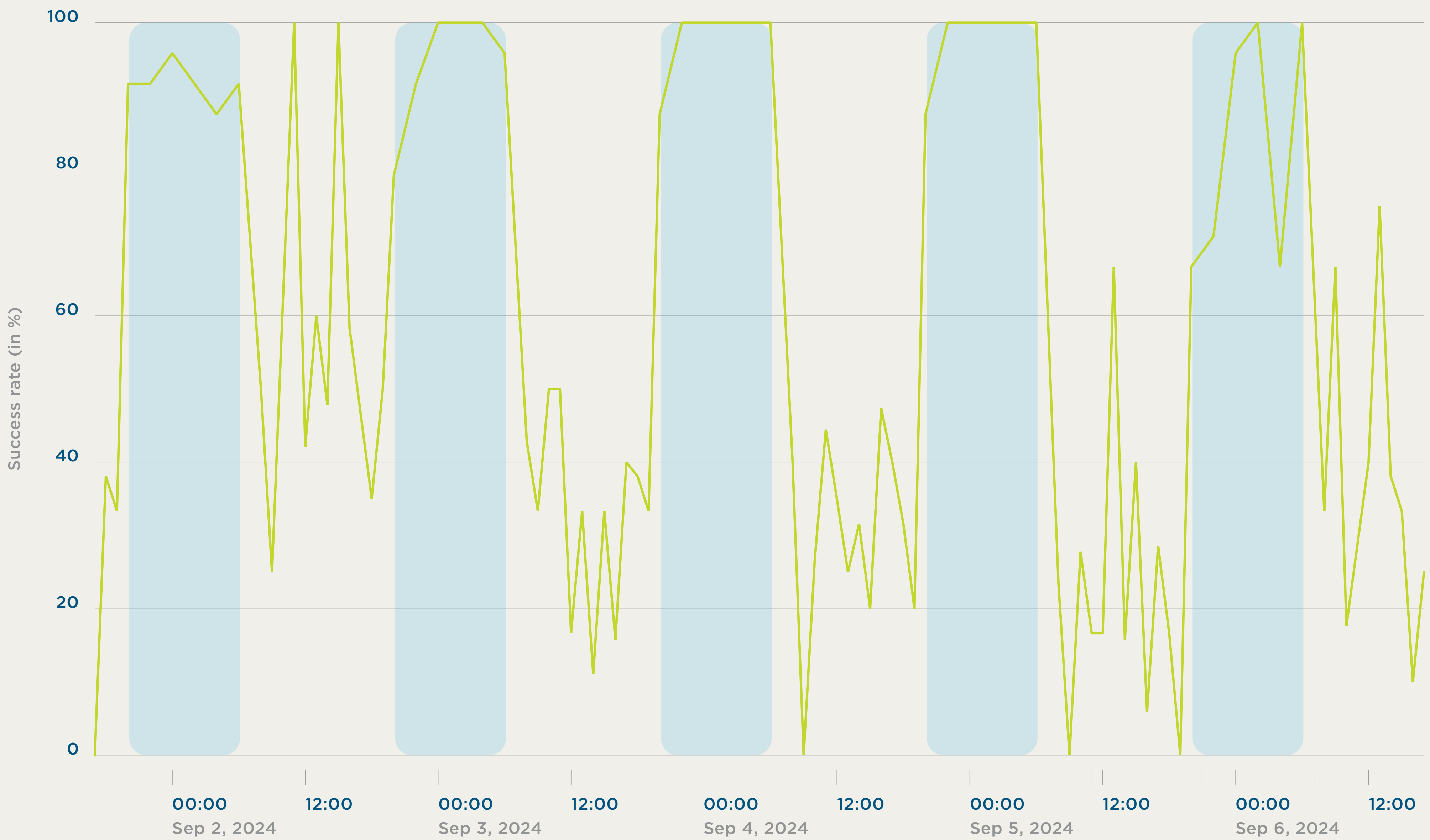


Figure 17
PLC transmission success rate over time prior to the installation of batteries

Based on the Living Lab results, PLC communication should be considered a critical constraint when designing future smart grid strategies involving real-time load management requiring significant additional investment.

Mitigation options

Several mitigation options emerge from the project experience:

- **Prioritise forecast-based load management** using calendar-based signals transmitted in advance — feasible with the existing PLC infrastructure.
- **Deploy stand-alone real-time capable relays** using alternative communication paths.
- **Targeted improvements of PLC communication robustness —** low-pass filters, additional data concentrators, and stricter compliance of inverter-based devices with the CENELEC and FCC emission standards.

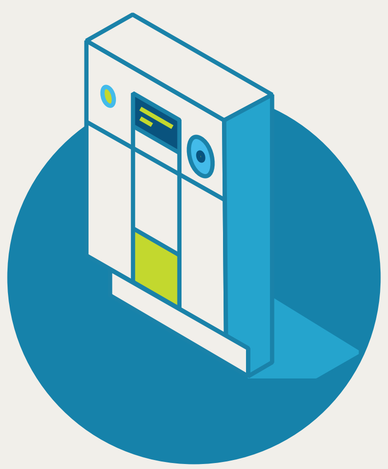
5.8

Insights from High Resolution LV Grid Measurements

Besides the load management tests and the customer behaviour tests, the Living Lab also serves as a proving ground for different real-time measuring devices. In addition to the smart meters — whose rollout has been completed country-wide in the Creos grid — several smart grid monitoring devices were installed to provide higher temporal resolution and additional parameters.

This section showcases the insights we can gather from these devices, focussing on the **LV feeder measurement device SGIM** installed at the transformer station (see section 5.4.3) and the **Smarty+ dongles** delivering granular insights from individual households (see section 5.4.2).

The benefits of these devices lie in the increased granularity, the availability of additional electrical quantities, and provision of data for individual phases. While smart meters are limited to 15-minute averages of active and reactive power, Smarty+ delivers measurements with 10-second resolution, and SGIM provides 1-minute averaged values as well as instantaneous maxima and minima within each minute. In addition, both systems measure voltage, current and frequency per phase, enabling analysis that are not possible with standard smart meter data alone.



Smart Meter

15 min
active & reactive power

Smarty+ Dongle

10 sec
household-level granularity

SGIM

1 min + inst.
feeder maxima/minima per phase

Summary

Granular measurement data significantly enhances the operational visibility of low-voltage grids compared to the 15-minute averaged smart meter data alone. High-resolution measurements reveal **short-lived consumption and injection peaks** that can substantially exceed the peak values visible in 15-minute averaged data, as well as **rapid power fluctuations** caused by intermittent cloud coverage and **pronounced phase imbalances** that may lead to single-phase overloading without being detected by conventional aggregated measurements.

In addition, voltage measurements at both transformer and household level provide a more accurate basis for assessing voltage quality and distinguishing between local and upstream drivers. These capabilities support more informed operational decisions, improve the assessment of grid constraints, and form a key enabler for advanced monitoring, protection, and load management strategies in future low-voltage networks.

Details

Temporal aggregation: 15-min vs. 1-min averages: The analysis starts with a comparison between the 15-minute averaged values and more granular 1-minute averages as well as instantaneous extrema derived from the feeder measurements provided by SGIM.

It is noticeable that the absolute peaks identified in these datasets do not necessarily occur at the same time.Taking the all-time consumption peak of the Living Lab on the 4th of February as an example (Figure 18), the peak based on the 1-minute averages occurred at 18:31 with 143 A, while the 15-minute average peak took place at 19:00 with 133 A. This discrepancy is caused by **strong variability within the 15-minute intervals**: brief load peaks captured by 1-minute averages may not result in a peak at the 15-minute level if loading remains lower for the rest of the interval. This phenomenon was observed on several occasions throughout the project.

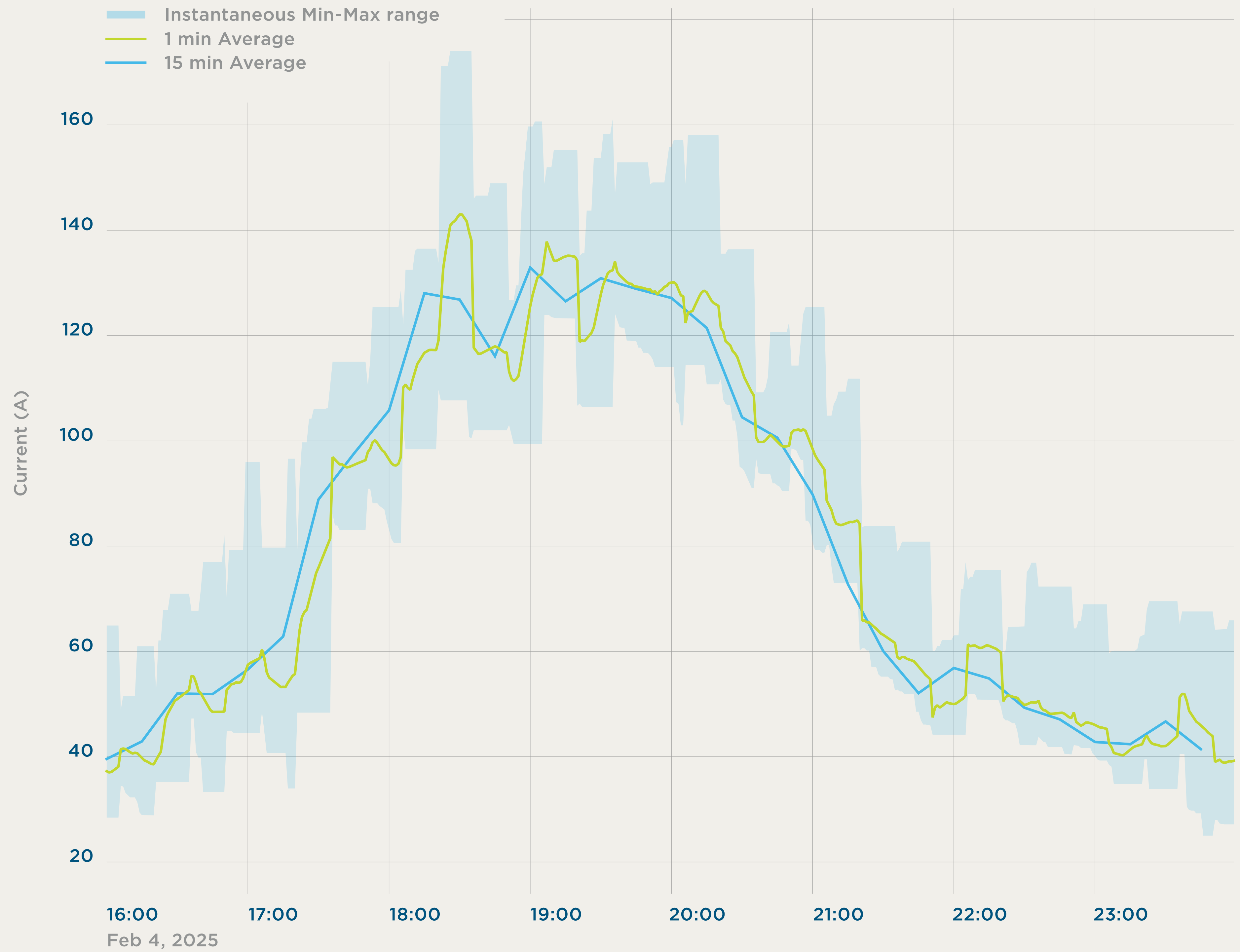


Figure 18
15-minute average and 1-minute average current measurements for the absolute consumption peak on the 4th of February 2025

The difference becomes even more pronounced when considering instantaneous maxima and minima. These values, visualised as a translucent band around the 1-minute averages, show that **instantaneous peaks consistently reach significantly higher values than the corresponding 1-minute averages**, with a maximum 174.5 A observed during the same event (+31.20% compared to the 15-minute peak). Notably, the instantaneous peak did not occur within the 15-minute interval that contained the highest 15-min average, further underlining the masking effect of temporal aggregation.

Another interesting observation is the **harsh impact of intermittent cloud coverage** on PV injection. Rapid transitions between sunny and cloudy conditions can lead to abrupt generation drops or rises within a single minute. On May 12 (Figure 19), net injection dropped by 87%, from 66.5 A at 13:14 to 8.17 A at 13:15 based on 1-minute averages.

The instantaneous maxima reflect this finding, dropping from 95.09 A down to 12.33 A within the same time frame. Such short-lived but pronounced fluctuations are strongly attenuated in 15-minute averaged smart meter data, meaning that the true dynamics of PV injection are not fully visible at that resolution.

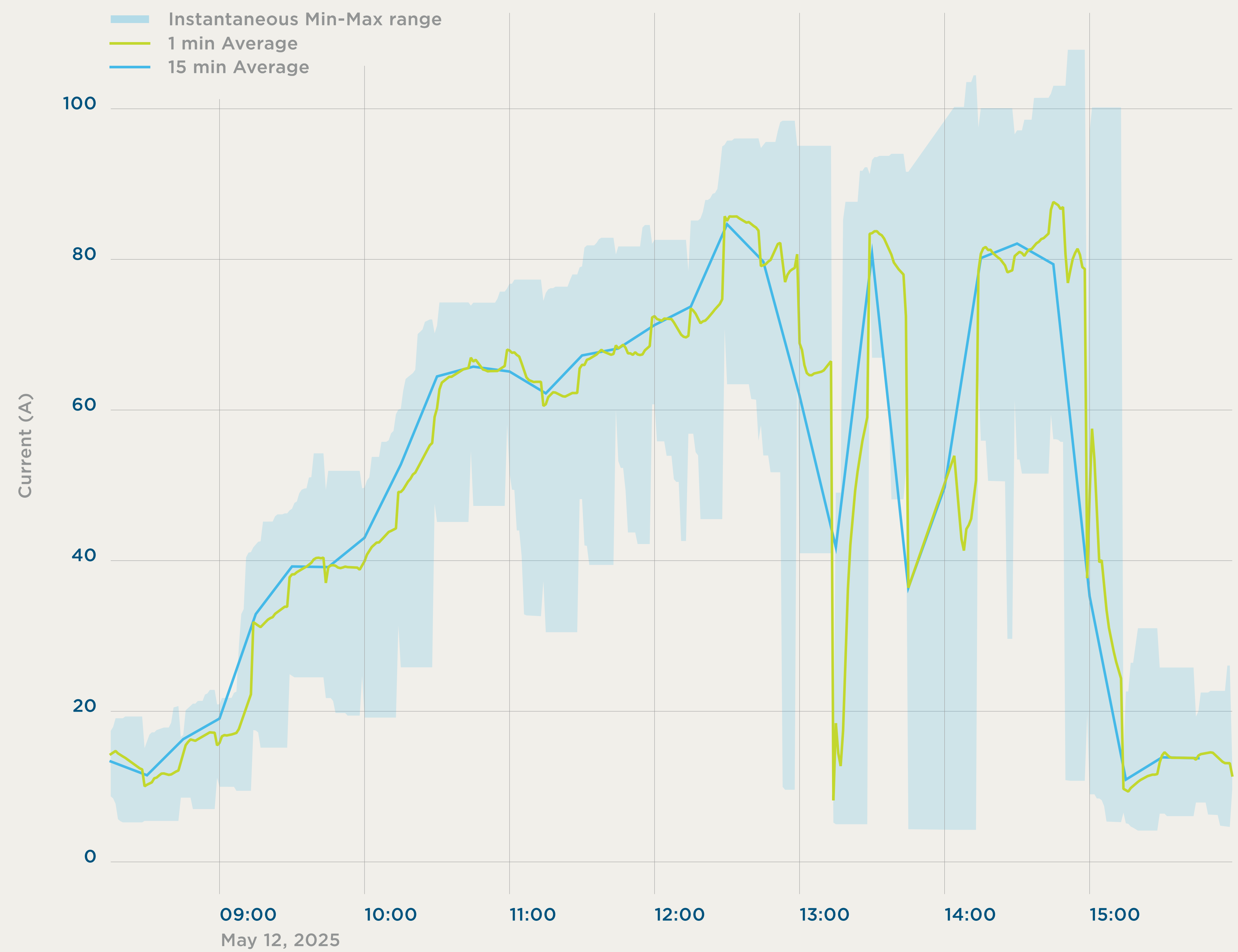


Figure 19
PV injection drops and rises related to intermittent cloud coverage on the 12th of May 2025

Per-phase insight & phase imbalance

In addition to temporal resolution, smart grid sensors also provide measurement data per phase. This enables insights into phase imbalances which are usually not visible on the LV grid. In this analysis, phase imbalance is defined as the deviation between the highest single-phase current and the three-phase average:

$$\text{Phase imbalance} = \max \begin{cases} I_{\text{phase L1}} - I_{\text{3phase average}} \\ I_{\text{phase L2}} - I_{\text{3phase average}} \\ I_{\text{phase L3}} - I_{\text{3phase average}} \end{cases}$$

From a grid operators' perspective, phase imbalances are particularly critical during peak periods, as overloading of a single phase is sufficient to cause operational issues. Therefore, the analysis focused on peak conditions by filtering values above the 95th percentile of the 1-minute averages. The resulting statistics are summarised Table 13.

Phase	Phase Imbalance (absolute value) based on 1-min averages	Phase imbalance (in %) based on 1-min averages	Phase Imbalance (absolute value) based on 15-min averages	Phase imbalance (in %) based on 15-min averages
Average	6.76 A	8.87%	7.65 A	6.80 %
Median	6.18 A	8.10 %	7.47 A	5.98 %
Standard deviation	3.90 A	5.15 %	4.92 A	4.51 %
Minimum	0.00 A	0.00 %	0.73 A	0.66 %
Maximum	33.79 A	46.30 %	26.13 A	24.35 %

Table 13
Phase imbalance statistics during peak periods

The results show that significant phase imbalances occur during peak periods. In the selected street, **phase L3 frequently exhibited higher loading** than the other phases. This is illustrated in Figure 20, which shows a relevant example with the second highest consumption peak and high imbalances of 25.1% between phase L3 and the three-phase 1-minute average.

Importantly, it underlines that **significant phase imbalances can endure over extended periods**, contributing to high single phase line loading under the radar of the three-phase 15-minute average data that is typically available. In this case, the single-phase 15-minute peak was 12.77% higher than the three-phase 15-minute peak.

A **similar observation was made on the absolute peak of the test year** on the 4th of February 2025, but only for shorter durations. Here, single-phase 1-minute average current on phase L3 reached 156A compared to 143 A for the three-phase 1-minute average, a deviation of 9.17%.

Voltage quality at both transformer and household

Finally, the smart grid sensors provide additional insights into voltage quality at both the transformer station (SGIM) and the household connection point (Smarty+), a capability not available through the smart meter infrastructure.

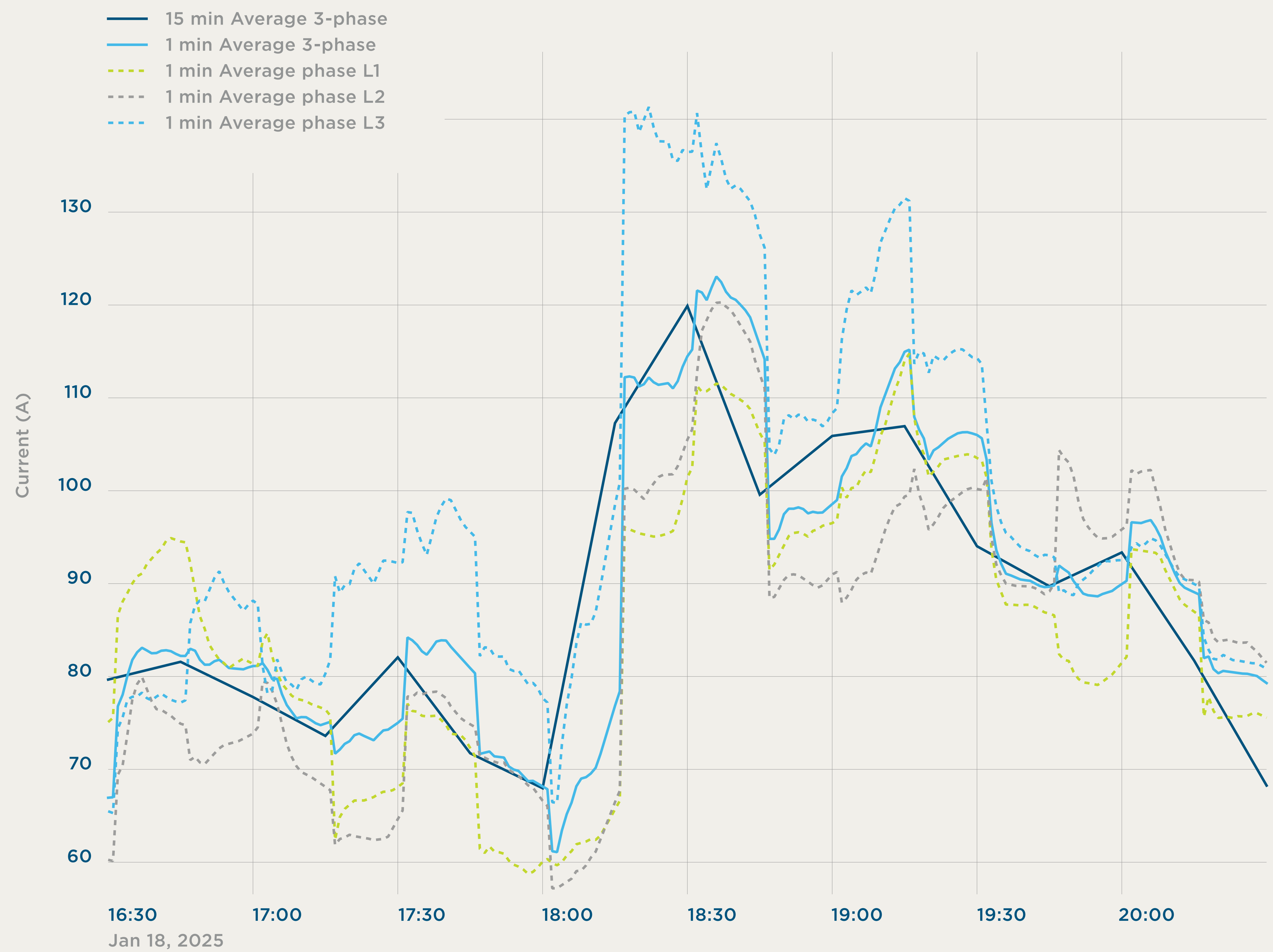


Figure 20
Phase imbalances (dotted lines) during a high load period due to cold weather on January 18th 2025

As already discussed in section 5.6.2, **voltage quality remained within the ±10% band** specified by DIN EN 50160 throughout the entire year. Overall, voltage variations showed only weak correlation with relatively low loads of the selected feeder and were primarily driven by upstream effects, such as load variations and tap changes at higher voltage levels. This is also visible in Figure 21, where two similar current loads correspond to vastly differing end-of-feeder voltages. Therefore, beside the absolute maximum and minimum measured voltages, the voltage sag and voltage swell along the feeder are of interest in the scope of this analysis. Whereof voltage swells are caused by high injection, and voltage sags are caused by high consumption.

Measured extremes within ±10 % band

As expected, voltage maxima occurred during high injection midday peaks reaching a **maximum of 244 V** at the end of the feeder in April, well below the permissible limit of 253 V. At the same time, the voltage at the transformer station was 238 V, corresponding to a **voltage swell** of 6.21 V equivalent to **2.61%**. Conversely, the absolute **minimum voltage** was observed during the highest consumption peak, with **216 V** at the end of the feeder and 227.45 V at the transformer station. This corresponds to a **maximum voltage sag** of 11.45 V or **5.03%**.

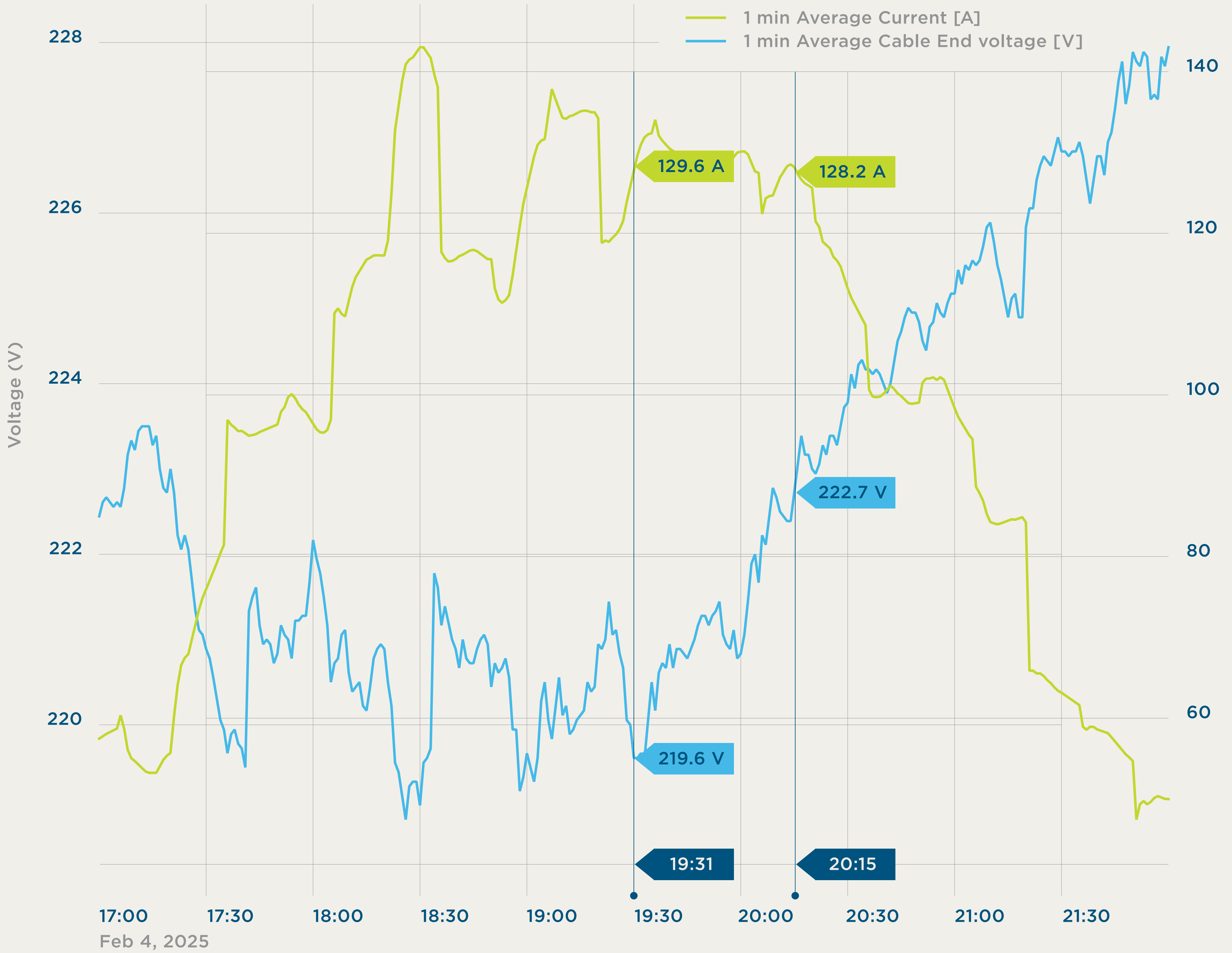


Figure 21
Weak correlation between feeder current and end-of-feeder voltage

6 Customer behaviour

6.1

General description of customer behaviour phases

During the Creos Living Lab, there are two types of test phases related to the participants:

- Active participation phases, detailed in section 6.1.1, where participants optimise their behaviour according to different instructions
- Passive participation phases, detailed in section 6.1.2, where participants are requested to adapt a “worst-case” behaviour

Every two months, a meeting is organised between the participants and the project team. The goal of these meetings is to review the past phase, receive feedback from participants and introduce the next test phase.

	Jul/Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Meetings with participants	●○	○●	○○	○●	○○	○●	○○	○●	○○	●○	○●
Introduction phase	●●	○○	○○	○○	○○	○○	○○	○○	○○	○○	○○
Cost optimisation	○○	○○	●●	○○	○○	○○	○○	○○	○○	○○	○○
Consumption peak shaving (no HEMS)	○○	○○	○○	○○	●●	○○	○○	○○	○○	○○	○○
Baseline Winter	○○	○○	○○	○○	○○	●○	○○	○○	○○	○○	○○
Consumption peak shaving with HEMS	○○	○○	○○	○○	○○	○○	○●	●○	○○	○○	○○
Baseline Summer	○○	○○	○○	○○	○○	○○	○○	○○	○●	○○	○○
Production peak shaving (batteries not optimized)	○○	○○	○○	○○	○○	○○	○○	○○	○○	●●	○○
Production peak shaving (optimized batteries)	○○	○○	○○	○○	○○	○○	○○	○○	○○	○○	●●

Table 12
Indicative timeline of the different test phases related to customer behaviour

6.1.1

Active participation phases

During active participation phases, participants receive clear instructions to adopt a given behaviour. The table below summarizes the planned test phases, their goal and general approach.

Introduction phase	Get used to electromobility.	The first two months, participants get time to get used to their EV. No instructions are given.
Cost optimisation	Simulate the impact of clients responding to dynamic supplier tariffs, as well as the new low voltage grid tariff[8], officially introduced on 1 January 2025.	Give participants access to their HEMS, which automates the charging of the car according to dynamic tariffs. Participants can shift other devices, such as the dishwasher, manually to profit from low prices.
Baseline Winter	Create a baseline of the average “worst-case” behaviour for the grid in winter to: • compare with the peak shaving phases • compare with the smart grid phases	Participants receive instructions on how to behave negatively for the grid infrastructure: • charge once they get home during peak hours, • charge with 11 kW, • remove all charge calendars and other settings from their EV
Consumption peak shaving without HEMS	Simulate the impact of simple every-day gestures to shift and flatten the evening consumption peak. Participants should only use tools which already commonly exist in most households. The HEMS should not be used in this phase.	Give participants everyday instructions which can contribute to peak shaving (consumption). Participants should not use the HEMS, but they can use the onboarded app in the car.
Consumption peak shaving with HEMS	Simulate the impact of adding automatization and digitalisation via the HEMS to shift and flatten the evening consumption peak.	Give participants everyday actions which can contribute to peak shaving (consumption). Allow them to use digital tools (HEMS, apps) to help automate the shift of the assets.
Baseline Summer	Create a baseline of the average “worst-case” behaviour for the grid in summer to: • compare with the peak shaving phases • compare with the smart grid phases	Participants receive instructions on how to behave negatively for the grid infrastructure: • charge once they get home during peak hours, • charge with 11 kW • do not necessarily consume when there is PV production
Injection peak shaving with and without battery optimization	Simulate the impact of simple every-day gestures to shift and flatten the midday production peak. Participants can use their preferred digital tools to achieve this. The batteries are operated with an unoptimized and an optimized charging strategy.	Give participants everyday actions which can contribute to peak shaving (production). Participants can use their preferred tools, such as the HEMS, or the onboarded app in the car.

Table 13
Description of the goals of the planned customer behaviour phases

[8] **A detailed description of the new Luxembourgish low voltage grid tariff can be found here:** https://www.creos-net.lu/en/individuals/practical-info/new-tariff-structure

6.1.2

Passive participation phases during smart grid test phases

In-between the active participation phases, participants are required to simulate a “worst-case” scenario. This allows to retrieve the baseline behaviour for both winter and summer months. Furthermore, the smart grid test phases are always conducted between the active participation phases. During smart grid tests, adopting a “worst-case” behaviour is essential to fully evaluate the potential of these tools.

The following behaviour is expected during the “worst-case scenario”:

- The EV charges with 11 kW and as soon as it is plugged in. No charging calendars or charging strategies with reduced power are permitted
- Participants are expected to consume whenever needed, even during peak hours. They should not try to delay the use of certain appliances

6.2

Identified challenges

6.2.1

Energy literacy

Energy literacy is a key element of the energy transition, as it empowers individuals to understand their energy consumption and its impact. In the pilot project, participants were introduced to the customer behaviour phases and the digital tools by focusing on enhancing the understanding of their electricity use. To facilitate this, they received personalized information about their consumption, which is an essential step in increasing the acceptance of new habits.

However, the initial learning curve is steep. For many, grasping the abstract concept of electricity consumption and the specific energy use of different appliances was not intuitive. To address this challenge, participants were guided according to their individual situation. The first customer behaviour phase was therefore a learning period, which allowed participants to build their knowledge.

Digital tools, such as the HEMS, played a crucial role in this phase. By visualizing real-time electricity consumption, the HEMS helped participants to identify energy-intensive devices in their homes, enabling them to optimize usage and adopt more grid-friendly habits.

Nonetheless, the complexity of the learning phase during the first active customer behaviour phase was challenging. Participants were introduced to multiple concepts, such as electricity consumption, peak reduction, and dynamic tariffs, all at once. In hindsight, a more gradual approach, introducing one concept at a time, might have made the process less overwhelming and more effective in supporting the participants' behaviour change.

6.2.2

Engaging participants

Engaging participants over the different test phases is crucial for the project's success. A good relationship between the project team and the participants is critical for effective collaboration. Participants should feel confident to report issues or concerns as soon as they arise, ensuring that any challenges can be addressed quickly.

Moreover, during the project, participants share data with the project team, which can help better understand certain consumption patterns. During active participation phases, participants receive regular, personalized feedback and tips, based on their assets and personal situation. This increases the understanding of their own consumption, which is beneficial even beyond the project. Participants therefore associate the project with a learning experience, which is a motivating factor for many of them.

To further improve engagement, challenges and gamification are integrated into the test phases. Each test phase includes a small challenge. The KPIs are published in a transparent manner before the beginning of the test phase to ensure clarity. Participants who excel in the challenge receive a reward at the end of the test phase, which adds motivation to the process.

In the selected street, the neighbours already had a close community, which greatly facilitates exchanges and participation in the different test phases. This highlights once again the importance of the selection process, which is a building block for the project's success.

This combination of trust, learning, and small challenges fosters a positive and collaborative environment. By associating the project with education and achievement, participants remain motivated and committed.

6.3

Insights on consumption behaviour of different energy transition assets

6.3.1

Heat pump consumption in winter

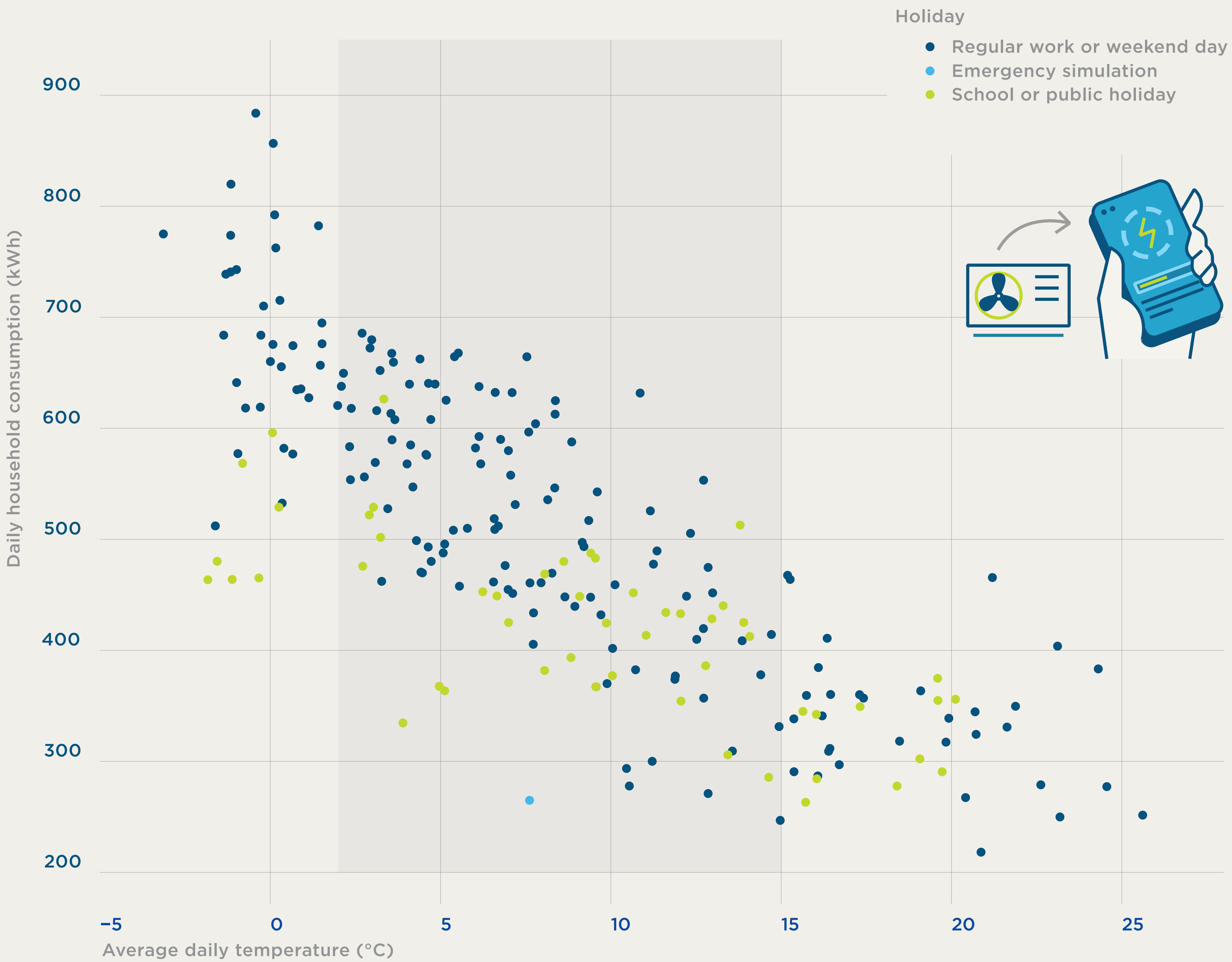
The impact of heat pumps is highly weather-dependent, as their consumption and peak demand rise when temperatures drop. To measure this effect, household consumption is analyzed without EV charging, as heat pumps are the main driver of how household load changes with temperature.

Figure 22 shows the sum of the daily household consumption for the entire Living Lab street as a function of average daily temperature. Consumption from the EVs is excluded. Holidays are highlighted, as they occasionally lead to outliers because participants reduce their heating when they are away. The emergency simulation day, described in section 6.4.3 below, is also highlighted as an outlier.

Heat pumps have a "**bivalence point**", which is the outdoor temperature below which they can no longer cover the heating demand of the house. Below this point, the heating rod, which is an inefficient electric resistance, either complements or substitutes the heat pump. Optimizing the bivalence point helps reduce unnecessary heating rod use and improves overall efficiency.

In the Living Lab, many heat pumps were not configured optimally, causing the heating rod to activate more often than needed, which increased the impact on the grid during cold weather.

> Modern heat pumps can provide the required heat efficiently **even at low temperatures**. The use of the heating rod can often also be optimized separately in the heat pump's parametrization, which limits its use to fault or emergency situations only. To ensure that heat pumps work efficiently throughout the day and reduce their strain on the grid, even at very low temperatures, **proper dimensioning and optimization** of the system is crucial. This is only possible by properly training installers and raising awareness among consumers on how to easily monitor their system's efficiency and health.



Three phases can be highlighted:

- **Mild temperatures (>15°C):** the relationship between daily household consumption and temperature is constant, since the heat pump is no longer used to heat the houses, but only for warm water, which is independent from the weather. The heat pumps from the Living Lab do not provide cooling, otherwise their consumption would rise again at higher temperatures.
- **Moderate temperatures (2-15°C):** the relationship between daily consumption and air temperature is almost linear. For each lost degree, the daily household consumption, dominated mostly by the heat pump consumption, increases. In this temperature range, the heat pumps operate the most efficiently.
- **Low temperatures (<2°C):** for each lost degree, the daily consumption increases significantly quicker. At very low temperatures, the system loses efficiency and occasionally relies on the use of the heating rods to complement the heating.

Figure 22
Sum of daily household consumption of all the Living Lab participants in kWh as a function of average daily temperature in °C. The data excludes EV consumption.

6.3.2

Simultaneity of EV charging

Figure 23 shows the cumulative distribution function (CDF)[9] of simultaneous EV charging sessions. Figure 24 also shows the CDF for simultaneous EV charging sessions, but only for periods when at least one EV is charging.

The data from EV charging shows that simultaneity is generally low, with the median of the number of EVs charging being 1. As shown in Figure 23, more than 95% of the time, less than 3 out of 14 EVs are charging at the same time. It also shows that while it is unlikely that more than 5 EVs are charging simultaneously, it is not impossible to have more extreme situations. The maximum number of simultaneous charges recorded during the Living Lab was 8, which occurred only twice: once for a duration of 15 minutes, and once for 1 hour during the time-of-use phase (see section 6.4.1 below).

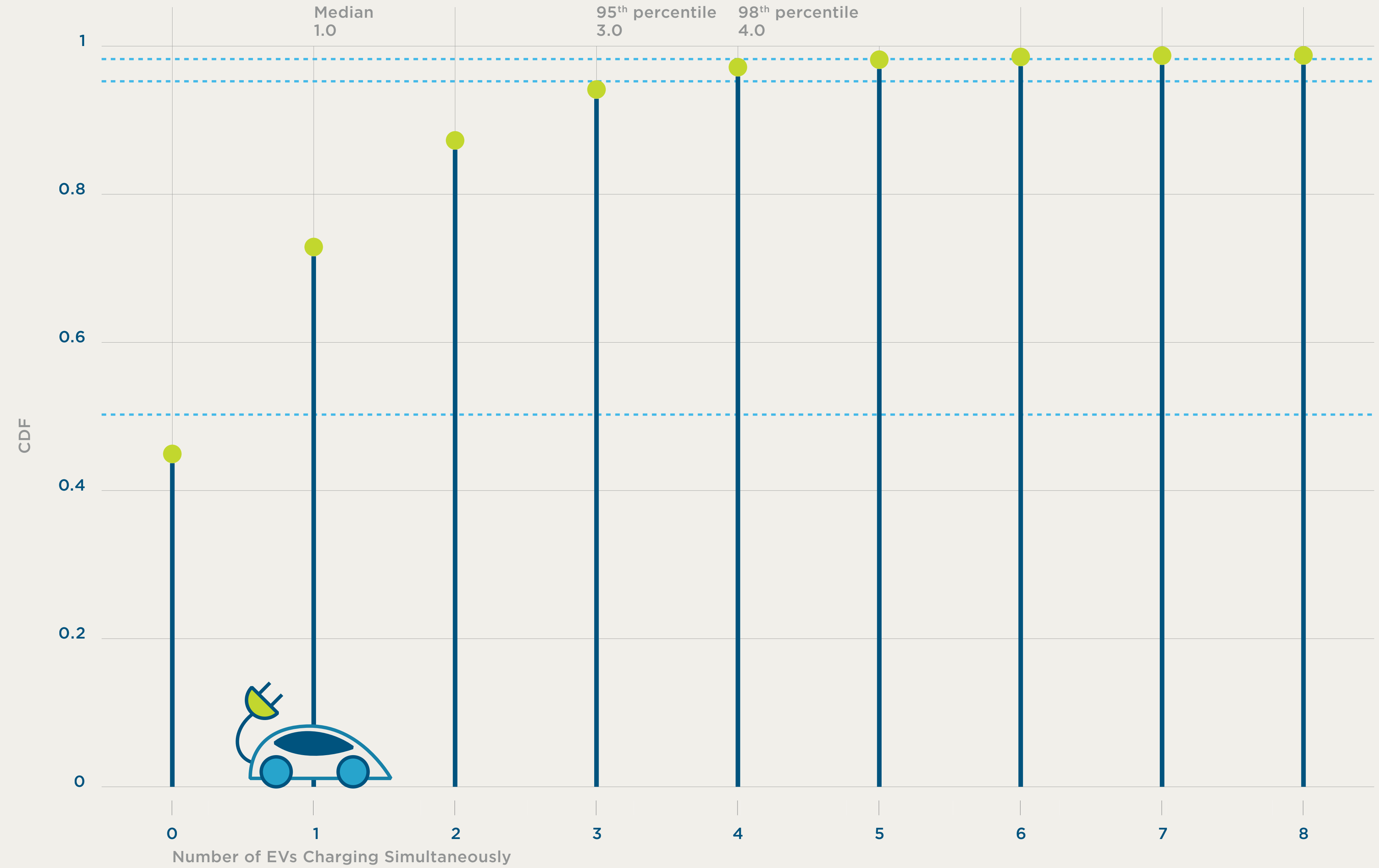


Figure 23
Cumulative distribution function for the number of simultaneous EV charging sessions. Periods when no EVs are charging are included

[9] The CDF ranges from 0 to 1 and gives the probability distribution of a variable. Percentiles can be directly derived from the graph on the vertical axis. In Figure 23, the number of EVs charging simultaneously is shown on the horizontal axis. For example, the value of the CDF for 1 EV charging is 0,75. This means that 75% of the time, 1 EV or less is charging.

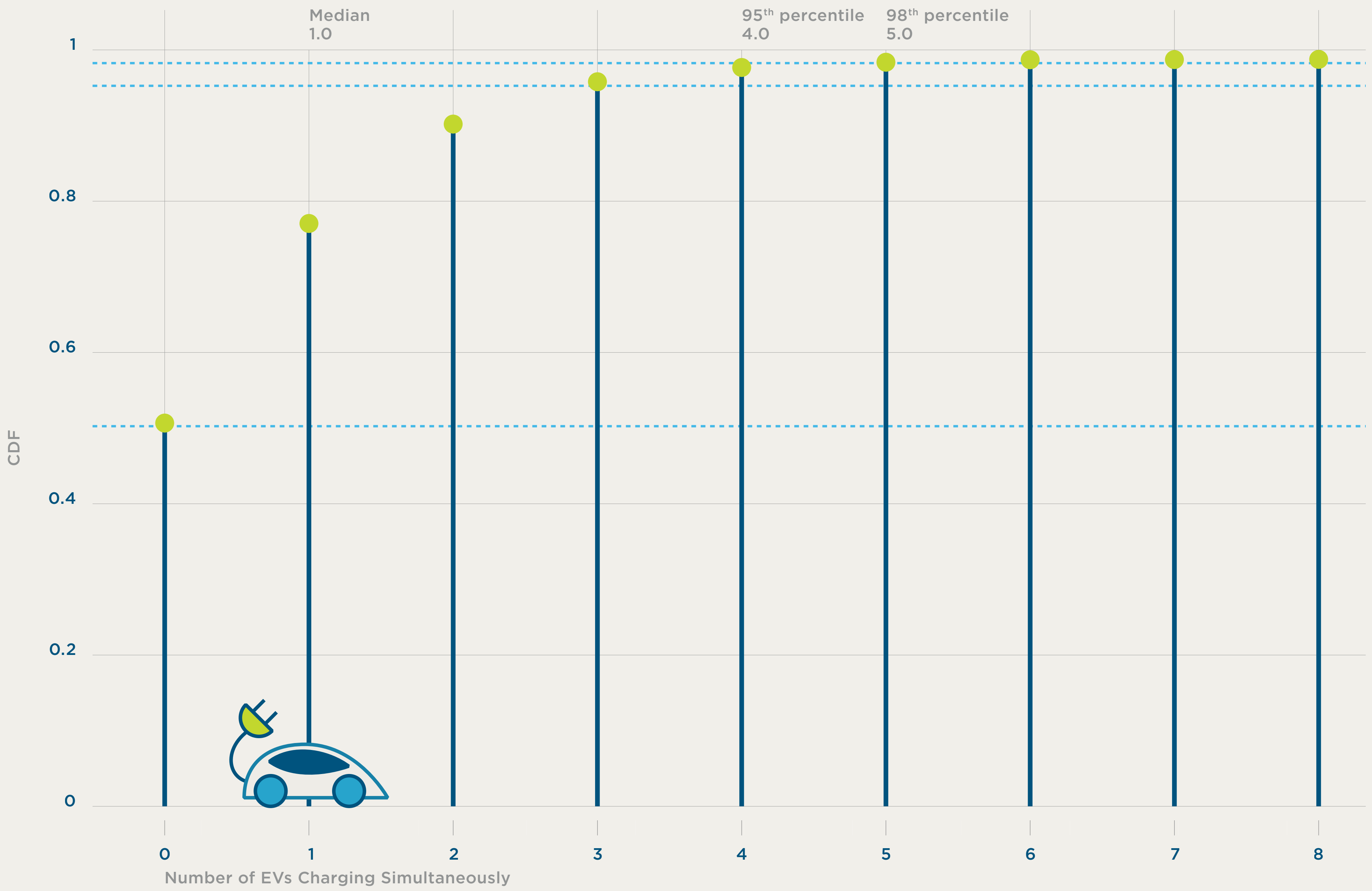


Figure 24
Cumulative distribution function for the number of simultaneous EV charging sessions, when at least 1 EV is charging. Periods when no EVs are charging are excluded

Table 16 shows that the simultaneity is slightly higher during weekdays than during weekends, which can be explained by the common 9-to-5 workday schedules which most households are bound to. The differences can nevertheless be considered negligible.

	Week overall	Weekend	Weekday
Median	1	1	1
95th percentile	3	3	4
98th percentile	4	4	4
Maximum	8	7	8
Standarddeviation	1,2	1,1	1,3

Table 16
Statistical characteristics of EV charging simultaneity between weekend days and weekdays

Simultaneity is already low, but when looking at the distribution of the load when at least one EV is charging (Figure 25), it can be observed that the maximum load due to EVs was merely over **55 kW, which corresponds to 5 EVs charging at full power (11 kW)**. As discussed in the previous paragraphs, in rare moments, up to 8 EVs were charging.

This shows that the **number of simultaneous charges alone is not a reliable indicator for grid impact**, as charging sessions with reduced power increase the duration, and therefore the simultaneity of the charges. This does not necessarily mean that the impact on the grid is also increased. This effect is further detailed in section 6.4 below.

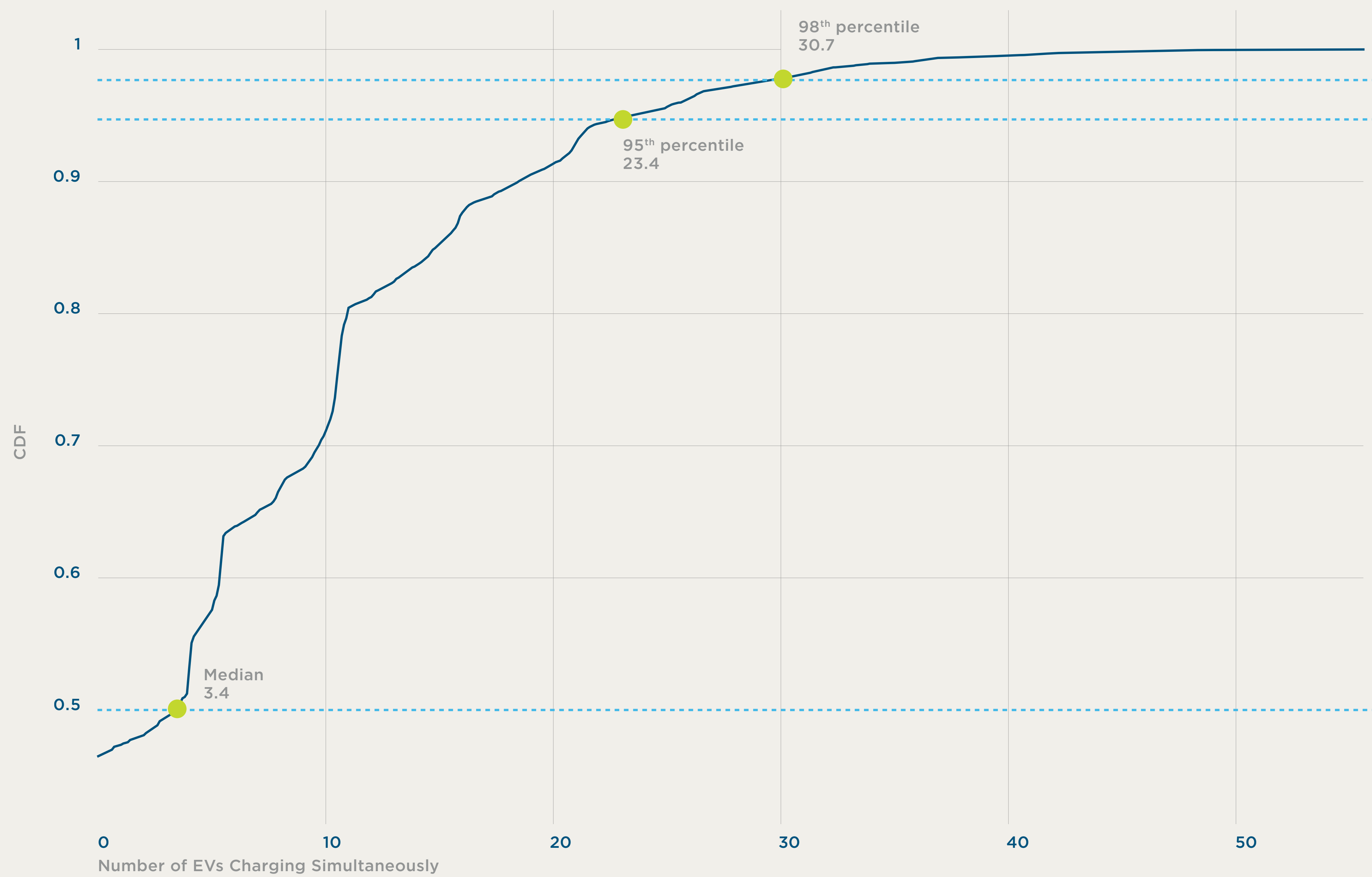


Figure 25
Cumulative distribution function of the load of EV charging sessions, when at least 1 EV is charging. Periods when no EVs are charging are excluded

6.4

Outcomes on reducing consumption peaks in winter with incentives on the consumption tariff

The results confirm that in winter, shifting the EV load outside of the evening peak hours and charging with reduced power reduced the stress on the low-voltage grid of the Living Lab. Even if EV simultaneity can occasionally increase with mechanisms such as time-of-use tariffs, the EV charging sessions have generally a low simultaneity. Combined with the effects mentioned above, this mitigates the harmful effects on the grid.

6.4.1

Description of the test phases

Since participants could not control their heat pumps during the project, the analysis in the following sections focuses on the isolated EV load to better assess the impact of behavioral changes. By excluding heat pump consumption, this approach reduces the bias caused by weather-dependent changes in heating demand.

Winter baseline

Scenario: Participants were asked to consume whenever needed without considering any “grid-friendly” behavior. They charged their car at full power with 11 kW and plugged it in as soon as needed, for instance when arriving home from work.

Findings: During weekdays, there is less charge during the day when most participants are absent, and more charge in the late evening. During weekend days, an additional charging peak appears around midday.

Consumption Peak Shaving with Simple Gestures

Scenario: Simulate the impact of simple everyday gestures to shift and flatten the evening consumption peak. Participants activated reduced charging speed in their car's settings and charged mostly during the night, when other appliances weren't running. They also made efforts to avoid the simultaneous use of household appliances.

Findings: Most participants did not feel that their comfort was negatively impacted once they got used to this new routine. Some even stated that their new habits became natural, and they had to readapt again for the worst-case scenario phases.

It is therefore possible to encourage a routine change if users are correctly informed and sensitized. The increased understanding of their actions' impact, whether it is for ecological or financial reasons, helps them to adopt new, grid-friendlier habits.

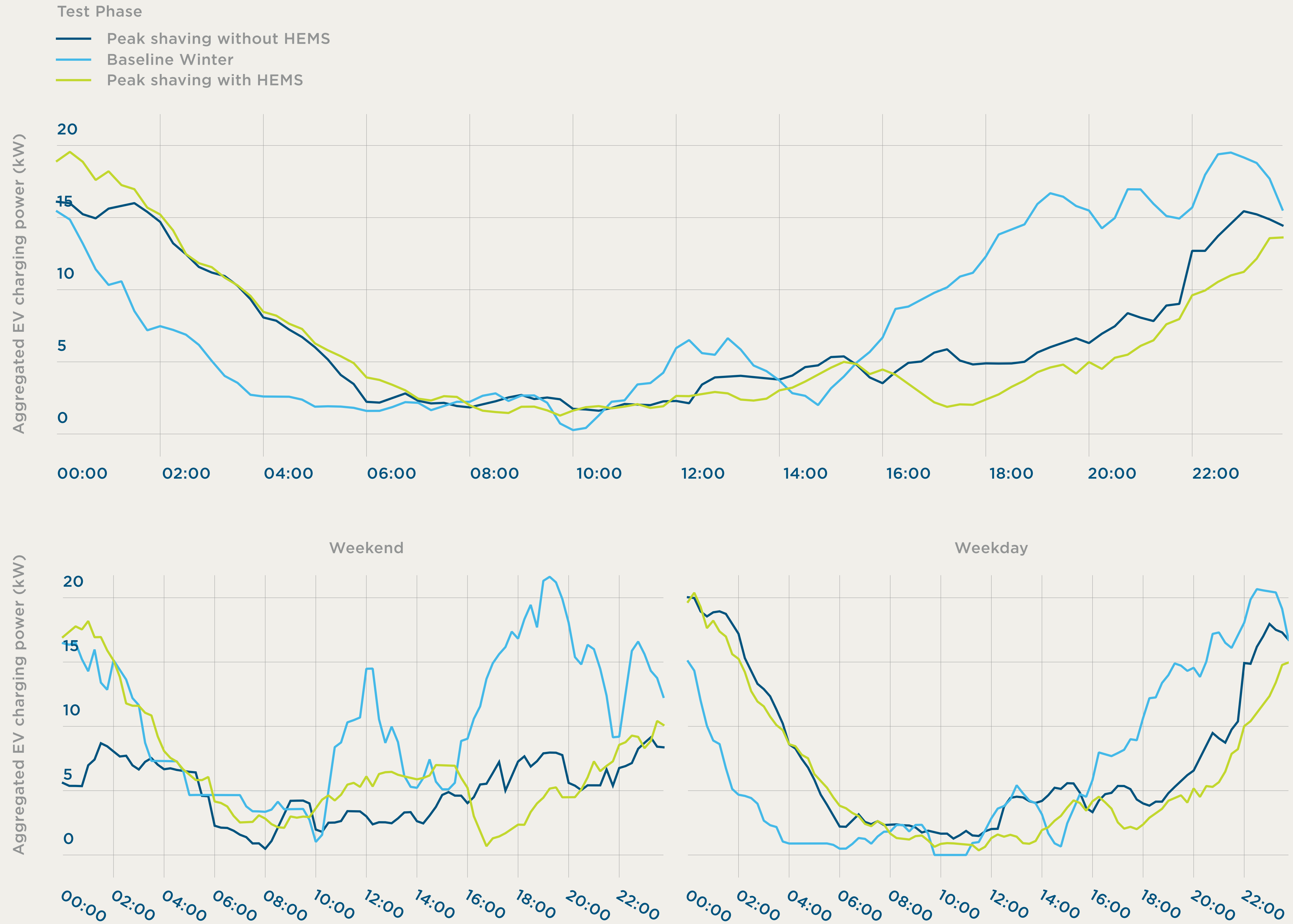


Figure 26
Evolution of the standard daily EV charging load curve between the winter baseline and consumption peak shaving phases (simple gestures and time-of-use). The bottom graphs differentiate between weekends (left) and weekdays (right)

Consumption Peak Shaving with a HEMS/Time-of-Use (ToU) tariff

Scenario: Simulate the impact of adding automatization and digitalisation via the HEMS to shift and flatten the evening consumption peak.

The initial idea was to use the HEMS with an updated functionality to delay the charge of the EV to a later point in time, even if the EV was already plugged in. However, a behaviour appeared where in some cases, the EV "fell asleep" when put on stand-by for some hours, and the HEMS was no longer able to resume the charge with an external message. This resulted in the EV not being charged in the morning, which can be a major inconvenience. For this reason, the instructions were changed mid-way through the test phase, and participants were asked to use the charging calendars from their EVs to delay the charge until midnight, thus simulating a Time-of-Use (ToU)[10] tariff.

Findings: Most participants did not feel that their comfort was negatively impacted, as they had full control over how they optimised their consumption, and they could easily adjust to their families' needs.

Generally, using a HEMS was perceived as positive as it allows users to better understand the energy consumption and to program and optimize their charge. However, the complexity of some HEMS applications can be a barrier. A simple, user-friendly interface with intuitive parameters, such as km instead of kWh, is essential to attract the larger public. Moreover, bugs or unexpected behaviour of complex automation algorithms can lead to trust issues and reluctance. Therefore, the simplest solutions, such as simple gestures and simple charging calendars, often had the most success in terms of adoption rate in the Living Lab.

[10] A ToU tariff is a time-based tariff, where the price rate can vary depending on different time slots. A classic ToU tariff are day-night tariffs, where the electricity is cheaper during the night and more expensive during the day. Today, new pricing schemes are emerging to incentivize customers to consume renewable electricity when it is available, such as cheap electricity slots around midday, when solar electricity is abundant.

Cost optimization phase

Scenario: Simulate the impact of clients responding to dynamic supplier tariffs, as well as the new low voltage grid tariff, officially introduced on January 1st 2025.

Dynamic tariffs as well as the new grid tariff were integrated into the HEMS. Participants received the instruction to try avoiding simultaneous usages, such as turning on the dishwasher while the car is charging. For non-automated assets, such as whiteware, participants could look up the dynamic tariffs in their HEMS and program them for the cheapest hours. The EV charge was automatically optimized in the HEMS to charge with minimum power (4,2 kW) during expensive hours and quicker during cheap hours.

Findings: For most participants, changing the charging behavior of their EV was acceptable. For the whiteware, which cannot be as easily automated, most participants reported that using dynamic tariffs **negatively impacted their comfort**. Since the tariffs change each hour and each day, planning the week ahead was not possible. Participants expressed the need to have a certain stability in the tariffs to make them more manageable and less stressful. Some also explained that programmable household devices are necessary to reduce the mental load and manual effort.

The complexity of dynamic tariffs in everyday life for private households is a barrier to their popularity. Dynamic tariffs require users to be well-equipped with production and storage installations to manage price surges. Advanced level of automation and a good understanding of digital tools is also a prerequisite, which makes dynamic tariffs a difficult tool to mobilize the general public to participate in the energy transition. As this phase was a learning period for participants, the results are not integrated in the quantitative cross-phase analysis below.

6.4.2

Cross-phase analysis

Figure 27 shows the standard daily consumption load curve in the different winter test phases. All consumption assets are included, whereas the production assets, such as PV and batteries, are excluded to reduce bias from variable PV production.

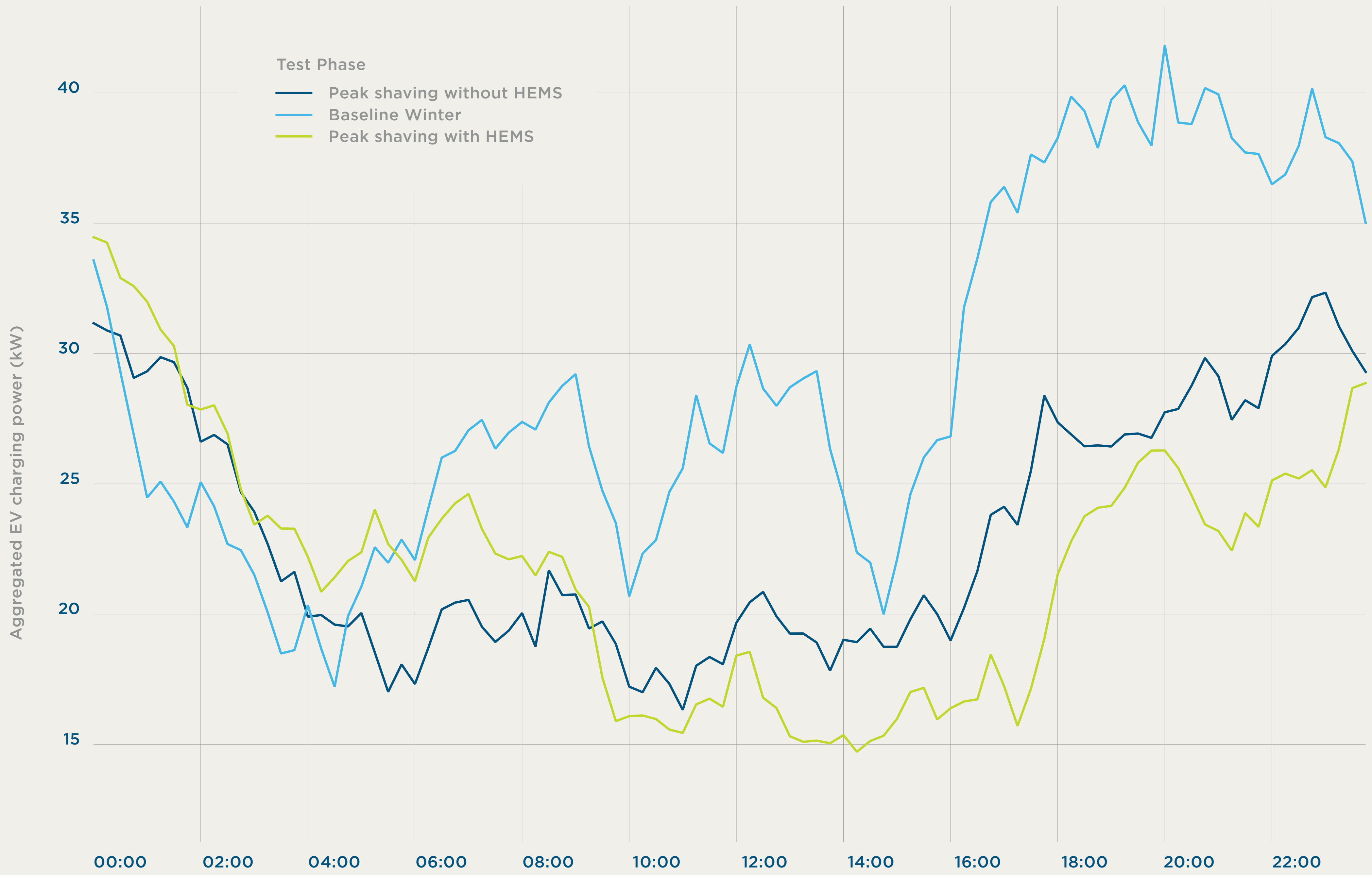


Figure 27
Standard daily consumption load curve in the Living Lab (household and EV charge, without production units)

Table 17 and Table 18 provide an overview of the main characteristics of each winter phase. They allow to compare how participants' charging behavior, temperature and heat pump operation impacted the load on the grid.

Phase	T During Peak (°C)	Peak (kW)	Date/Time	# EVs at Peak	Ev Load at Peak (kW)	# HPs On Heat Rod
Winter Baseline	0.6	71.3	18/01/2025 18:30	4 (1 reduced)	38	1
Simple Gestures	6.1 (+5.5)[11]	65.1 (−6.2)	05/12/2024 23:45	7 (5 reduced)	45 (+7)	1
ToU tariff	4.6 (+4.0)	61.8 (−9.5)	12/03/2025 00:00	8 (8 reduced)	42 (+4)	0

Table 17
Overview of peak characteristics in the different winter test phases

Phase	Avg T (°C)	95^{th} pct. P (kW)	EV charge 17–22h	EV charge 22–6h	Peak EV load (kW)	95^{th} pct. EV (kW)	Max # EVs sim.	95^{th} pct. # EVs
Winter Baseline	1.2	49.1	39%	40%	41.7	29.3	5	4
Simple Gestures	4.3 (+3.1)	41.8 (−7.3)	20% (−19)	59% (+19)	46.1 (+4.4)	24.8 (−4.5)	8 (+3)	5 (+1)
ToU tariff	6.2 (+5.0)	37.3 (−11.8)	15% (−24)	65% (+25)	43.2 (+1.5)	24.0 (−5.8)	8 (+3)	4 (0)

Table 18
Overview of the general characteristics during the different winter test phases

[11] All comparisons are in reference to the winter baseline phase.

Influence of weather conditions on cross-phase comparisons

In the winter baseline phase, the weather was significantly colder than during the peak shaving phases. As highlighted in section 6.3.1 above, heat pump consumption increases significantly with each lost degree. Therefore, part of the load in the baseline is caused by the weather rather than by customer behavior. This effect is essential to consider when quantifying the improvements during the peak shaving phases.

To assess the impact of behavior independently from weather, three representative 4-day periods (Wednesday to Saturday) were identified in each phase where temperature and weather conditions were the most similar. These short periods allow a direct comparison under comparable external conditions.

Results show that despite similar weather conditions, both the peak load and the 95th percentile were still **positively impacted in both peak shaving phases**. The standard daily consumption load curves, shown in Figure 28, highlight the impact of shifting the EV charging to low-consumption periods. This shows that the improvements in peak reduction are positively influenced by customer behavior and not only due to milder temperatures.

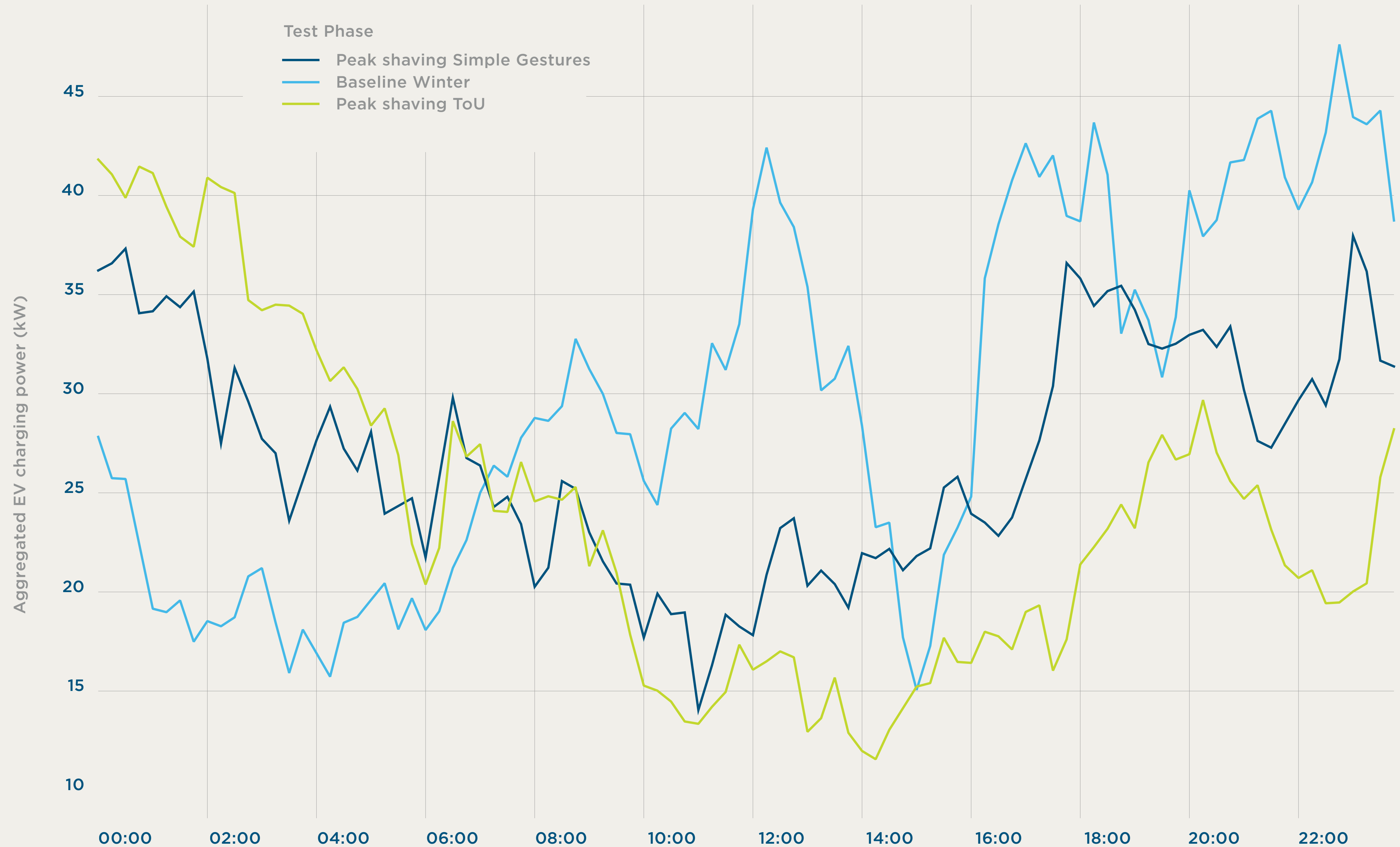


Figure 28
Evolution of the daily standard consumption in the Living Lab street (production excluded) during three periods with similar weather conditions, but different behavior strategies

Phase	Average temperature (°C)	Maximum temperature (°C)	Minimum temperature (°C)	Peak (kW)	95th percentile (kW)
Winter Baseline	0.9	5.6	−2.1	71.3	55.7
Simple Gestures	1.3 (+0.3)	4.3 (−1.3)	1.4 (+0.7)	56.8 (−14.5)	41.7 (−14)
ToU tariff	3.9 (+3.0)	9.6 (+4.0)	−2.1 (0)	61.8 (−9.5)	45.5 (−10.2)

Table 19
Overview of the characteristics during slots with similar weather conditions in the winter test phases

General results

Participants' charging habits evolved drastically in the peak shaving phases. More specifically, the EV was mostly charged during the night, and not during the typical evening peak:

- **Winter baseline**: 39% of the charge occurred between 17 and 22h.
- **Simple Gestures**: 20% of the charge occurred between 17 and 22h.
- **ToU**: Only 15% of the charge occurred during the evening phase.

During the peak shaving phases, most participants also charged their vehicles with reduced power. The charging sessions were therefore longer, which increased the probability of simultaneous charges. This can be seen in the maximum number of EVs charging simultaneously, which was 8 during the peak shaving phases and only 5 during the baseline.

However, on average, due to low simultaneity of the EVs, the EV load was still generally reduced during the peak shaving phases. This can be seen in the decrease of the 95th percentile of the EV load. As highlighted in section 6.3.2 above, most of the time, less than 3 EVs are charging.

During the ToU phase, the charging calendars caused many cars to start their charge at midnight. This produced a consumption gap between 23:45 and midnight, visible in the standard load curve. However, thanks to reduced EV charging power and the shift of the load into the night, when the household baseload is low, both the peak and the 95th percentile were still lower than in the baseline.

Conclusion: Grid peaks decreased in the peak shaving phases despite an occasional increase in EV charging peaks:

- Charging with reduced power extends the charging sessions, which occasionally increased EV simultaneity.
- However, the EV load was shifted outside the evening peak hours in the peak shaving phases.
- Therefore, the total grid load was generally lower because the EV peaks no longer aligned with the evening household peaks.

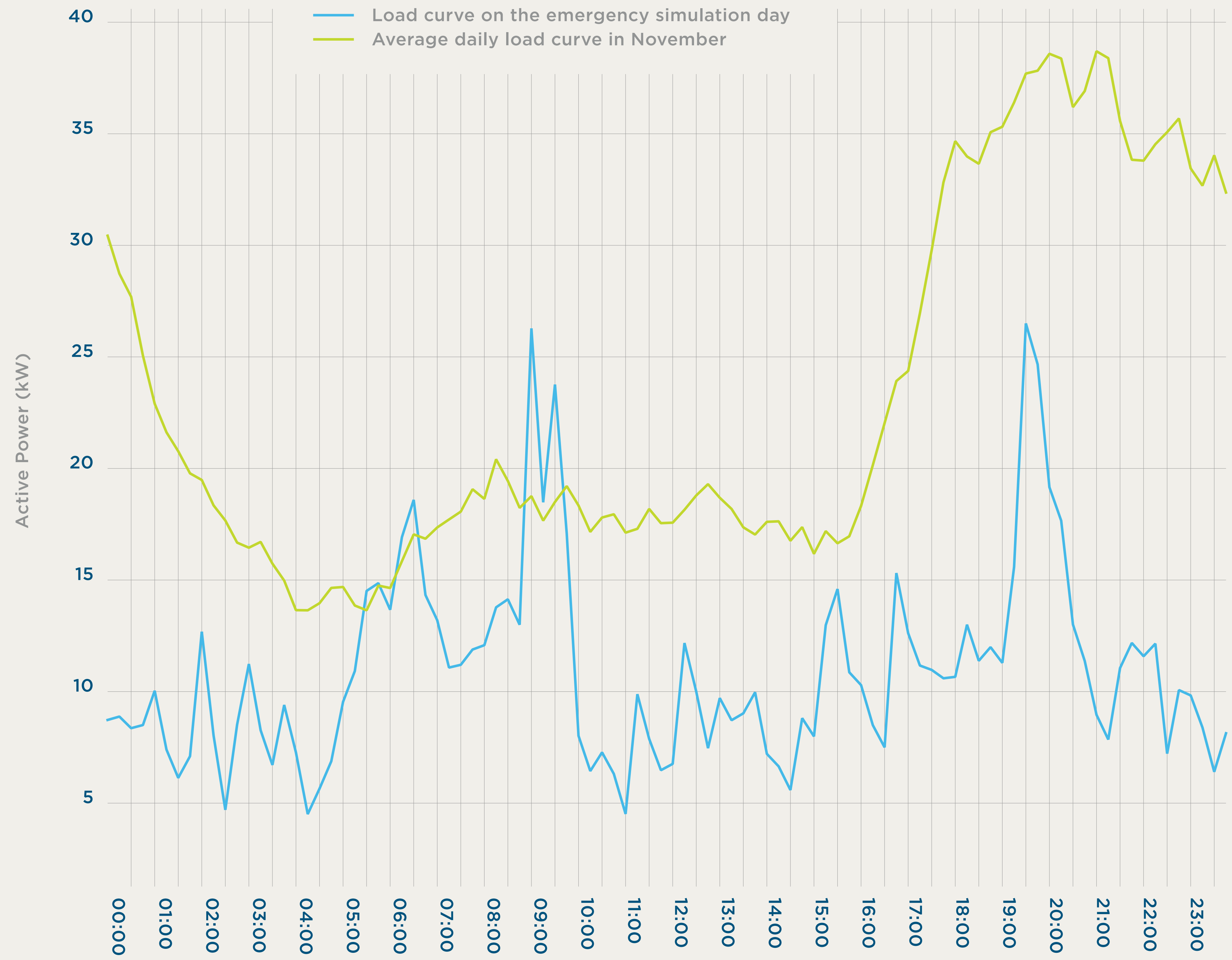
6.4.3

Emergency Simulation

On the evening of 17 December 2024, participants got the notification that an emergency simulation will take place the following day. The instructions were to reduce electricity consumption as much as possible to protect the grid due to a fictional emergency, simulating a **red signal on Creos' power barometer** StroumMonitor[12].

Participants underwent significant efforts to reduce their electricity consumption. This included not charging their EV, not doing any laundry and not turning on their dishwasher. Some also reduced the indoor temperature or plugged off electrical devices on standby or which were not necessary, such as a second fridge for beverages.Households found creative ways to reduce consumption, such as replacing cooking with cold meals and substituting screen time with screen-free activities. On average, Living Lab **participants reduced their individual consumption by 51%** in comparison with their average daily consumption from November. Some peaks can still be observed, such as at around 9:00 and 9:30, caused by a heat pump which was malfunctioning and heating with the heating rod.

[12] More information on StroumMonitor: https://www.creos-net.lu/particuliers/infos-pratiques/stroummonitor



Nevertheless, this test proved that **the solidarity of household consumers can be a leverage for emergency situations**, resulting in a significant impact. As this was a short test phase of only one day, participants were willing to strongly adapt their behavior, without feeling a loss of comfort. Their acceptance to adapt was linked to the fact that they were contributing to a greater (fictional) cause, which was only temporary.

Figure 29
Comparison between participants' average daily consumption in November and the Challenge Day

6.5

Outcomes on reducing injection peaks in summer with incentives on the consumption tariff

The production peak shaving phase demonstrates that **customer behavior alone** — incentives on the consumption tariff — has great potential to increase overall consumption of local solar electricity, but is insufficient to reduce the absolute grid injection peak.

The combination of no EVs charging and incomplete battery cycling led to reduced flexibility when it was most needed. The small number of flexible assets available in the low-voltage grid of the Living Lab reduces the smoothing effect that would normally appear in a larger population of users. This increases the probability that unfavorable combinations of customer behavior occur, such as no EV charging at all. This scenario highlights the importance of **complementary methods to manage congestion** due to production installations in low-voltage grids.

6.5.1
PV Control Sites

Two photovoltaic (PV) installations were not subject to load management during the project and therefore served as **control sites**. These installations helped to quantify some of the external influences, such as the seasonal variations in solar production, which could affect comparisons with other phases.

Upon analyzing both the variation in production peaks (kW) and energy production (kWh) throughout the year, the most comparable periods for evaluating the production peak shaving phase were identified as **July 2024 and June 2025**.

6.5.2
Evolution of consumption behavior

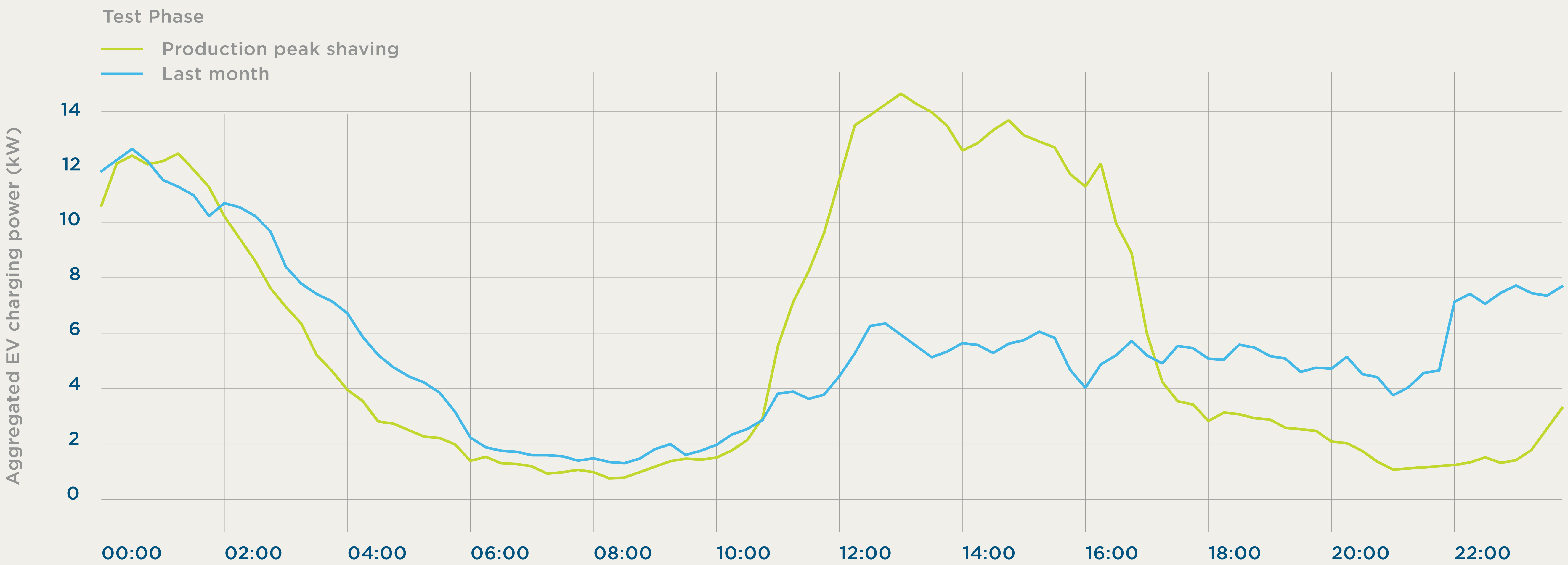


Figure 30
Daily standard load curve of EV charging between phase “production peak shaving” (21/04/2025 – 31/05/2025) and the last month of the project (1/06/2025 – 30/06/2025)

The analysis of EV charging behavior during the test phase "production peak shaving" shows a clear shift in customer habits. As illustrated in the standard daily EV charging load curve in Figure 30, participants adapted their routines during the production peak shaving phase, making a noticeable effort to charge their EVs primarily during sunny hours (between 11:00 and 17:00), thereby aligning consumption with PV generation. 56% of kWh linked to EV charge were done during the midday period.

In contrast, during the last month, when participants were free to choose their preferred charging routine based on what they had experienced during the project, part of the midday charge was shifted back to late evening hours, after 22:00, especially on weekdays, as illustrated in Figure 31. Overall, only **28% of the charge was done during the midday period**, which is half as much as during the production peak shaving phase. This indicates that the self-consumption rate observed during the production peak shaving phase represents an optimistic, best-case scenario.

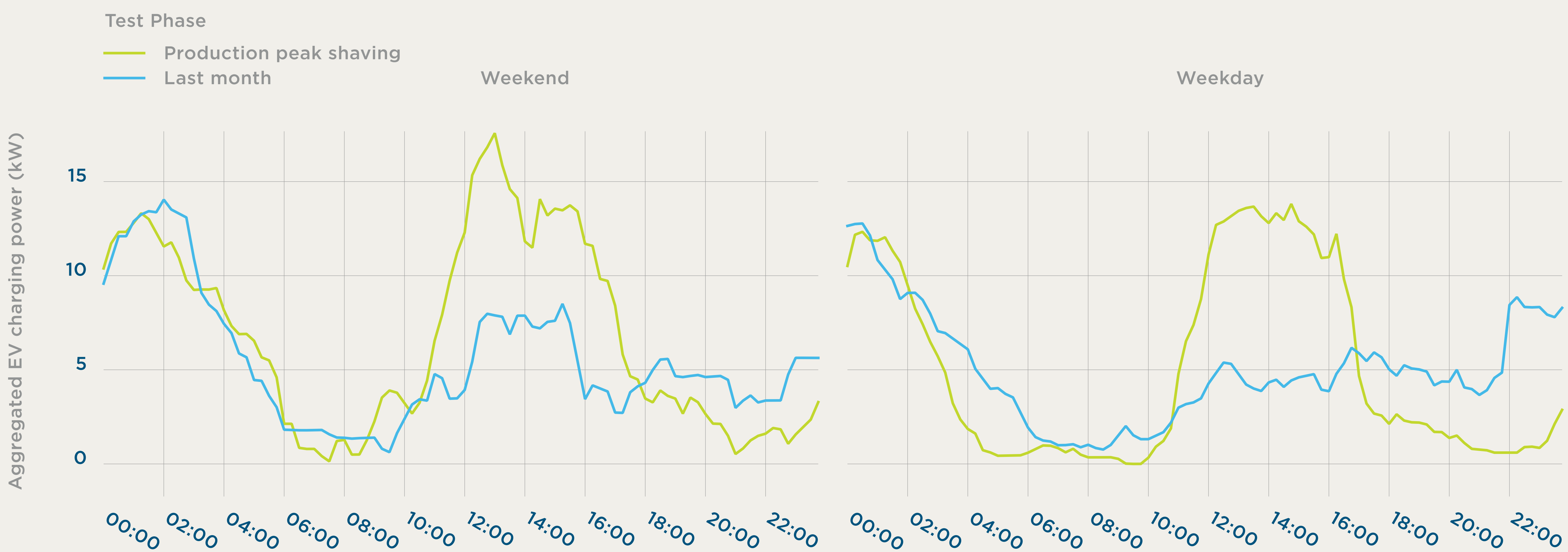


Figure 31
Daily standard load curve of EV charging between phase "production peak shaving" and the last month of the project, separated by weekend day and weekday

6.5.3

Impact of the phase on the injection into the grid

During the summer months, when PV production levels were similar, the injection peak into the grid was typically around **15% lower than the actual production peak**, due to a constant base load from local consumption. No improvement was observed during the peak shaving phase.

Despite no improvement in terms of peak reduction, in general, shifting EV charging to midday hours increased local self-consumption and generally reduced injection into the grid. In total, **57% of the electricity generated was consumed within the street**, which is 10% more than in June 2025, despite occasional PV curtailment from smart grid tests. This can also be seen in the decrease of the 95th percentile of net injection, as shown in Figure 32. Nevertheless, these efforts remained insufficient to reduce the absolute injection peak.

If the EV charge load curve is removed altogether from the consumption load curve, the injection peak would have been **58,9 kW**, meaning only about 4,5 kW (8,2%) higher than with the EVs. The 95th percentile however would have been 53,9 kW and therefore 20,2 kW (60%) higher, which underlines the previous observations that while consumer behavior helps to consume more energy locally and generally reduces injection, it does not significantly reduce the overall injection peak.

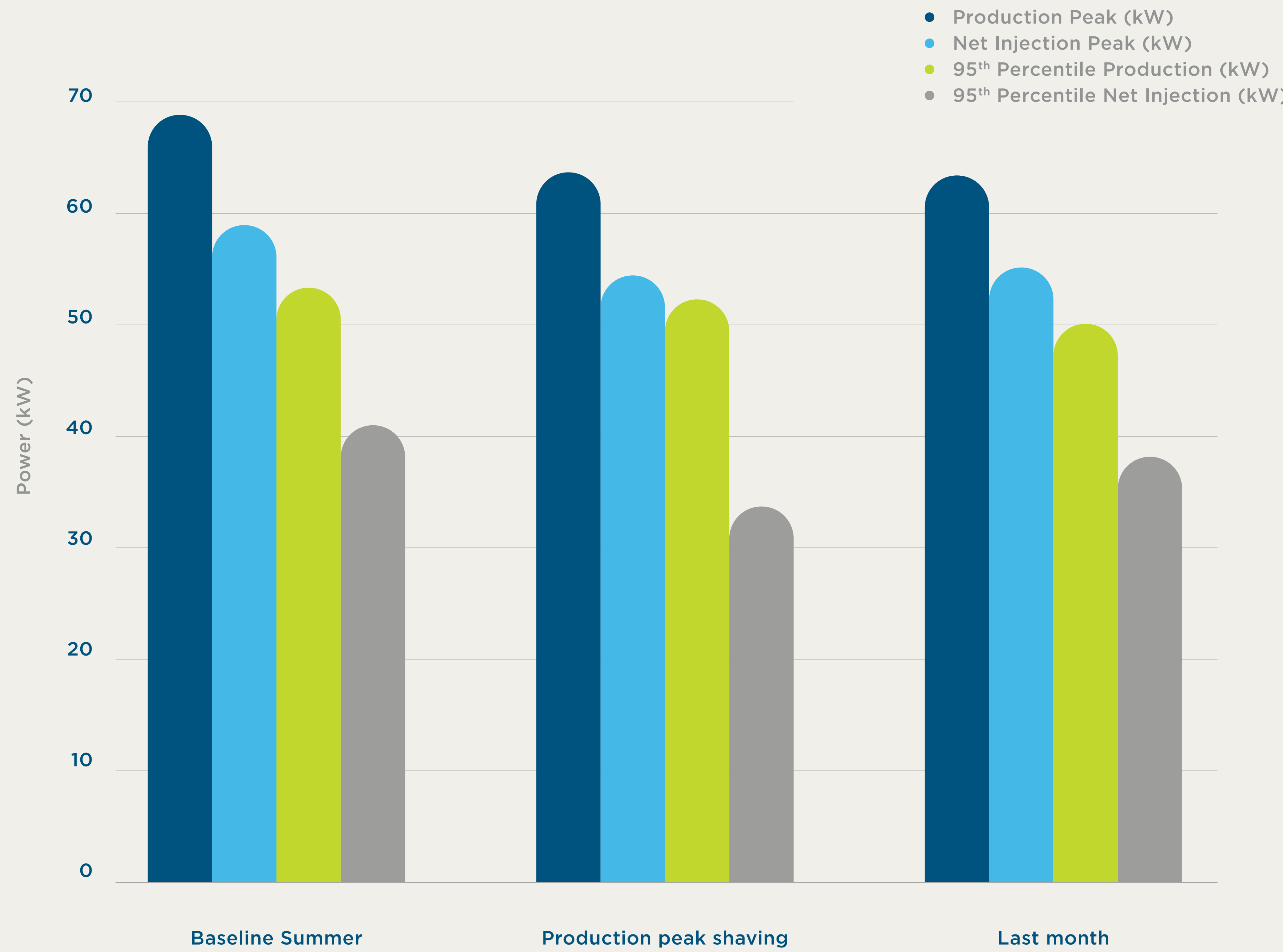


Figure 32
Evolution of injection peaks throughout the Living Lab phases

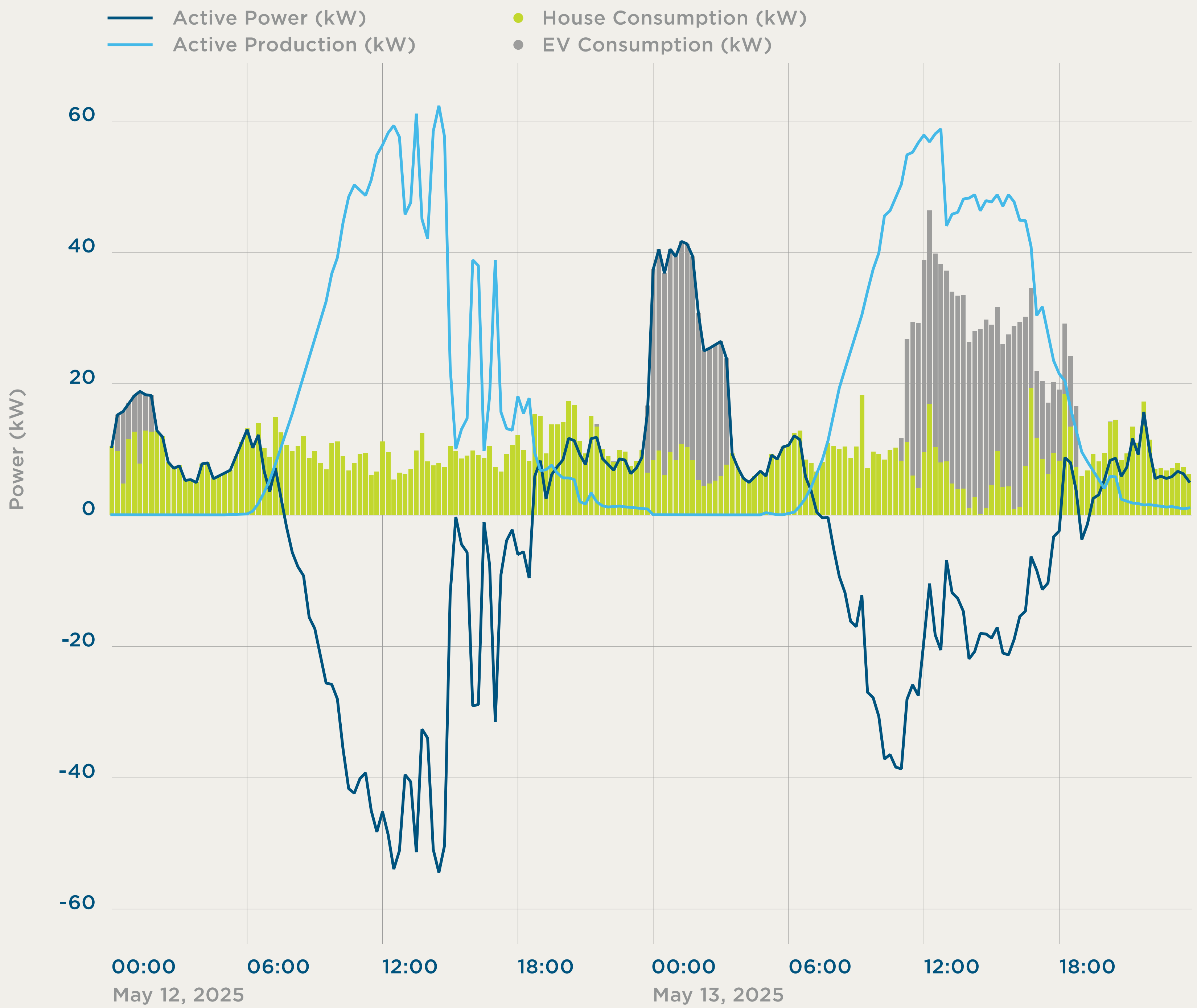


Figure 33
Evolution of power during the injection peak day, where no EVs charged, and the following day, where several EVs charged during the day

The highest injection occurred on **Monday, 12 May 2025**, at 14:30. On that specific day, no EVs were charged, which significantly lowered the collective self-consumption rate. Meanwhile, the battery systems were programmed to start charging after 13:00 to mitigate the injection peak, and they did activate as planned.

However, due to a technical malfunction, and overall low household consumption, the four batteries did not fully discharge during the preceding night, resulting in **high states of charge (55–80%) in the morning**. Consequently, three of the four batteries reached full capacity within 30 minutes, while the fourth battery reached full charge at 14:30, which coincides with the observed injection peak.

Even though the batteries started the day with a high SoC, their contribution still helped to partially mitigate the peak. Nevertheless, to effectively reduce the midday injection peaks, **systematic discharge during the night and strategic operation for peak shaving remain essential** to use their full potential as a grid-friendly support.

6.6

Insights into operating home storage batteries as grid support

In the Living Lab, four households were equipped with 10-kWh home storage batteries. The PV installations had installed capacities of 7, 10 and 12 kWp. The results highlight the **limits of operating batteries in self-consumption mode** to support the grid, both in winter and in summer.

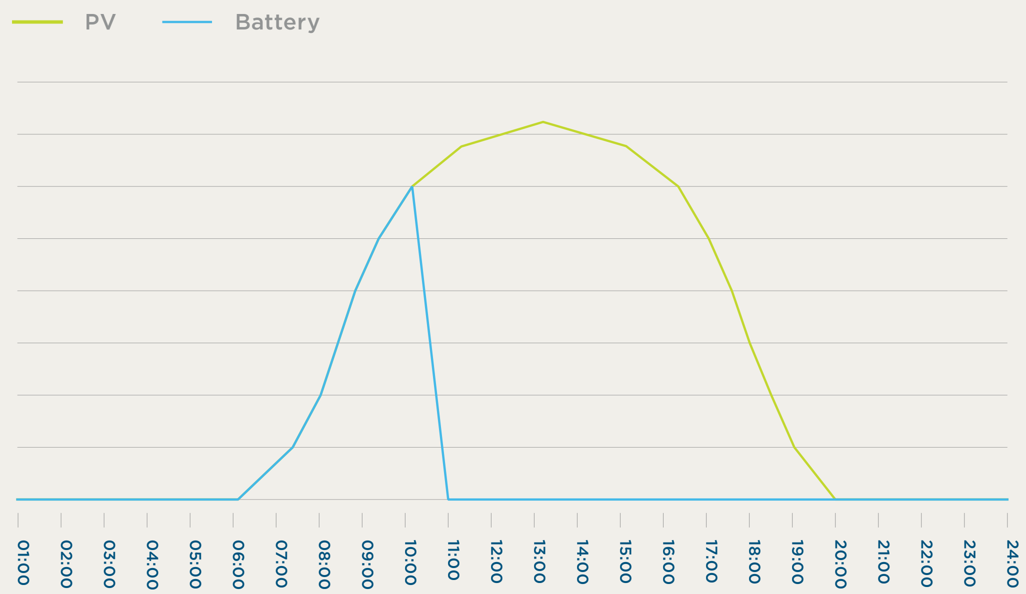
While in winter, there is often not enough PV generation to charge the battery, which limits the batteries' potential to shave the evening consumption peak, in summer, due to lower household consumption, the battery might not be fully discharged during the night. This limits their potential to contribute to shaving the injection peak.

6.6.1

Battery operation strategies

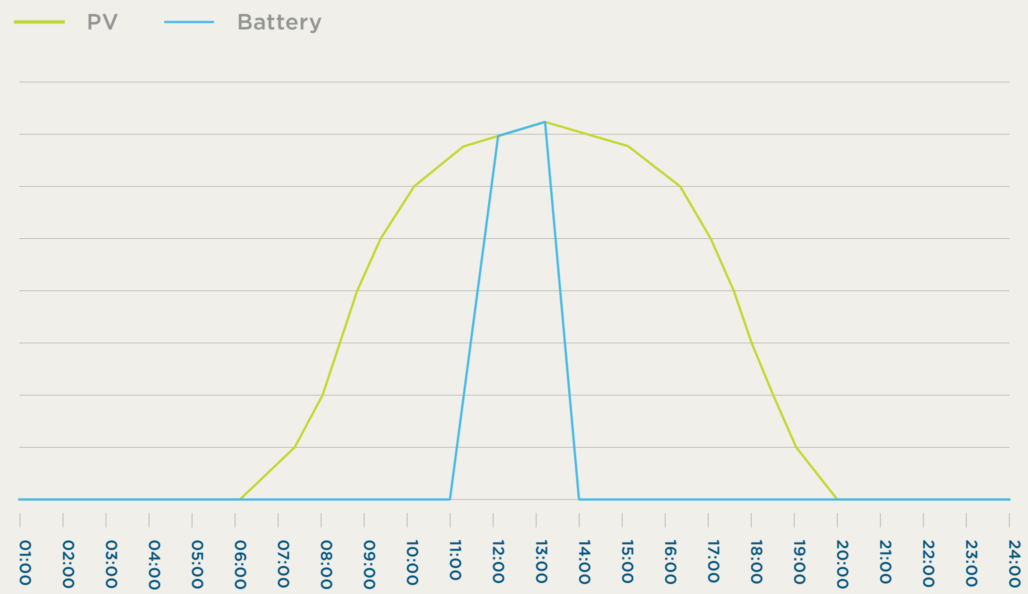
During the project, the batteries were operated in a charging range between 10 and 100%. Two operating modes were tested:

Mode 1
Charge as soon as excess PV electicityis available



Mode “Charge as soon as possible”: batteries charge as soon as excess PV generation is available and discharge as soon as PV generation does not cover the consumption.

Mode 2
Charge to reduce injection peak around midday



Mode “Midday delay”: if the forecast of the HEMS foresees that the battery is fully charged before 13:00, with enough production scheduled for the afternoon, then the charge is delayed and starts only after 13:00. This is to try and charge as much as possible during the injection peak.

6.6.2

Mitigation of injection peak in spring and summer with batteries operating in self-consumption

Mode “Charge as soon as possible”

Until end of April, batteries were regularly fully charged before 13:00, meaning that they did not contribute to shaving the injection peak. Between 21 April and 11 May, the first 3 weeks of the injection peak shaving phase, there were 12 sunny days where the control sites produced more than 75% of their general daily production on a sunny spring day. During this same period, the two largest PV installations fully charged the battery before 13:00 on 7, respectively 12 out of the 12 sunny days. The other 2 installations, due to more self-consumption during the day and slightly smaller PV installations, were fully charged before 13:00 on only 3 days. On the other days, they were fully charged after 13:00.

On sunny days, where injection peaks can lead to potential issues, many household-sized battery storage systems, if operated in the “charge as soon as possible” mode, are **most likely fully charged before the injection peak** and therefore do not help mitigate the impact from excessive injection. This is especially the case if no significant consumption is shifted to the midday period.

Mode “Midday delay”

For this reason, a second operating mode was implemented during the Living Lab. This mode allowed the batteries to better target the injection peak. However, due to lower household consumption in spring and summer, when the heat pumps no longer heat the houses, it was observed that on some days, the batteries did not fully discharge during the night. For this reason, even if the battery mode was optimized, the potential to shave the injection peak could be reduced if their SoC remains at a high level.

It is to be noted that the batteries were initially parametrized to not discharge into the EV. In winter, this makes sense to avoid discharging the battery quickly into the EV. Instead, the storage battery was primarily used to cover the household and heat pump consumption during the evening and the night. In spring and summer, however, once the battery no longer discharges through household consumption alone, the parameters were updated to discharge into the EV. In this manner, the EV can be charged daily through the battery.

> This shows that if a battery is operated on self-consumption and discharging exclusively into the household, their **potential to mitigate the midday injection peak in spring and summer can be strongly limited**.

6.6.3

Potential to mitigate the consumption peak in winter with batteries operating in self-consumption

From 1 November 2024 until 28 February 2025, the PV control site, with an installed capacity of 12 kWp and a south-east orientation, produced less than 10 kWh on **83 out of 120 days (70%)**. From November to January, the median daily electricity production was only 2,7 kWh, which means that on 50% of the days, even if the PV production is solely used to charge the 10-kWh-battery, its SoC would barely reach 36% in the best case.

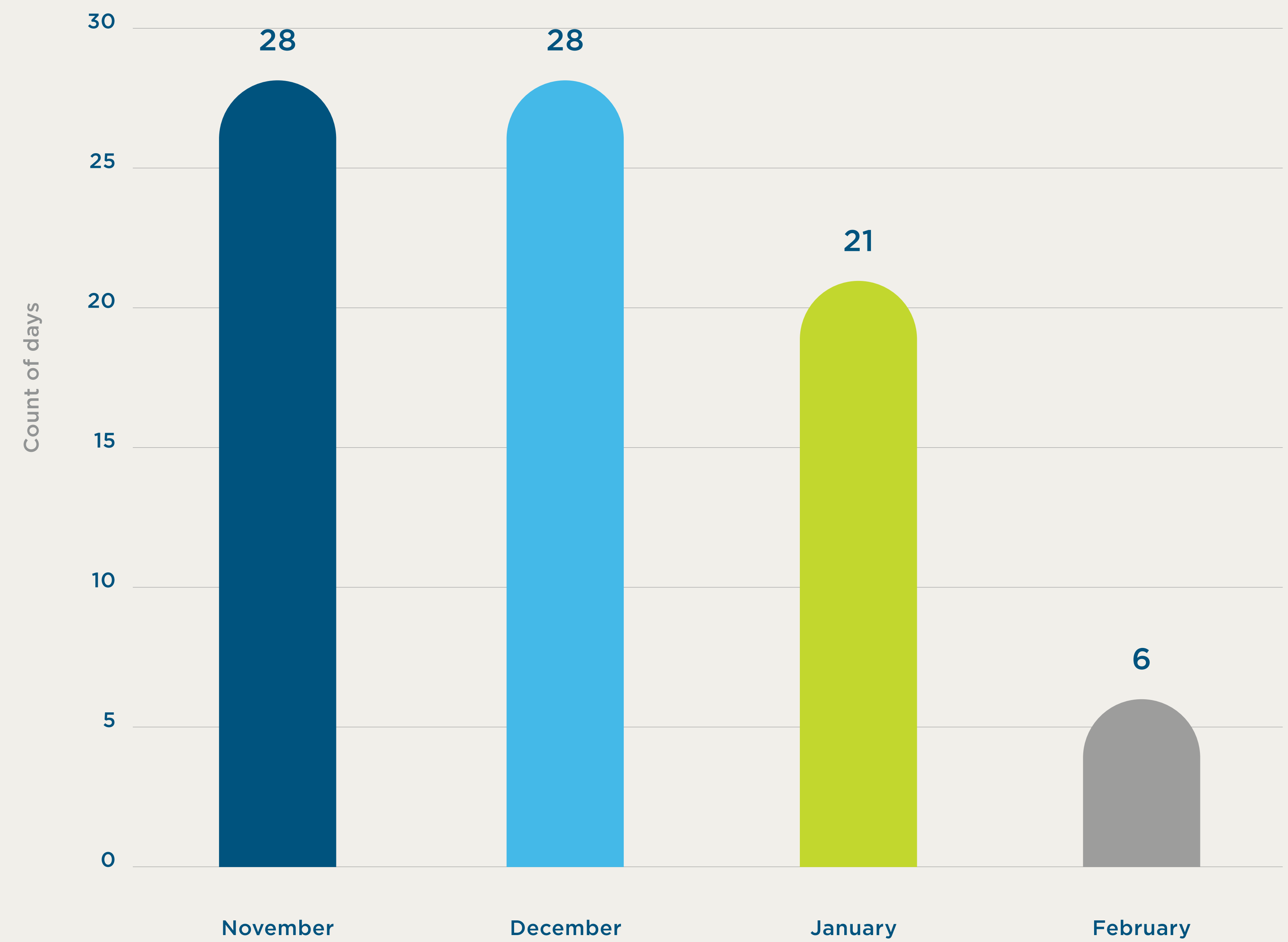


Figure 34
Number of days during winter 2024-2025 where the control site produced less than 10 kWh

Average daily PV generation from November to January (kWh)	6.2
Median daily PV generation from November to January (kWh)	2.7
90th percentile daily PV generation from November to January (kWh)	12.3

Table 20
Statistical values of production quantity of the control site during winter 2024-2025

These results can vary according to different factors, such as weather and the parameters of a PV installation:

- According to Meteolux, winter 2024/2025 was particularly rainy and dark, with 15% more rain and 18% less sunshine than the reference period (1991-2020).
- Moreover, solar panels have improved in efficiency, especially with diffused or indirect sunlight. Recent PV installations can therefore produce electricity even in cloudy weather.

Nevertheless, despite slight variations depending on weather and PV installation, this shows that if a battery is operated on self-consumption and charging exclusively from PV production, **their potential to mitigate the evening consumption peak in winter can be strongly limited**.

7 Out of Scope

This chapter gives an overview of subjects which were considered, but not integrated into the scope of the Creos Living Lab.

7.1

Vehicle-to-Grid (V2G)

While we are aware of the growing role of V2G in upcoming years, we decided to focus on smart charging first, based on the current maturity of the technology.

7.2

Load management of heat pumps

In combination with buffer storage, heat pumps are valuable in offering flexibility to the electricity system. However, managing the load of heat pumps was not included in the project, as the installed systems did not allow an integration into the HEMS for steering without major changes in the existing installations.

7.3

Energy communities

In the project, participants are not part of an energy community. In a first step, it was decided to restrict the scope to other priorities.

7.4

Testing new communication standards for the HEMS

Since HEMS solutions fall outside the Creos regulatory framework, we have not included the evaluation of the various protocols or communication standards in the scope of the project. For this reason, we have limited ourselves to available solutions on the market.

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