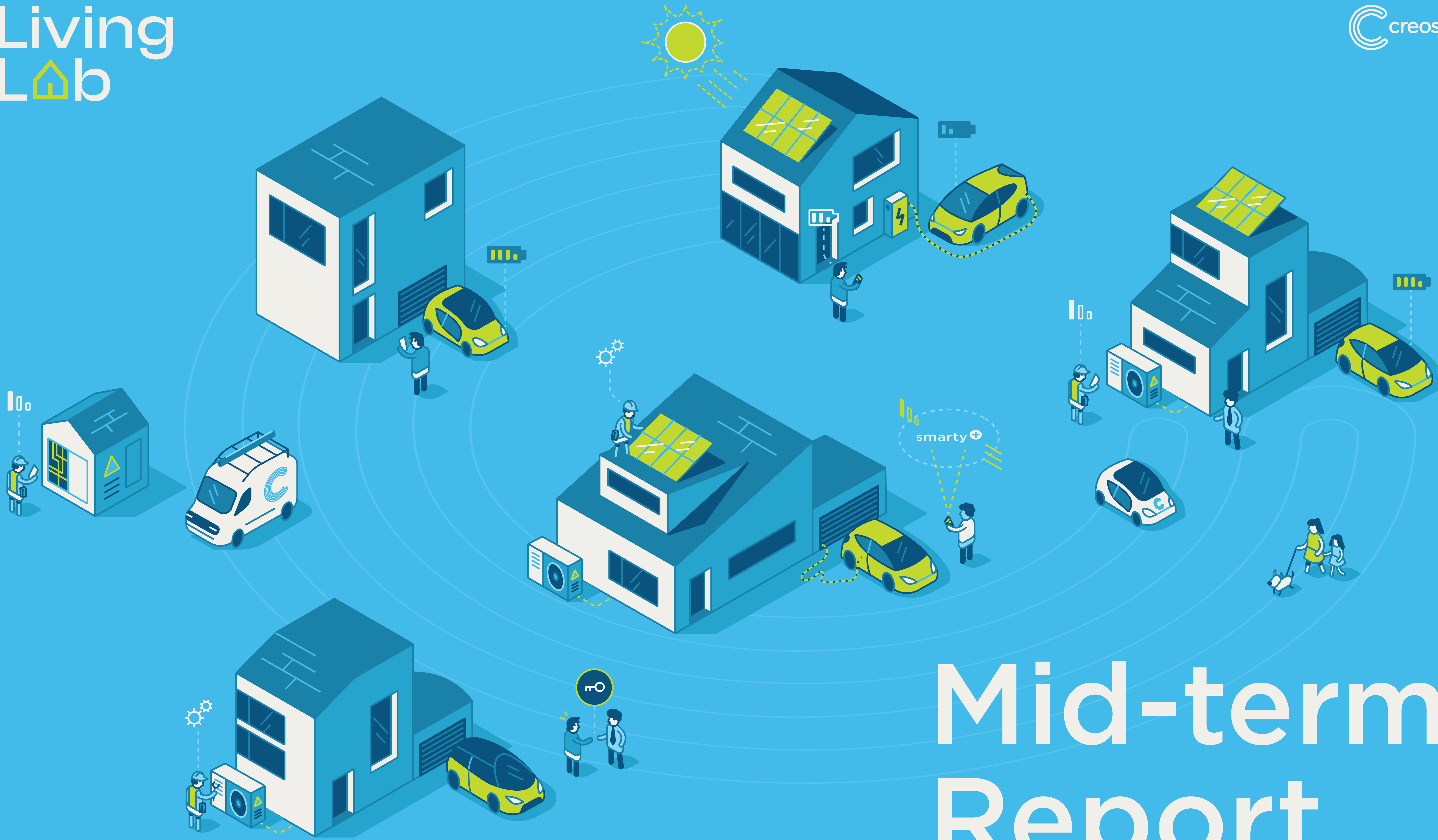
Living Lab

creos



Mid-term Report

Disclaimer

This mid-term report aims to provide an overview of the project's context, preparation, and general setup.

To ensure clarity and avoid potential misinterpretations, detailed project results have not been included in this report. These results will be presented in the final report, which will be published after the project's completion.

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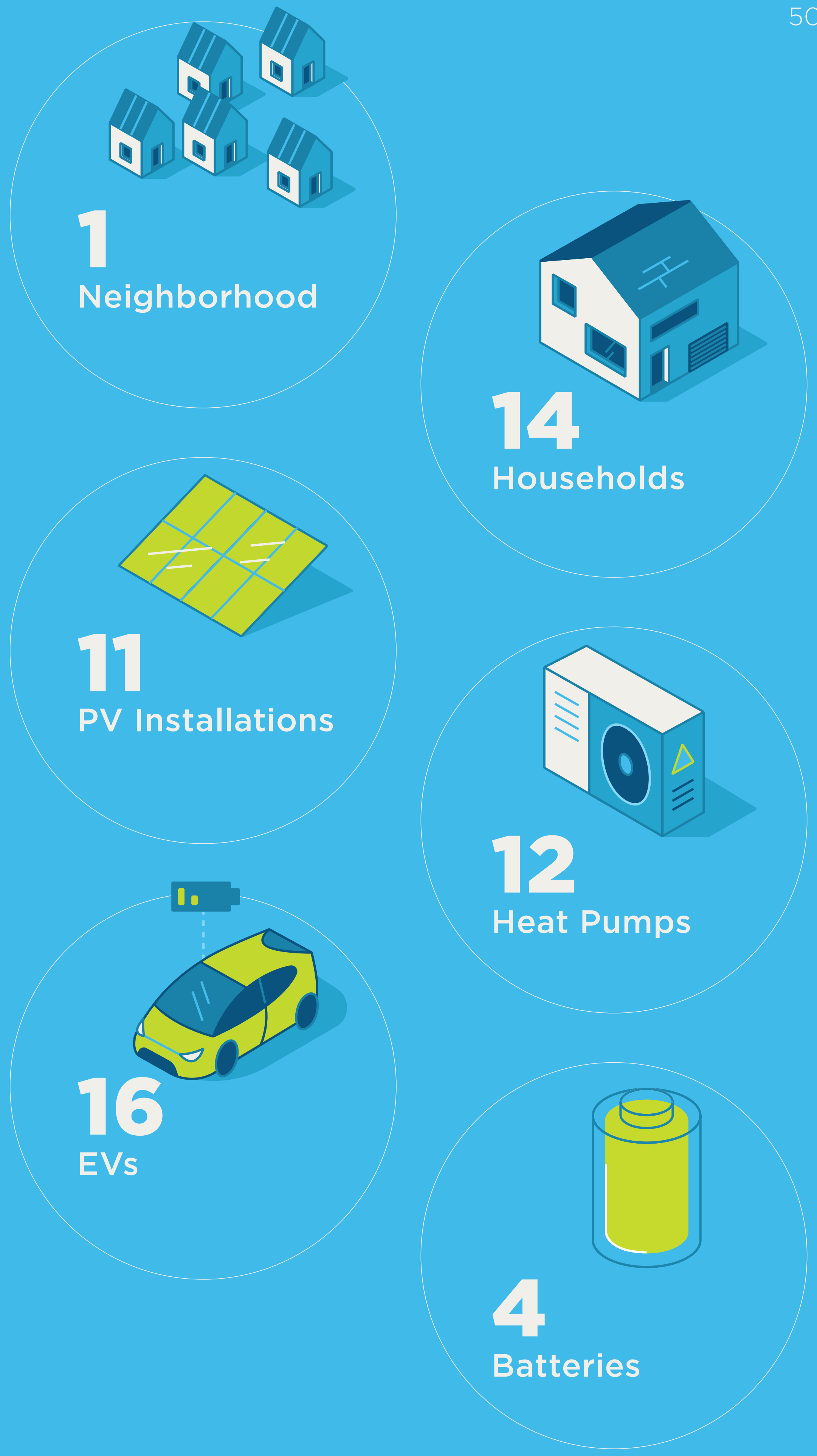
List of abbreviations

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
TAB	“Technische Anschlussbedingungen” or technical connection requirements
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.

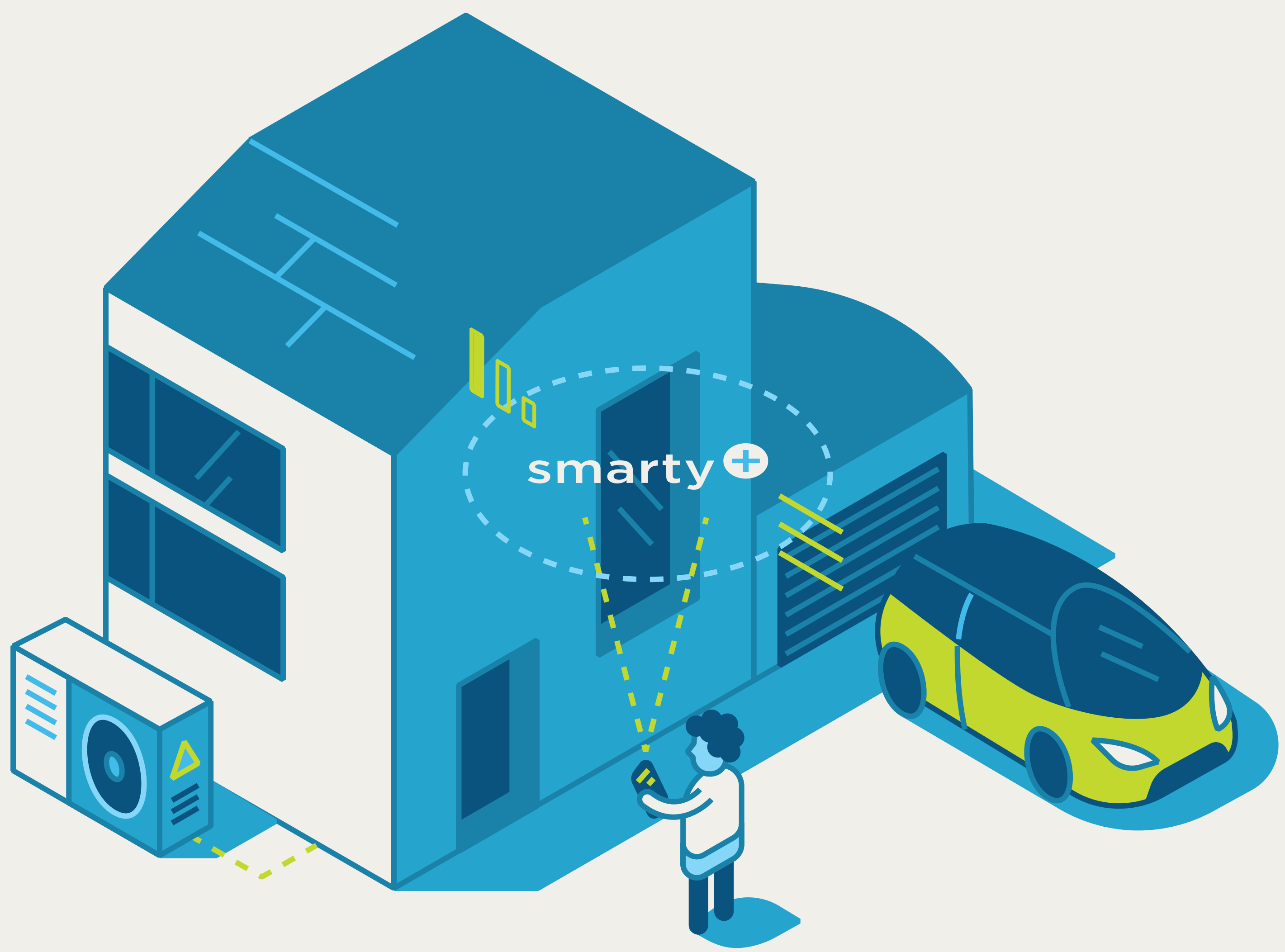


Figure 1
Future smart household

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 will help 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.

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 will publish both a mid-term and a final report. While this mid-term report highlights the project's progress and early findings, it will be complemented by the final report, scheduled for publication by the end of 2025, which will provide a comprehensive analysis of the results and lessons learned.

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.

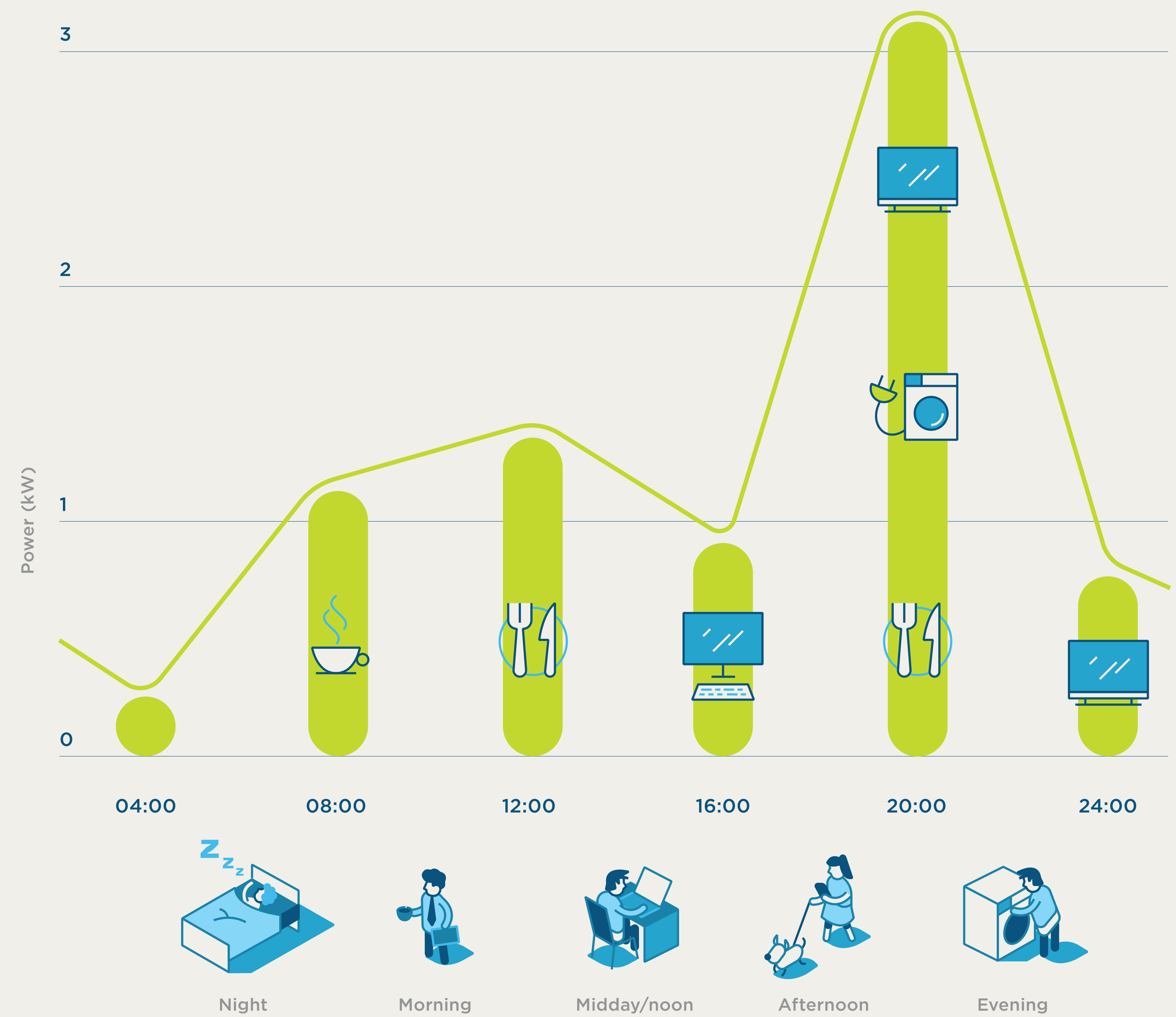
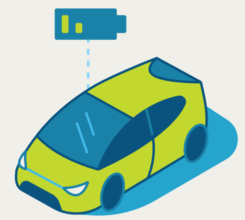
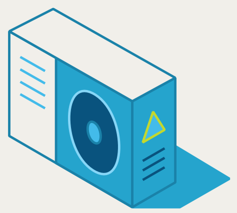


Figure 2a
Example of a load profile of a historical household consumer.
The evening consumption peak is usually between 17 and 21h.

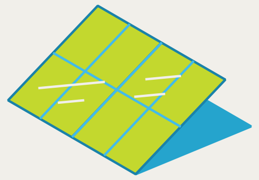
However, this load profile will change in the future with the addition of new assets, including:



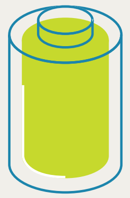
Electric Vehicles (EV): The average household in Luxembourg owns 1 to 2 vehicles. A high share of households will most probably be equipped with 11 kW wallboxes, which will thus add a considerable additional load. Currently, these chargers are mostly used during the evening peak times between 18h and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

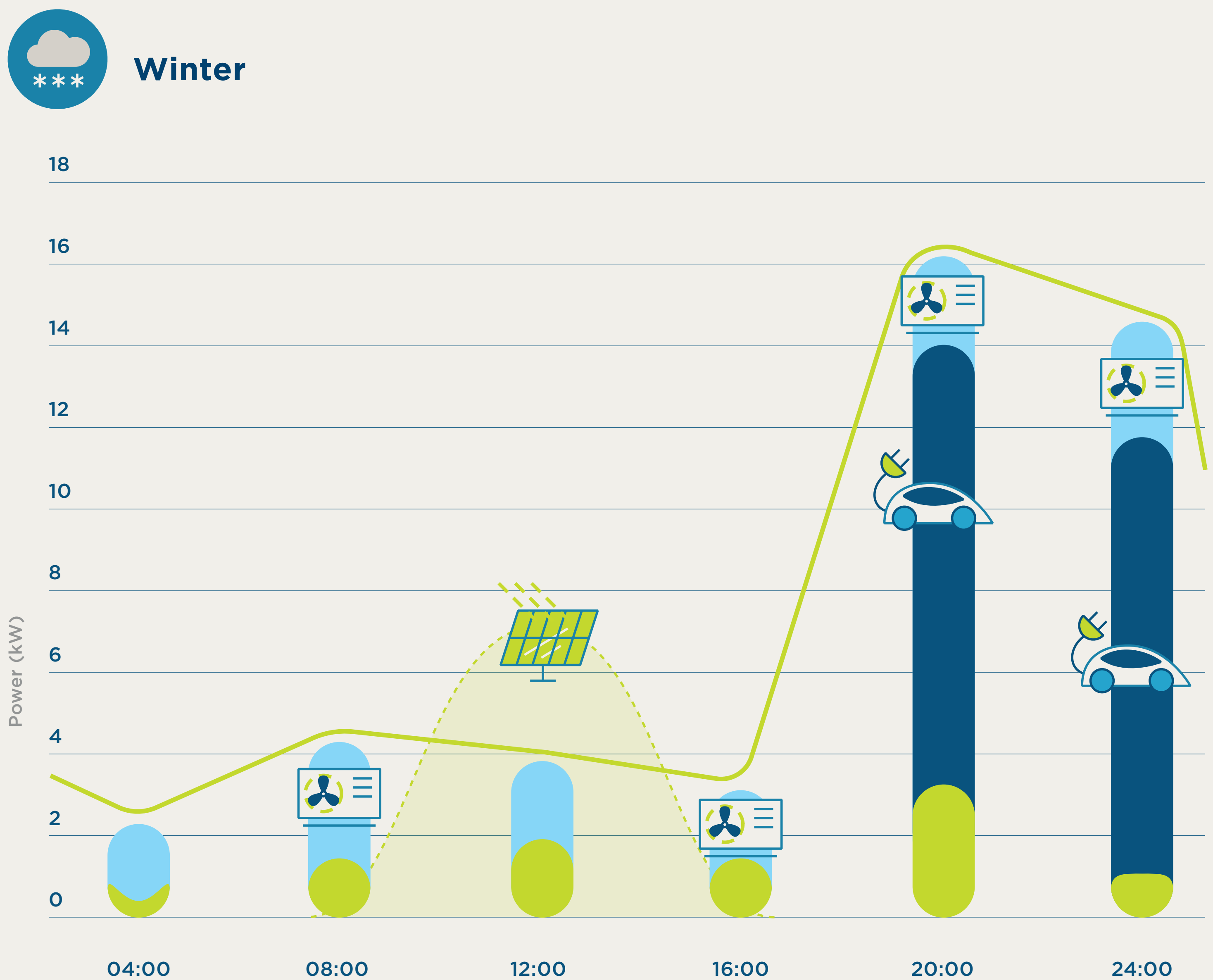


Figure 2b
Example of a load profile of a typical 2030 household prosumer in Winter, with the household consumption and the generation profile of a PV installation.

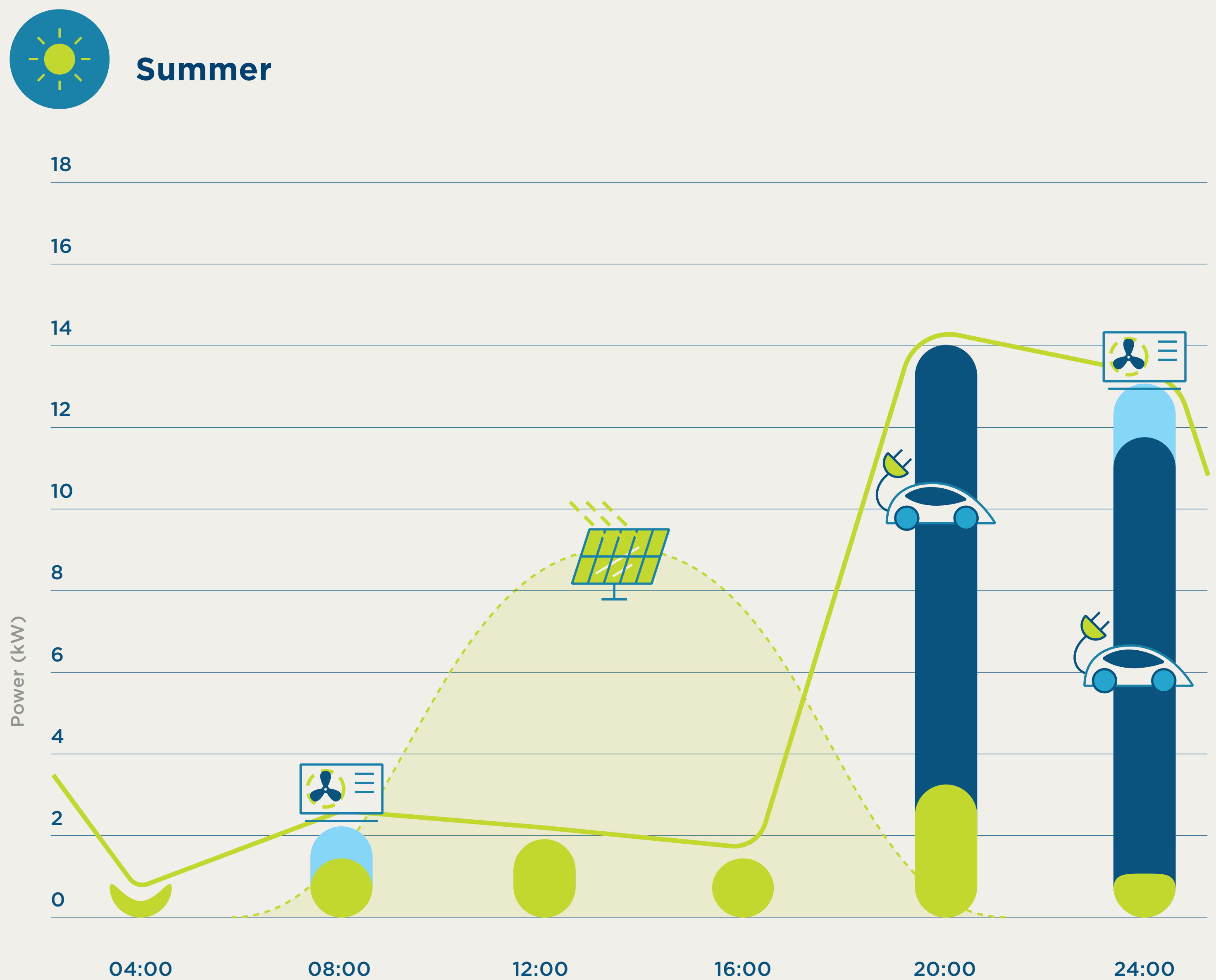


Figure 2c
Example of a load profile of a typical 2030 household prosumer in Summer, with the household consumption and the generation profile of a PV installation.

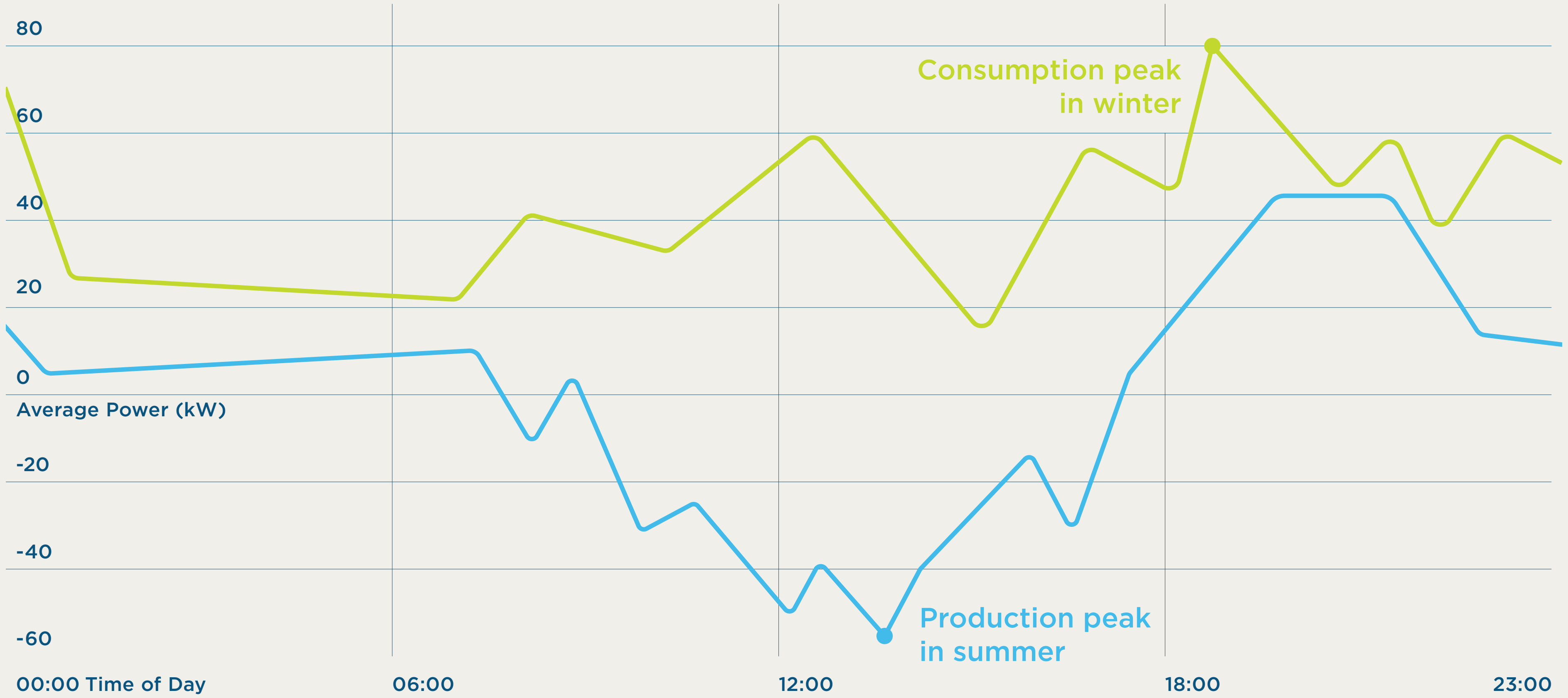
2.2

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.

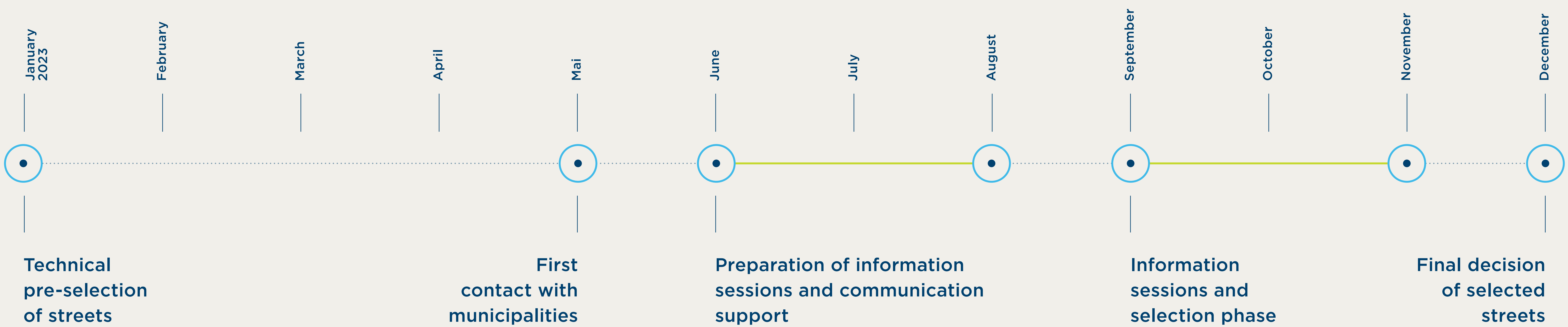


Table 1
Timeline of the selection process phases up until the project launch

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.

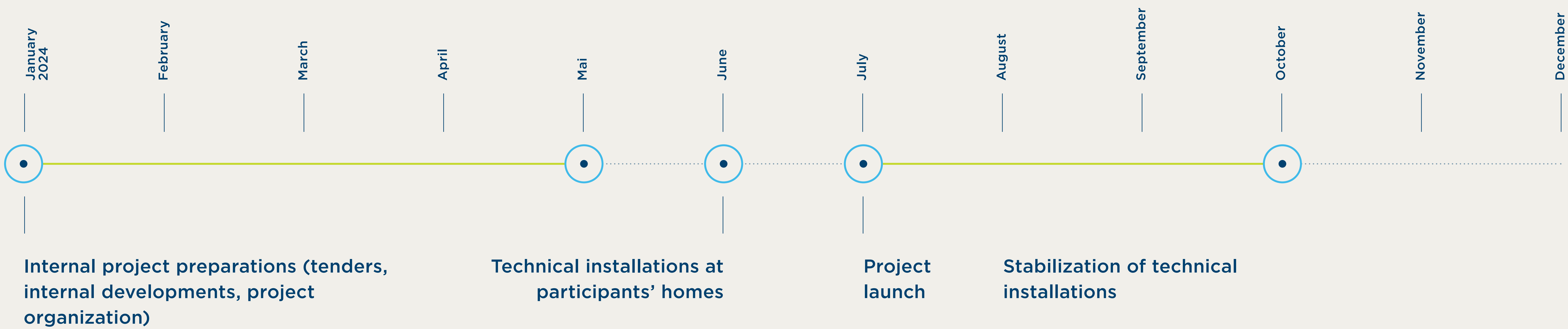


Table 2
Timeline of the phases linked to participants' technical installations

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

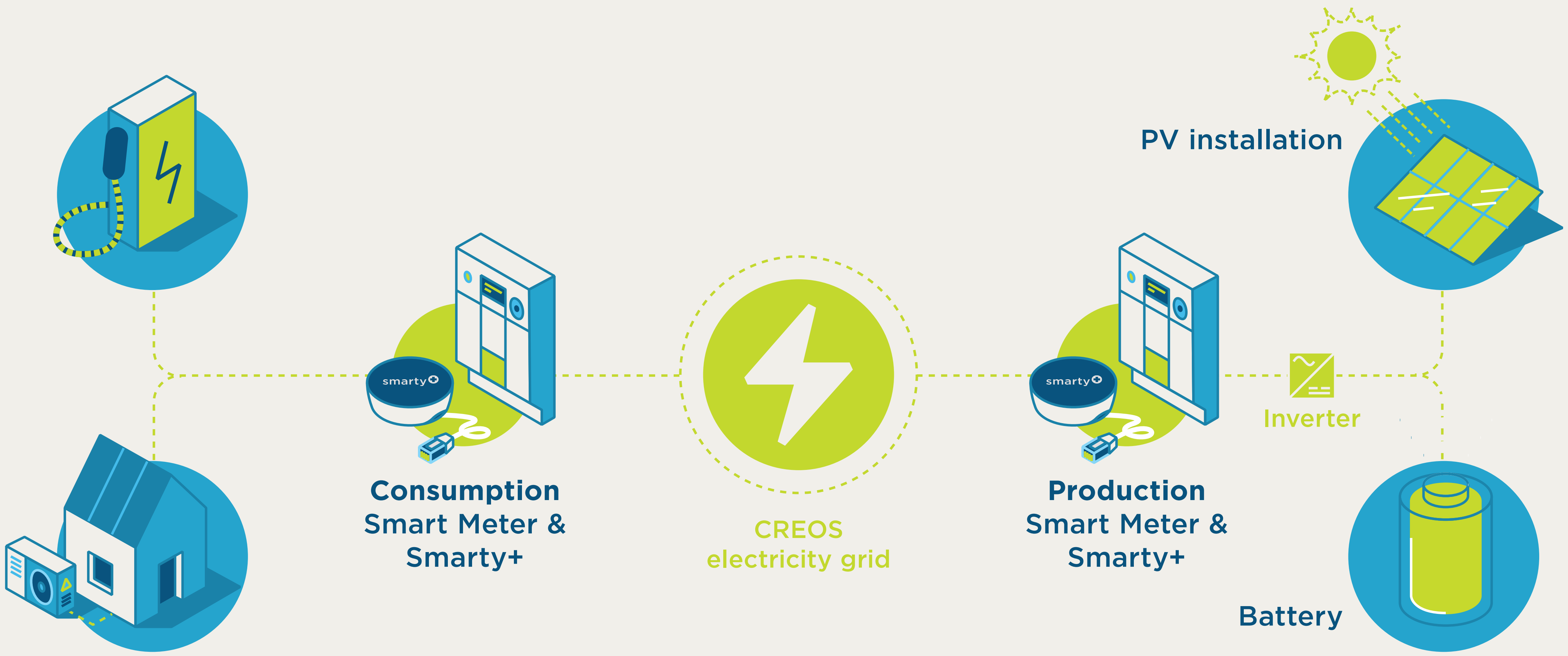
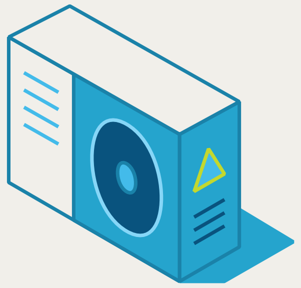


Figure 5
Visual representation of the target configuration of assets installed at participants' homes

4.2

Installed assets

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



4.2.1

Heat pumps

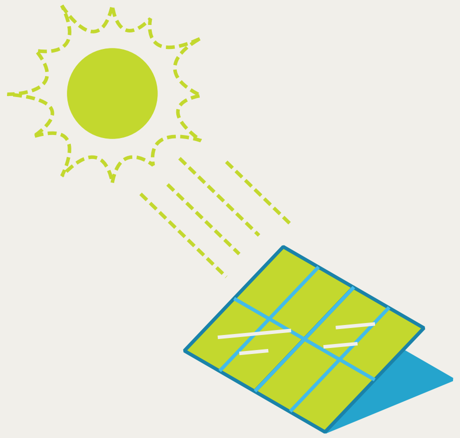
Table 3 - Key numbers: heat pumps

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.



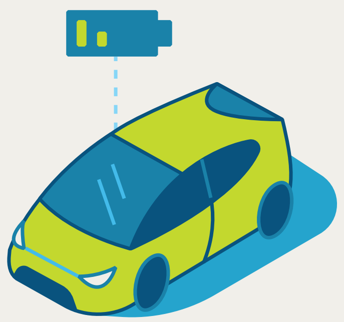
4.2.2

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

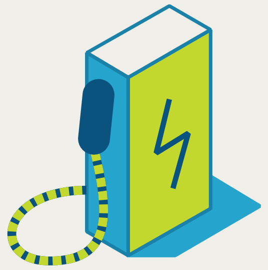
Table 5 - Key numbers: EVs

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

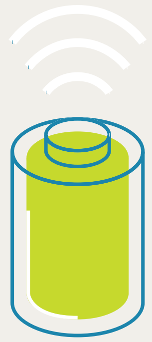
Total number of wallboxes	**14**
Communication protocol	**OCPP 1.6**
Range of power output in a three-phase configuration	**4,2 to 11 kW**

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.

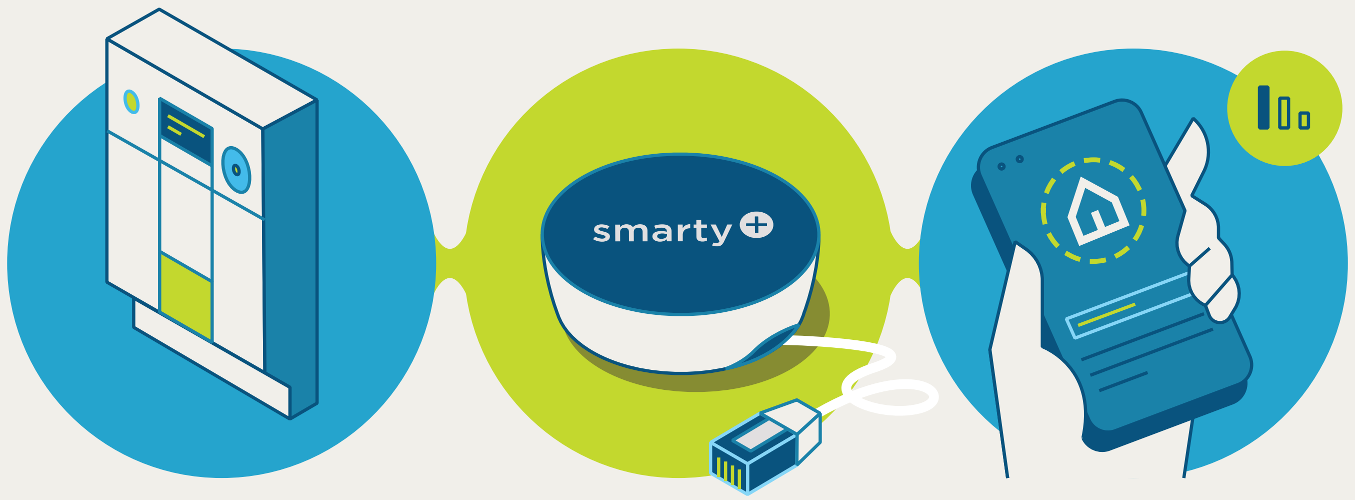


Figure 6
The Smarty+ dongle and its application for data visualization

[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.

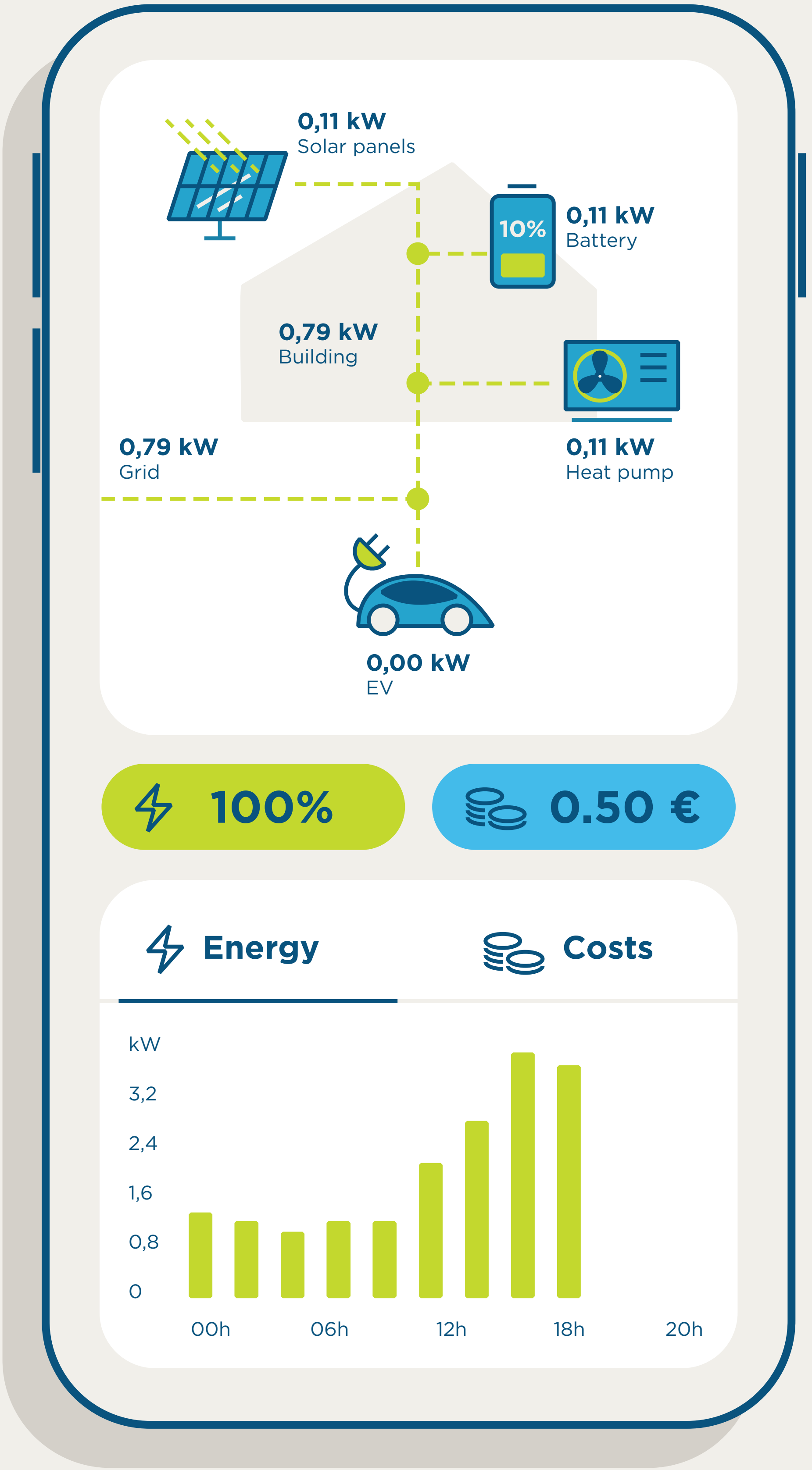


Figure 7
Example of the HEMS application showing the electricity consumption and production

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.

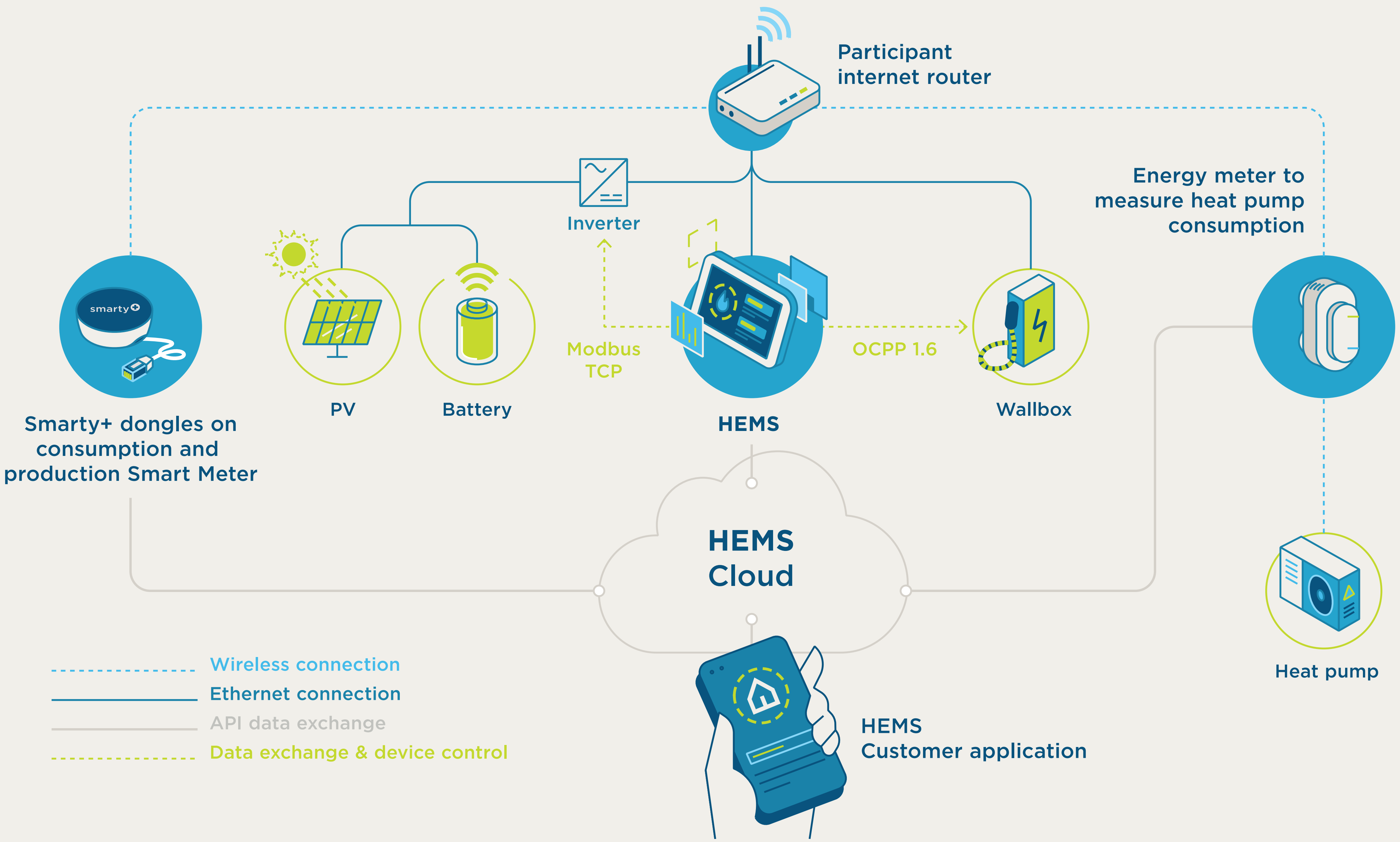


Figure 8
Communication flows on configuration with wallbox, PV installation and battery.

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 upskill-ing, 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 communi-cation 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 technol-ogies 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.

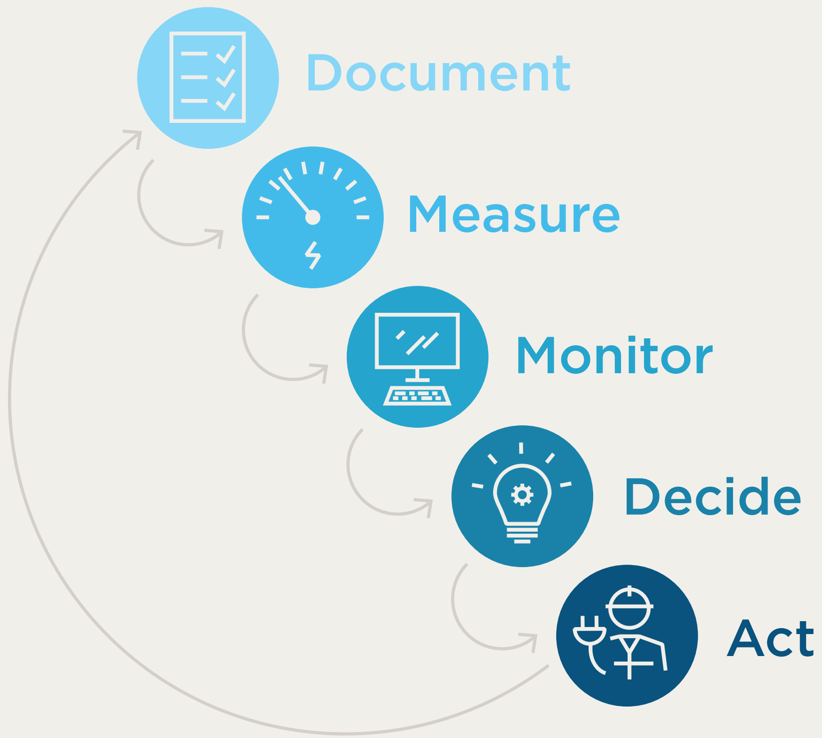
Today, the energy landscape has undergone significant transformation. The energy transition is accelerating, marked by the electrification of heating and mobility, but also by the development of PV installations resulting into bidirectional electricity flows. To enhance visibility into grid loads, Creos 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.

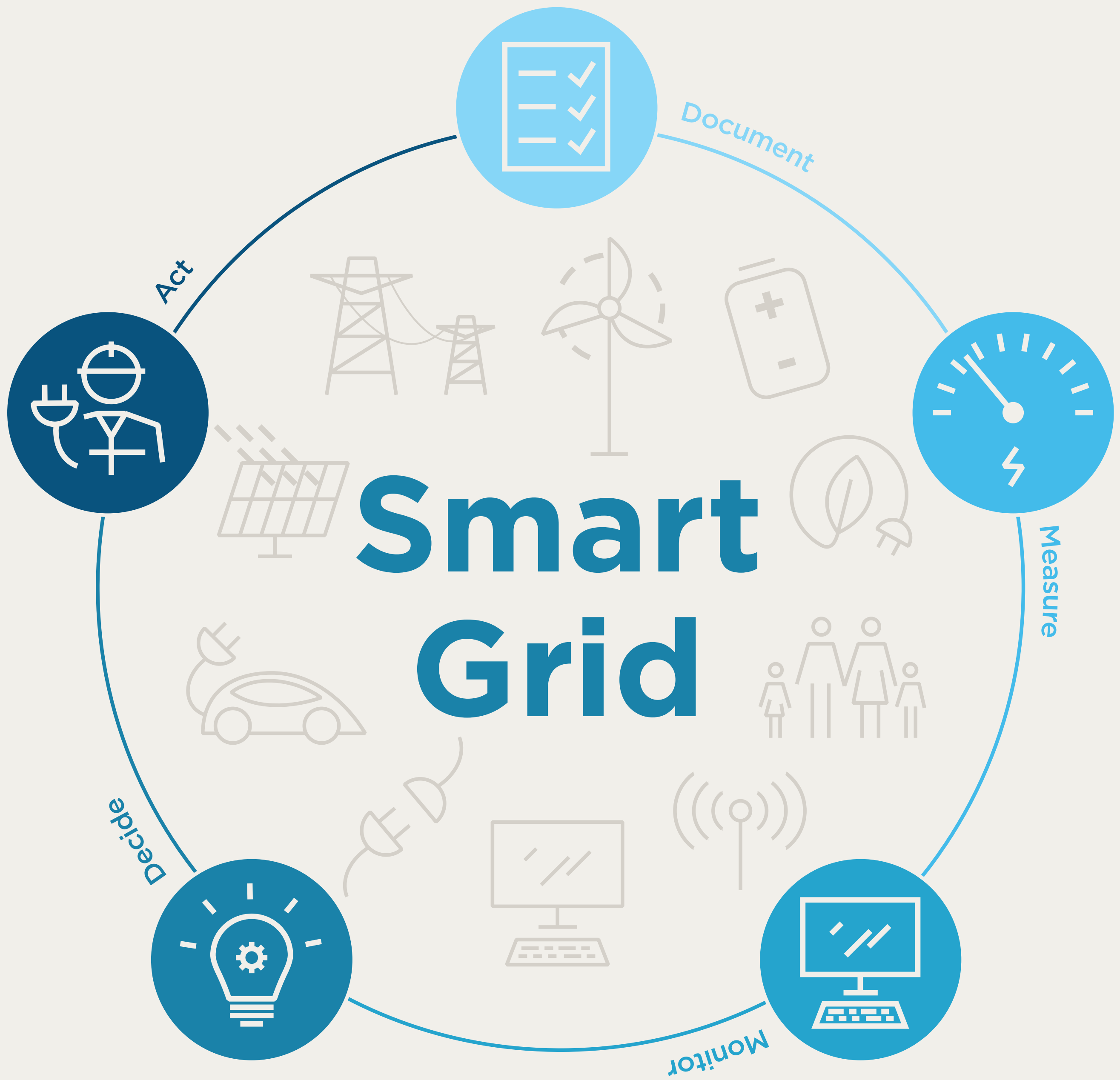


Figure 9
Creos Smart Grid Vision

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.

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.

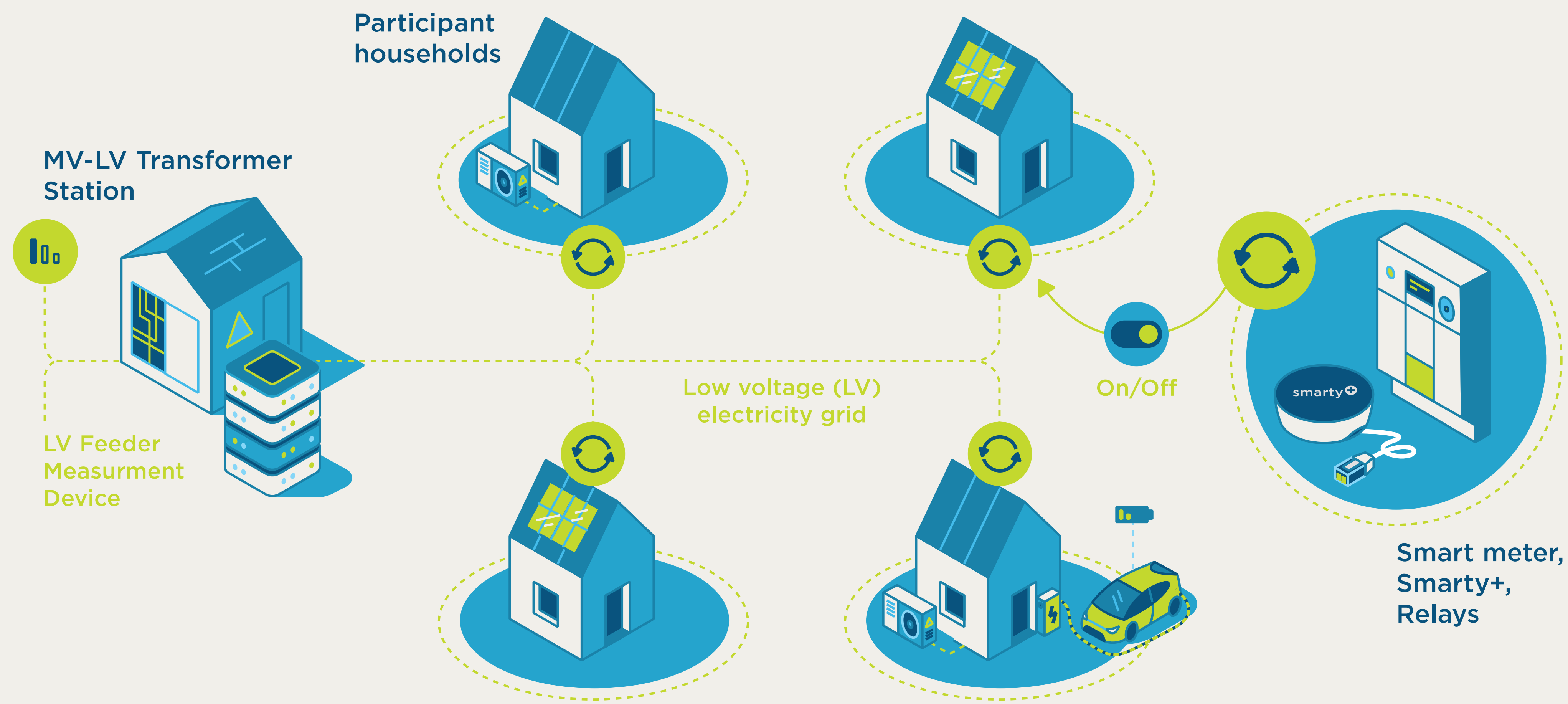


Figure 10
Placement of measuring devices in the LV grid

5.4.1

Smart Meter Data

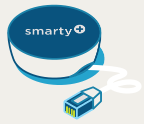
The smart meter is not particularly installed for the Living Lab, but its data is nevertheless an essential part of the project. Practically all households connected to the Creos grid are equipped with a smart energy meter named Smarty[7] in Luxembourg. This energy meter is situated at a customer's connection 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.

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.

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

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

Table 10
Smarty+ Technical Data Sheet

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.

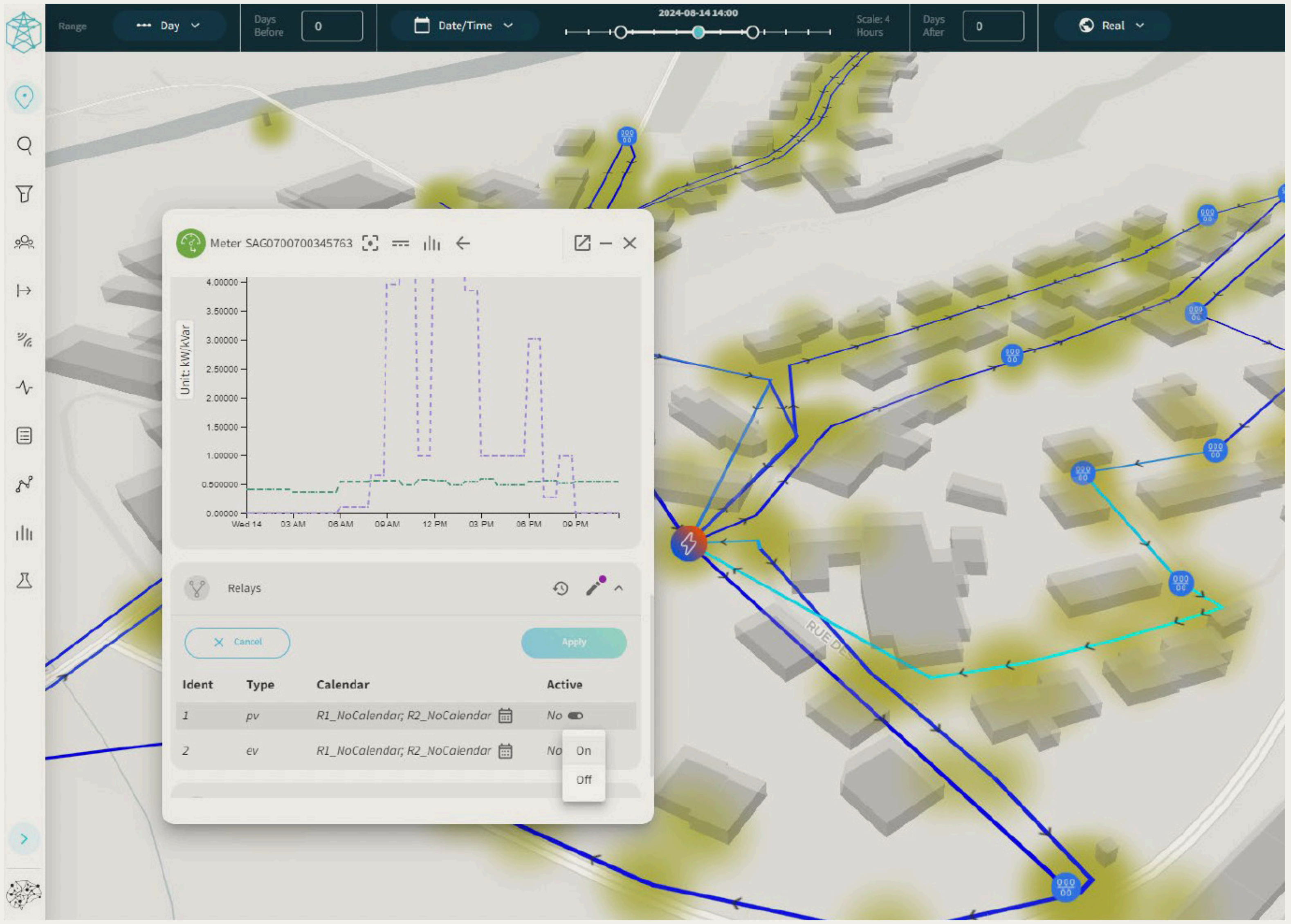


Figure 11
Kopr – The digital twin of the electricity grid

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.

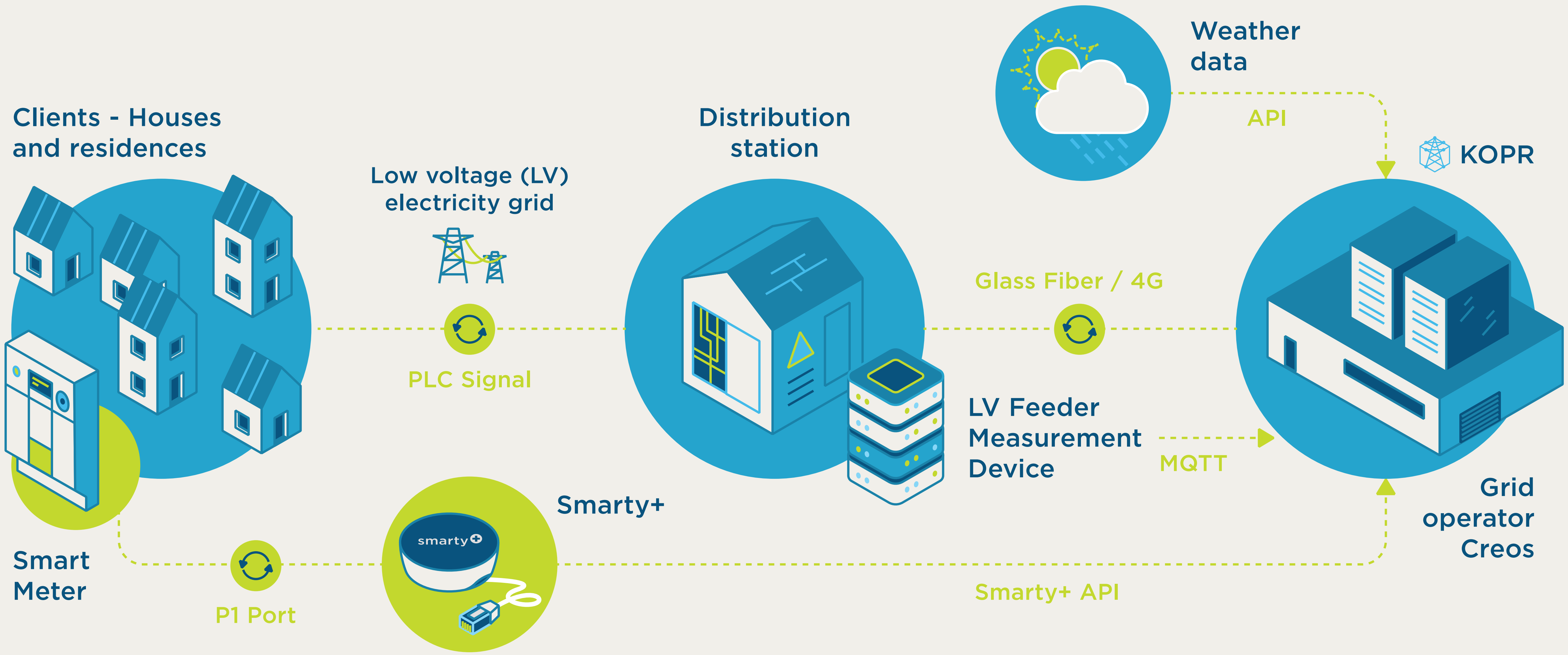
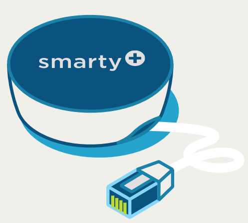


Figure 12
Data Flow Graph

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.

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 without battery optimization	Simulate the impact of production peak shaving with participants’ gestures and non-optimized batteries (charge as soon as possible)	Give participants everyday actions which can contribute to peak shaving (production). Allow them to use digital tools (HEMS, apps) to help automate the shift of the assets. The battery charges as soon as excess PV production is available
Injection peak shaving with battery optimization	Simulate the impact of production peak shaving with participants’ gestures and optimized batteries (charge during midday peak)	Give participants everyday actions which can contribute to peak shaving (production). Allow them to use digital tools (HEMS, apps) to help automate the shift of the assets. The battery is optimized to charge during midday to reduce the injection peak

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.

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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