Platone

PLATFORM FOR OPERATION OF DISTRIBUTION NETWORKS

Platone

PLATform for Operation of distribution NEtworks

D5.7

Final Report

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Abstract

This deliverable is a Final Report of the German Demonstrator under lead of Avacon. It summarizes the results of the performance of Use Case (UC) 1 "Virtual Islanding", UC 2 "Flexibility Provision" and UC 3 and 4 "Bulk Energy Supply". It delves into the overall demonstration setup and the developed algorithms and solutions necessary for the successful finalization of the above-mentioned UCs. The results of these UCs are quantitatively analysed based on a set of key performance indicators. By conducting this analysis, this deliverable summarizes the lessons learned from all UC applications including the lessons relevant for the future implementation and operation of the developed solutions. Finally, open questions and potential areas for further research are discussed.

Keyword list

Smart Grids, Decentral Flexibility Management, Automated Flexibility Management, Energy Community, Battery Storage, Local Balancing

Executive Summary

“Innovation for the customers, innovation for the grid” is the vision of project Platone - Platform for Operation of distribution Networks. Within the H2020 programme “A single, smart European electricity grid”, Platone addresses the topic “Flexibility and retail market options for the distribution grid”. Modern power grids are moving away from centralised, infrastructure-heavy transmission system operators (TSOs) towards distribution system operators (DSOs) that are flexible and more capable of managing diverse renewable energy sources. DSOs require new ways of managing the increased number of producers, end users and more volatile power distribution systems of the future.

This report is dedicated to the results of performance analysis and lessons learned from Use Case (UC) applications in the German demonstrator under lead of Avacon. The results in this report show the successful achievement of demo objectives to implement a local balancing mechanism implemented in coordination with centralized grid operation; develop allocation strategies for flexibility in local networks; establish the effective temporal uncoupling of low and medium voltage (MV) networks; and maintain the safe operation of the distribution network by utilizing the flexibility of distributed energy resources. To achieve UCs objectives, an Energy Management System (EMS), integrated in the Platone Open Framework, has been developed from the scratch and applied in a selected community in the Low Voltage (LV) grid level which displays rural characteristics and high installed generation capacities from Photovoltaic (PV). A Community Battery Storage (CBES) has been installed to provide flexibility for the control actions of the DSO. Additionally, residential customers have been recruited and equipped with Household Battery Storage (HBES) for monitoring and control. Algorithms of the proposed EMS have been developed to perform balancing mechanisms between the generation and consumption of the selected community with limited data such as the power measurement data at the Point of Common Coupling (PCC) of the community to the MV grid and the measurement data of CBES.

UC performance analysis summarized in this deliverable confirm the successful implementation of UC 1 “Virtual Islanding", UC 2 “Flexibility Provision” and UC 3 and 4 "Bulk Energy Supply", and the subsequent reduction of power peaks in MV and LV grids and increase of local PV self-consumption within the community. UC 1 in this report is evaluated for two UC subversions. Subversion UC 1.0 applies near Real Time Operation (RTO) mode by applying a rule-based logic with 15-minute measurement-and-control cycles on measured data from secondary substation and is re-evaluated with a larger data set.. Additionally, a first analysis is conducted for UC subversion UC 1.1, that implements a Schedule-Based Operation (SBO) mode by applying an optimization logic on the day ahead forecast of the community residual power exchange at PCC. Considering that the community experiences high exports of power due to high feed-in from PVs, the evaluation based on Key Performance Indicators (KPI) showcased great performance in peak reduction (especially peak exports) and increase of local self-consumption. However, peak import increasing effects were observed on some unsteady and overcast days for RTO and especially for SBO (in the case of overestimation of PV generation). RTO performance in the field can be improved by reducing the control cycle from 15-minute intervals to shorter ones but considering the limitations in place for near-real time measurement-and-control actions associated with the existing communication infrastructure and the controllability and responsiveness of storage units . The SBO can be improved by using more accurate forecast inputs and identification and sensitivity analysis of external factors influencing the power exchange at PCC. For a 24h boundary condition, the SBO shows potential to overperform RTO, when storage capacity of CBES is limited. Additional modes of operation to improve UC 1 performance, such as intraday plausibility checks of forecast are also discussed.

KPI evaluation of UC 2 confirmed the ability to coordinate flexibility control in times of multiple requests and the ability of the EMS to balance the generation and consumption within the community and to achieve e requested value of power exchange at PPC. UC 3 and 4 have shown the successful energy import and export scheme based on energy bulks to achieve a power peak reduction on the MV grid.

Additionally, this deliverable gives special attention to the lessons learned in the areas of project management, public relation and customer engagement, development and implementation, field test assembling and operation, data analysis and dissemination, UC handling and concludes with implications on relevant future implications in each of the topic areas.

In conclusion, the developed EMS in conjunction with the Platone Open Framework has demonstrated excellent results and showcased the great potential for the DSO to improve safety of grid operation and

to facilitate the energy transition. The results and learned lessons added great value in all areas of Avacon's business department ranging from the education area to legal, IT, gird operation, field installation, etc. areas.

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1. Introduction

The project “PLATform for Operation of distribution Networks – Platone” aims to develop an architecture for testing and implementing a data acquisition system based on a two-layer Blockchain approach: an “Access Layer” to connect customers to the Distribution System Operator (DSO) and a “Service Layer” to link customers and DSO to the Flexibility Market environment (Market Place, Aggregators, …). The two layers are linked by a Shared Customer Database, containing all the data certified by Blockchain and made available to all the relevant stakeholders of the two layers. This Platone Open Framework architecture allows a greater stakeholder involvement and enables an efficient and smart network management. The tools used for this purpose will be based on platforms able to receive data from different sources, such as weather forecasting systems or distributed smart devices spread all over the urban area. These platforms, by talking to each other and exchanging data, will allow collecting and elaborating information useful for DSOs, transmission system operators (TSOs), market, customers and aggregators. In particular, the DSOs will invest in a standard, open, non-discriminatory, blockchain-based, economic dispute settlement infrastructure, to give to both the customers and to the aggregator the possibility to more easily become flexibility market players. This solution will allow the DSO to acquire a new role as a market enabler for end users and a smarter observer of the distribution network. By defining this innovative two-layer architecture, Platone strongly contributes to aim removing technical and economic barriers to the achievement of a carbon-free society by 2050, creating the ecosystem for new market mechanisms for a rapid roll out among DSOs and for a large involvement of customers in the active management of grids and in the flexibility markets.

In WP 5 of the Platone project, Avacon implements a decentral Energy Management System (EMS) prototype in a local low voltage (LV) grid representative for a rural community with significant photovoltaic energy generation. This EMS is named Avacon Local Flex Controller (ALF-C) and it can provide decentral SCADA / ADMS functionalities for DSO, TSO and customers. The principle of the ALF-C follows the edge computing paradigm. The functionalities enable automatized monitoring of LV networks and local balancing mechanisms to foster the integration of renewable energy generation and increase the efficiency of existing grids.

In four different Use Case (UCs), the balancing scheme applied by the ALF-C prototype controls a large-scale community battery energy storage (CBES) in such a way that a community is energetically uncoupled from the MV grid based on different control modes. UC 1 and UC 2 focus on the decoupling of the LV community from the MV grid with and without predefined requests of power at the Pointpf Common Coupling (PCC). Energy deficits of an LV community shall be provided ex-ante in UC 3 and surplus of generation exported ex-post in UC 4. The algorithms in all UCUCs aim at reducing the stress in the MV grid and the MV/LV feeder and increase the local PV self-consumption.

UC 1, 2, 3 and 4 with near Real-Time Operation (RTO) operation mode have been evaluated in previous reports of the German demonstrator [1], [2] and [3]. Since the evaluation of UC 1.0 in the first demonstration report has been evaluated based on a dataset covering a relatively short period of UCUC application and since UC 1 has additionally been implemented and applied in the field with a scheduled-based control (SBO) mode (UC1.1), this report is dedicated to a second analysis of UC 1.0 that covers a larger number of days and a first analysis of UC 1.1.

1.1. Task 5.4

Deliverable 5.6 is the result of Task 5.4 “Field Test Design and Execution”, that aims for an in-depth analysis of the demonstration results based on Key Performance Indicators (KPI) applied to the field test setup implemented in Task 5.5. “Installation and operation of field test equipment”. Further, this deliverable is the result of Task 5.3.1 “Local balancing of LV network with high penetration of Distributed Energy Resources […] to maximize the consumption of locally generated energy”, Task 5.3.3 “Supplying energy to the local network in bulk in advance at suitable times” and Task 5.3.4 "Exporting energy from the local network in bulk ex-post at suitable times". These tasks aim to implement a balancing scheme for the prediction of residual load and energy demand, surplus of energy generation and deficits as well as the scheduling of energy bulks for export or import to serve the predicated demand of a community in the LV grid.

1.2. Objectives of the Work Reported in this Deliverable

The objective of this deliverable is to exemplify the implemented schedule-based balancing approach applied to UC 1 “Virtual Islanding”, supplying energy to communities located in LV grids ex-ante (UC 3) and export surplus generation in bulk ex-post at suitable times. Further, this deliverable evaluates the demonstration results based on KPI and describes UC specific and general lessons learned gained during the project. Open issues and potential areas for further research identified during the UC evaluation and IT-implementations shall be pointed out.

1.3. Outline of the Deliverable

The report is structured as follows: Chapter 1 provides a general introduction and explanation of the topic. Chapter 2 summarizes the UCs, gives an explanation on the subversion of UC 1 and its related modes of operation (RTO and SBO) and defines data and sign conventions. Chapter 3 gives an overview of the implemented IT solution (ALF-C) and components of field test setup of the demonstrator. The chapter further highlights changes of technical properties during the field test phase relevant for the UC evaluations. Chapter 4 summarizes KPI results for a new computation for UC 1 with SBO and UC application evaluated in previous demonstration reports. Chapter 5 outlines the lessons learned, conclusions and implications on forthcoming applications. Chapter 6 describes open issues and potential areas for further research.

1.4. How to Read this Document

This report presents explanation of algorithm and KPI calculation for all UCs and summarizes Lessons Learned. UCs of the German demonstrator are described in Deliverable 5.2 [4], related algorithm in Deliverable 5.3 [5]. A draft of a detailed description of all assets implemented in the demonstrator. An intermediate result of UC 1 is provided in Deliverable 5.4 [6]. UC 2 and demonstration results including evaluation based on KPIs are provided in D5.5 [2]. A detailed description of UC 3 and 4 algorithm and demonstration results with KPIs are provided in Deliverable 5.6 [3]. The Platone Open Framework, after its revision, is described in D2.2 [7]. Also, the platforms that were utilized in the German Demo, namely the Platone DSO Technical Platform (DSOTP) and the Blockchain Access Layer (BAL), are reported in D2.8 [8] and D2.13 [9] respectively.

2. UCs

This chapter gives an overview of UCs that have been implemented in the demonstrator. With the UCs implemented by the EMS, named Avacon Local Flex Controller (ALF-C), Avacon achieves its objectives to:

- demonstrate a local balancing mechanism implemented in coordination with centralized grid operation and DSO owned flexibility mechanism.
- develop allocation strategies for flexibility in local networks for maximum benefit to DSO and customers.
- demonstrate the effective informational and temporary uncoupling of LV and MV networks by handling energy supply and export in bulk packages rather than a real time exchange.
- maintain the safe operation of the distribution network by utilizing the flexibility of DERs. Use DERs to alleviate violations in a cost optimal and practical manner.

2.1. UC 1

UC 1 aims to enable citizens located in an LV grid section to practice collective self-consumption by using available flexibility from a CBES. The collective self-consumption requires the synchronization of generation from local PV with available battery charging by the ALF-C. The trial is implemented in a local LV grid section located in a rural region, that is representative for future renewable energy communities, consisting of private agricultural buildings, customer households with privately owned flexible loads, storages and photovoltaic generators. The UC 1 targets the investigation of different approaches of a local balancing scheme to synchronize generation and consumption and simulate the behaviour of energy communities that practice collective self-consumption. Specifically, the net power and energy exchange at the grid connection point (MV-feeder) shall be examined and minimized during the UC 1 application. For this reason, two UC versions have been developed and implemented, “UC 1.0” and “UC 1.1.”. UC 1.0 applies a near real time operation (RTO) mode with rule-based logics. UC 1.1 applies a Schedule-based Operation (SBO) mode with optimization. Both modes of UC 1 operation are described in subchapter 2.5.

2.1.1. UC 1 Operation Modes

UC 1.0 has been implemented with a RTO and UC 1.1 with a SBO mode of operation. Both modes are defined as follows:

Near Real Time Operation with rule-based logic

The near real time RTO mode of operation applies rule-based logic to measured data of the power exchange data of the community at PCC. Measurements indicate the residual power exchange based only on 15-min measurements. The RTO takes into account the boundary conditions for CBES including its size, initial state of charge and the maximum charging and discharging power limits. Additional information are provided in [10].

Schedule-based Operation with optimization

The SBO mode balances the power exchange of the community by applying a optimization logic with a 24 hour boundary condition to a day ahead forecast of the community residual power exchange with the MV grid at PCC, which is calculated according to a generation forecast (based on weather forecast) and a calibrated standard load profile (SLP) for household consumption, see [11]. For all

The weather forecast data is provided by a commercial weather service and gives the expected power generation for a defined PV system. At the start of the field test, the PV generation forecast consisted of 1-hour mean values for power but since June 2022 has been upgraded to 15-minute mean values. While each PV system located in the field could be modelled individually, neither their precise properties nor direct measurements are readily available to German DSOs on a large scale. Another data source containing information about installed PV systems is the publicly available Marktstammdatenregister (Core Energy Market Data Register, [12]). However, necessary properties such as slope and facing are only entered as categorical data. Thus, individual modelling of PV systems is not easily feasible. Instead, the ALF-C aggregates all PV systems of the community into a single PV system by summing up their peak power generation. The initial assumption that such modelled PV system faces 180° south and has a slope between 30° and 45° was confirmed by manually checking all PV systems in Abbenhausen; the average facing is 175° south with a slope of 40°. The SLP scales with the number of households and their annual energy consumption. For the SBO, the SLP is further calibrated by a constant scaling factor derived from power measurements at the PCC during night hours from 1 to 4 a.m.

The day-ahead net active power forecast for the PCC is created just before midnight each day by combining the total PV generation and household consumption forecasts. The net active power forecast is then sent to a balancer optimisation module within the ALF-C that—given the current state of charge of the CBES—computes an optimal schedule for the CBES with the optimization goal of minimising the power at the PCC during the UC time period, given the technical limits of CBES as constraints. For more details, see [13]. For UC1, the above-mentioned PV generation forecast and household load profiles are used to generate a net active power forecast at PCC for the community which is fed as input to the SBO in addition to the technical limits of CBES (as well as other flexible assets). For UC3 and UC4, apart from the UC1 inputs, SBO is fed also with the necessary inputs about the bulk windows. Please refer to D 5.6 [3] for additional information. An overview of implemented UC control approaches and Parameter for setting are provided in section 3.1.

2.2. UC 2

Avacon aims at implementing a balancing scheme that enables local LV grids or energy communities to provide a constant set value of power at the MV/LV grid connection point upon an accepted request from a DSO, a TSO or a market participant. The balancing schemes apply algorithms, developed by RWTH Aachen, that use the battery storages in the grid and try to compensate power fluctuations of the community. Furthermore, UC 2 includes a coordination scheme of central and decentral organized flexibilities, based on a prioritization mechanism for relevant market participants, e.g., TSO, DSO, aggregator and others. The prioritization mechanism respects the ranking of the requesting market participants, requested power value, requested duration and time of submission. Further details are provided in deliverable D 5.5 [2].

2.3. UC 3

The target of UC 3 is to uncouple the load and energy demand of the community from its feeding MV-line by employing a package-based approach for energy supply. The UC shall be applied on demand driven days, at which the predicted daily residual energy demand in a 24h interval is higher than the local generation. The predicted residual energy demand of the community of a 24h period (considering local generation and consumption) shall be provided intraday as bulk (import from the MV grid), but before CBES is fully discharged and at times of low power loads in the MV grid. Thus, the predicted energy deficits of the community is buffered in local storages as bulk, i.e., CBES. The community later can withdraw energy from the storage as requested without creating additional peak loads on the MV feeder. U3 applies RTO with rule-based logic with 15-minutes intervals of measurement and control to reduce power and energy exchange to zero outside of bulk window. Further explanations on UC objectives and requirements of bulk window identifications are described in D5.6 [3].

2.4. UC 4

The opposite principle described in UC 3 applies to UC 4. UC 4 shall be applied on a generation driven day, for which higher energy export than import is predicted. A day ahead forecast predicts the residual surplus of generation for the next day 24h interval. Intraday surplus of generation shall be buffered in batteries located in the LV community, i.e. CBES, and exported into the LV grid level at PCC at non-critical times for the MV grid, i.e., times of relatively low power loads, and before the CBES reaches its maximum state of charge. The concept aim at a reduction of power peaks in the MV level. UC4 applies RTO with rule-based logic with 15-minutes intervals of measurement and control to reduce power and energy exchange to zero outside of bulk window. Further explanations on UC objectives and requirements of bulk window identifications are described in D5.6 [3].

2.5. UC Operation Modes

UC 1.0 has been implemented with a RTO and UC 1.1 with a SBO mode of operation. Both modes are defined as follows:

Near Real Time Operation with rule-based logic

The near real time RTO mode of operation applies rule-based logic to measured data of the power exchange data of the community at PCC. Measurements indicate the residual power exchange based only on 15-min measurements. The RTO takes into account the boundary conditions for CBES including its size, initial state of charge and the maximum charging and discharging power limits. Additional information are provided in [10].

Schedule-based Operation with optimization

The SBO mode balances the power exchange of the community by applying a optimization logic with a 24 hour boundary condition to a day ahead forecast of the community residual power exchange with the MV grid at PCC, which is calculated according to a generation forecast (based on weather forecast) and a calibrated standard load profile (SLP) for household consumption, see [11]. For all

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The day-ahead net active power forecast for the PCC is created just before midnight each day by combining the total PV generation and household consumption forecasts. The net active power forecast is then sent to a balancer optimisation module within the ALF-C that—given the current state of charge of the CBES—computes an optimal schedule for the CBES with the optimization goal of minimising the power at the PCC during the UC time period, given the technical limits of CBES as constraints. For more details, see [13]. For UC1, the above-mentioned PV generation forecast and household load profiles are used to generate a net active power forecast at PCC for the community which is fed as input to the SBO in addition to the technical limits of CBES (as well as other flexible assets). For UC3 and UC4, apart from the UC1 inputs, SBO is fed also with the necessary inputs about the bulk windows. Please refer to D 5.6 [3] for additional information. An overview of implemented UC control approaches and Parameter for setting are provided in section 3.1.

2.6. Definition of Data for UC evaluations

An overview of measurement data and the sign conventions sign relevant for all UCs is listed in Table 1. In this table and for active powers, positive values indicate a load flow from the MV grid into the LV grid (to meet the LV grid local consumption) and negative values indicate export power flows. Similarly and with respect to the energy sign convention, positive values indicate the amount of energy provided by the MV grid (to meet the LV grid local consumption) and negative values indicate the export of the excess of energy from LV to MV grid. Finally, with respect to the charging and discharging power of CBES, positive values indicate battery consumption/charging and negative values indicate discharging of battery.

Table 1: Measurement data definition

Data	Definition
$P_{M,\ PCC}$	Active Power Measured at PCC The data are measured in kilowatt (kW) on the LV busbar of the MV/LV feeder. The values indicate the net load demand of the community of Abbenhausen considering its total local generation and consumption.
$E_{M,\ PCC}$	Energy Exchange Measured at PCC The data are measured in kilowatt hours (kWh) on the LV busbar of the MV/LV feeder. The values indicate the net energy demand of the community of Abbenhausen considering its total local generation and consumption.
$E_{PCC,im}$	Measured energy import at PCC, i.e., energy flow from MV grid into LV grid).
$E_{PCC,ex}$	Measured energy export at PCC, i.e., energy flow from LV grid into MV grid).
$E_{F,PCC,ex}$	Forecasted energy export at PCC, i.e., energy flow from LV grid into MV grid).
$E_{C,PCC,ex}$	Computed energy export at PCC, i.e., energy flow from LV grid into MV grid).
$E_{F,PCC,im}$	Forecasted energy import at PCC, i.e., energy flow from MV grid into LV grid).
$E_{C,PCC,im}$	Computed energy import at PCC, i.e., energy flow from MV grid into LV grid).
$E_{ave,ex}$	Average exported energy at PCC (measured, forecasted or computed)
E_{ave}	Average exchanged energy at PCC (measured, forecasted or computed)
$P_{C,\ PCC}$	Active Power Measured at PCC The data are measured in kilowatt (kW) on the LV busbar of the MV/LV feeder. The values indicate the net load demand of the community of Abbenhausen considering its total local generation and consumption.
P_{CBES}	Active Charging/Discharging Power of CBES The data are measured in kilowatt (kW) on the CBES grid connection point. The values indicate the load demand of the CBES (charging power + system requirements) P'_{CBES} - Setpoint for CBES charging or discharging P_{CBES} - Measured value

$P_{F,PCC}$	Forecast of Active Power Exchange at PCC The data are computed in kilowatt (kW). The value indicates the net load demand of the community of Abbenhausen considering its total local generation and consumption.
P_{peak}	Peak Power It is a measured value that indicates the maximum power value in a given time period during an UCs is activated.
$P_{peak,c}$	Computed Peak Power. The value indicates the computed maximum power value that would have been measured, if no UC would have been applied (baseline). The value is only relevant for periods at which a UC control is active.
UC_{st}	UC Start Time
UC_{end}	UC End Time
BW_{st}	Bulk Window Start Time
BW_{end}	Bulk Window End Time
SOC	State of Charge

3. Demonstrator Setup

During the project, Avacon has built up an extensive demonstrator for UC testing in an evironment that reflects characteristics of rural PV driven distribution grids. The field test setup illustrated in Figure 1 involves an LV grid of the community Abbenhausen (Twistringen), an EMS (ALF-C), a smart secondary substation with a Phasor Measurement Unit (PMU), a large scaled Community Battery Energy Storage system and resident customers with rooftop PV systems and household battery energy storage systems (HBES) acquired and technically integrated in the local EMS.

The following chapter gives an overview of technical characteristics of the systems and actors that have been implemented in the German demonstrator for UC testing in the field.

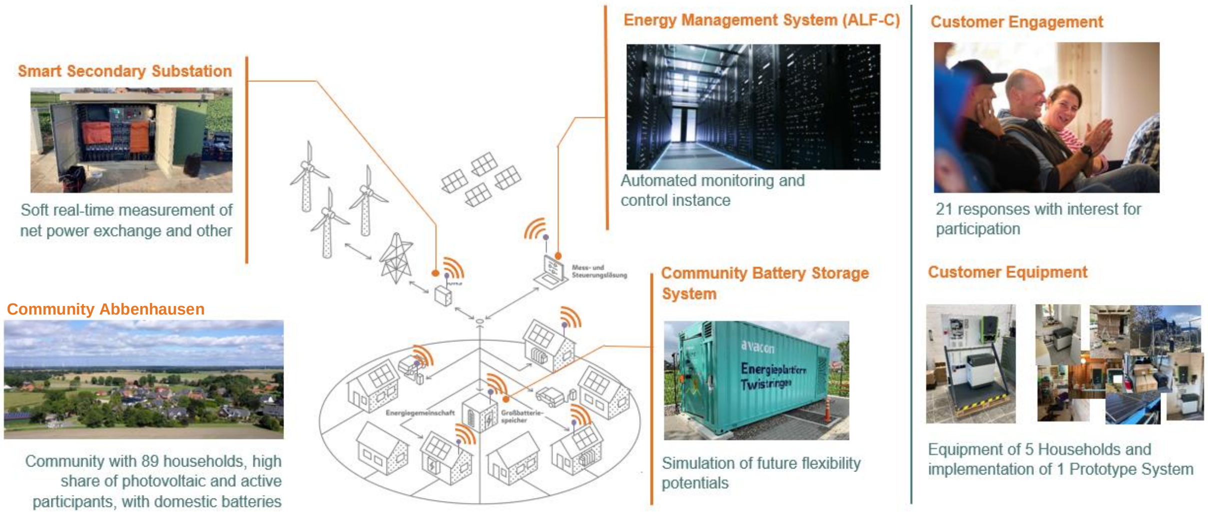

Figure 1: Overview of the field test setup of the German demonstrator.

3.1. Energy Management System (ALF-C)

The Avacon Local Flex Controller (ALF-C) is an EMS that was developed and implemented during the Platone Project for the deployment of distribution grid services in LV grids. The system is the Key Exploitable Result (KER) of the German demonstrator. It provides different functionalities and uses services provided by the Distribution System Operator Technical Platform (DSO TP) to implement different UCs relevant to DSO, TSO, market participants or communities (REC). The EMS provides basic SCADA and ADMS capabilities and functionalities to monitor generation and consumption, the grid state and is able to forecast generation, consumption and residual load and energy demand of a community. It balances the local generation and consumption based on different control approaches (rule-based control, schedule-based control with forecast and optimization) with direct control of flexibilities in LV grid levels of any type, such as CBES and HBESs in the demonstrator in response to violations of technical grid constraints or even external market signals.

The basic concept of the ALF-C foresees a decentral management scheme, to be operated in the edge, e.g., secondary substation or any other location outside of a central operated grid control system of the DSO. In the German demonstrator the prototype system has been implemented in a MS Azure environment and fully integrated in the Platone Open Framework. Some services relevant for the UCs are partly implemented in PowerApps in MS Azure. Other services are enabled by the Platone Open Framework following the updated architecture specification and functional requirements described in D2.2 [14], as well the interoperability mechanisms reported in D2.9 [15], D2.10 [16] and D2.16 [17].

Services relevant for UC implementation enabled by DSO TP are load profile-based forecasting and microgrid flexibility management. The DSO TP offers a variety of additional services such as data storage and visualization services to improve observation of the grid status. Services can be accessed by well-defined interfaces, in case of the German demonstrator REST API and individually used by transmitting .json data. Further, measured data generated by the PMU in the secondary substation are provided through the Blockchain Access Layer.

The Platone Blockchain Access Layer (BAL) developed by ENG in WP 2 has been installed on premises of Avacon. The BAL consists of the Platone Blockchain access Platform (BAP) and the Platone Shared Customer Database (SCD). The BAP utilizes blockchain technology through smart contracts and offers an interface for the integration of the data coming from the physical infrastructure. The SCD comprises all measurements, setpoints and other necessary data collected from customer's physical infrastructure. It provides easy access to data for other components and stakeholders of the Platone Open Framework while ensuring security and privacy are not compromised.

In the German Demonstrator both components have been implemented and tested successfully with a Phasor Measurement Unit (PMU) implemented in the secondary substation to provide high resolution data to monitor the load demand of the LV community Abbenhausen (Twistringen). Figure 2 illustrates the architecture of the German demonstrator.

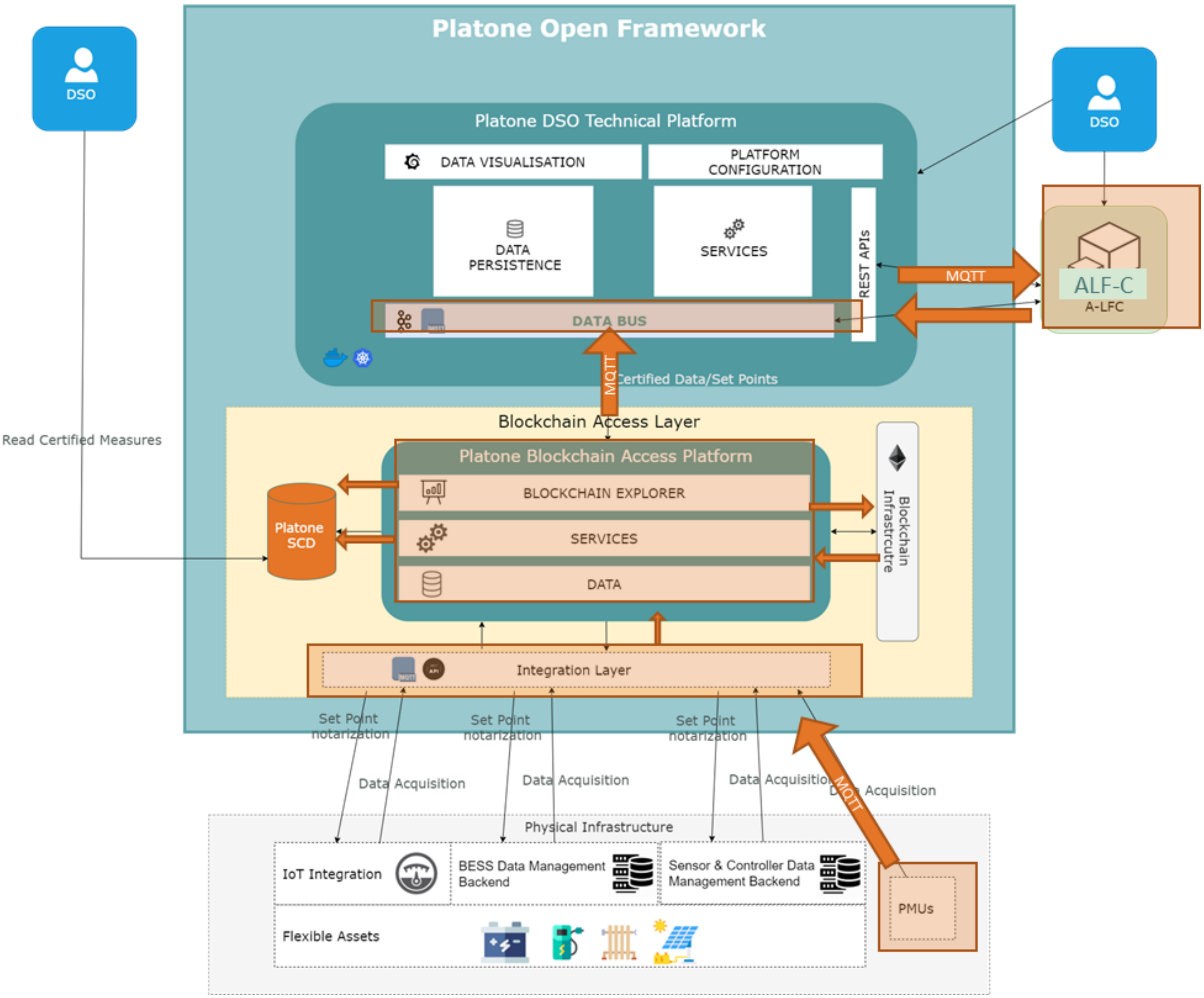

Figure 2: Platone Open Framework architecture (v3)

The ALF-C implements basic features for the DSO to enable following functions in low voltage grids and/or communities:

- monitoring of soft real-time generation and/or demand,
- forecasting of generation and demand, residual net-load demand,
- apply a local balancing based on different control approaches for batteries and
- coordinate flexibility activation with centralized grid management systems.
-

Table 2 gives an overview of different control approaches per UC and relevant parameters for setting and Figure 3 illustrates the user interface for UC parameterization of the ALF-C.

Table 2: Overview of UC control approaches and parameter for setting

UC	Control approach	Possible input data and parameters for setup
1	1.0 Rule-Based Control	None*
	1.1 Schedule-Based Control	None*
	1.2.0 Schedule-Based Control with Optimized Schedule (24h)	None*
	1.2.1 Schedule-Based Control with final SOC	State of Charge of CBES by UC end
	1.2.2 Schedule-Based / Implicit	
2	2.0 Rule-Based Control	User-Flex Demand, Priority*
3 and 4	3.0 / 4.0 Rule-Based Control	Bulk Delivery Start Time, Bulk Delivery End Time
	3.2.1 / 4.2.1 Schedule-Based Control with final SOC	Bulk Delivery Start Time, Bulk Delivery End Time, Bulk Energy (kWh), Final State of Flexibility (%)
	3.2.2 / 4.2.2 Schedule-Based Control / Implicit	Bulk Delivery Start Time, Bulk Delivery End Time, Bulk Energy (kWh)

A user interface (UI) has been implemented to enable the UC operator to parameterize UCs, see Figure 3.

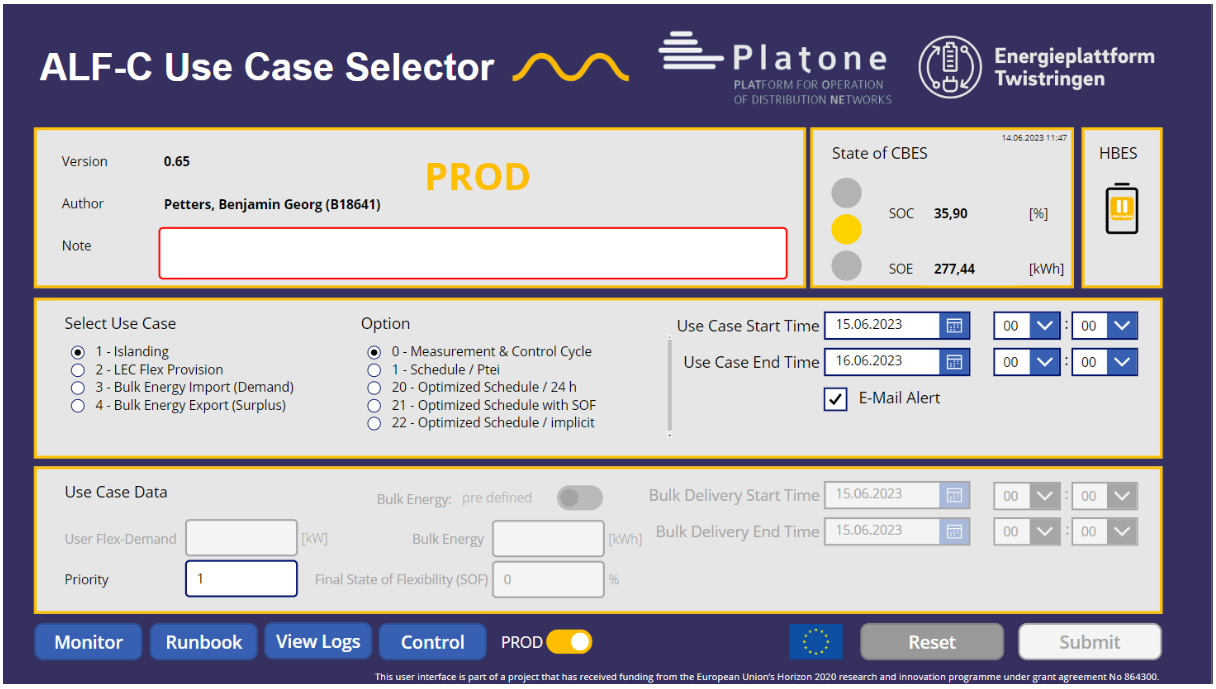

Figure 3: User interface for UC setting

Figure 4 gives and an overview of the modular structure and indicates, which services relevant for the implementation of UCs are hosted by the DSO TP and the ALF-C in Avacon's MS Azure environment.

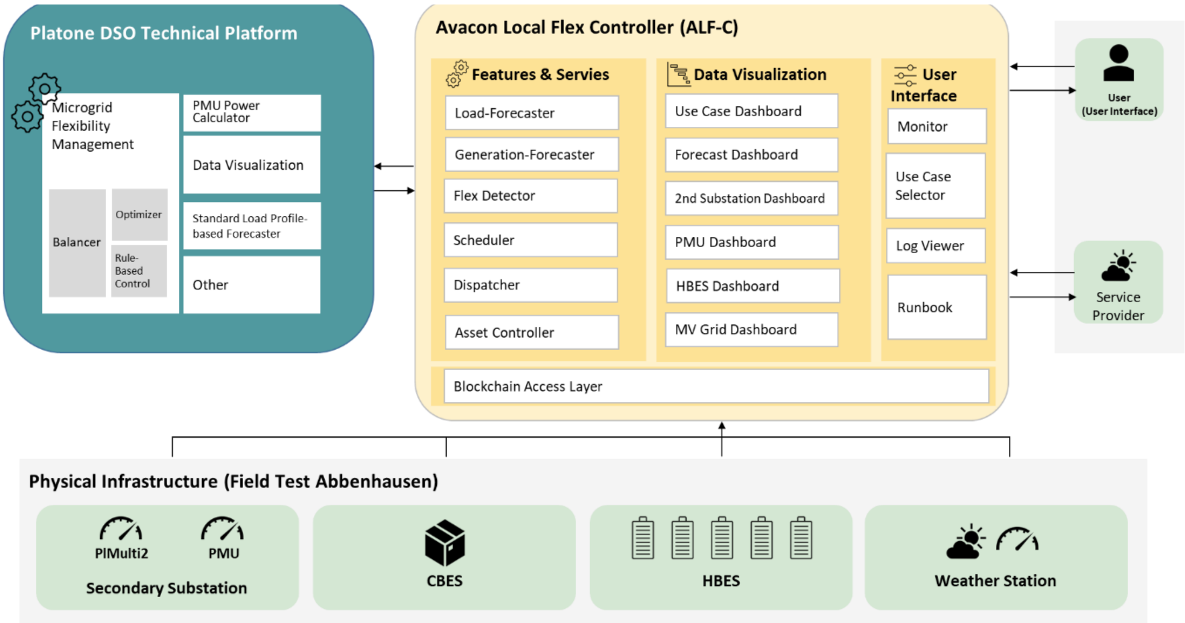

Figure 4: Overview of relevant actors and the modular structure of ALF-C.

ALF-C consists of 3 layers. One layer enables the features that are used to perform UCs. This layer is in interaction with the Platone DSO Technical Platform and uses its services. The second layer enables data visualisation. With this layer the operator, in this case Avacon, is able to see the measured effects of the control algorithms. The third layer enables the user to operate the features and data visualisation services of the ALF-C. For a straightforward application the user interface enables the user to trigger UCs with no restricting settings.

3.2. Field Test Site

The field test area is located in Abbenhausen, a small village in the federal state of Lower Saxony. The community consists of about 60 single-family detached houses that host about 89 households. About 23 houses are equipped with roof-top photovoltaic systems. Furthermore, the community consists of 5 agricultural buildings. All households, buildings and PV generators of Abbenhausen are connected to a single LV network. The LV network of Abbenhausen is connected by a single MV/LV transformer, located in a smart secondary substation to the MV grid. For the field test, the substation was equipped with sensors on its busbars and the measurements, e.g., active power $P_{\mathrm{M,\ PCC}}$, are sent to a cloud database.

The community is representative for future communities in distribution grids operated by Avacon as it:

1.) is located in a rural area with high share of renewable generation in all voltage levels (HV, MV and LV),

2.) is characterized by a high share of households owning a roof-top photovoltaic systems,

3.) hosts households using battery energy storage systems increasing PV self-consumption.

4.) displays increasing share of sector coupling technologies using electric energy for generating heat, e.g., heat pumps.

Figure 5 displays a picture of the community Abbenhausen selected for the field test trial of the demonstrator. Deliverable D5.3. provides an overview of relevant actors and components of the demonstrator [5]. However, after the provision of the demonstration report on UC 1 and UC 2, technical properties of the field test setup relevant for UC evaluation have changed and are described in subchapter 3.2.1 and 3.3.

Figure 5: Picture of the community Abbenhausen (Twistringen) selected as field test region

3.2.1. Residential Roof-Top Photovoltaic Systems

The community of Abbenhausen is characterized by a high share of residential customers with roof-top photovoltaics system, see Figure 6. The generated electricity is primary used for self-consumption by operating a household battery system (HBES) in combination with the PV system. The surplus of generation is fed into the grid which effects the load flow in the LV and MV grids. Furthermore, the installed generation capacity has changed during the field test phase, following the trend towards a steady increase of PV systems observed in the grid service area of Avacon.

Figure 6: Residential roof top PV systems in Abbenhausen (Twistringen)

As a consequence of the political developments starting in 2022, the resulting energy crisis and the commitment of the German Federal Government to promote more strongly the expansion of renewable energies, the demand in private sector for technologies improving self-consumption and the degree of self-sufficiency has been increasing. In the grid service area of Avacon Netz, a rising demand for grid connection of residential PV systems has been observed in the past years. Also in the field test area, the installed capacity of PV systems has increased during the demonstration phase. This increase is primarily caused by household owners actively participating in the demonstrator and building PV systems on their roof tops to take part in the project. Table 3 summarizes the changes of the installed PV generation capacity during the demonstrator phase.

Table 3: Development of installed PV generation capacity during the demonstration phase

	Beginning of the field test phase (March 2021)	**Date of UC 3 and 4 Demonstration Report 12. June 2023**
PV Installed Generation Capacity	410 kWp	445 kWp
Number of roof-top photovoltaic systems	26	30

3.2.2. Smart Secondary Substation

The smart secondary substation, owned and operated by Avacon, accommodates a variable-frequency transformer that connects the community to the MV grid. The community is fed with energy from this single point. The substation is equipped with two measurement devices, each with a separate communication device. Measurement device 1 (right corner of Figure 2) is a PLMulti II, a standard measurement component, that is pre-installed in this type of substation. Measurement device 2 is a PMU, developed by RWTH Aachen. This device is installed in the top left corner, shown in Figure 2.

Figure 7: Smart secondary substation – low-voltage connection to bus bar

Measurement Device 1 - PLMulti II

The PLMulti II is a digital panel measuring device connected to the busbar. The device has up to 12 measuring channels for current measurement and 4 measuring channels for voltage measurement (L1, L2, L3, N). It is used especially for the efficient and cost-effective monitoring and evaluation of electrical systems. The PLMulti II is especially designed for measurements in low-voltage distributions grids. An advantage of this device is the independent measurement of up to 3 three-phase or up to 12 single-phase measurements. The measurement data is stored on an exchangeable SDHC memory card as a table. Additionally, this device provides an integrated Modbus RTU interface for remote read out, which is used in this demonstrator. The extreme minimum and maximum values as well as the accumulated meter reading of the energy meter are also permanently saved in the internal EEPROM memory of the device and can be displayed. The device fulfils DIN 43700. It provides real-time and mean measurement data. The sensors, voltage and current dividers are located at the low-voltage bus bar. The device is a standard communication component, that is installed ex work in the used type of secondary substation.

Measurement Device 2 – PMU

The Phasor Measurement Unit is made for monitoring applications in distribution grids. The device was developed by RWTH Aachen. It is designed for a cost-efficient scalability in medium and low-voltage grids. The core component is a Raspberry PI (RPI) 3. It includes the communication libraries libiec61850 1 to send and receive data messages in Sampled Value format, according to the standard IEC 61850-90-5, and the code to acquire the samples and calculate the synchro phasor, frequency and ROCOF.

The RWTH Aachen has developed a software library with a set of algorithms to calculate synchro phasors, frequency and ROCOF. The calculation of active/reactive power can also be done in addition. The measurements are then encapsulated in the Sampled Value (SV) messages and later into UDP-IP packets, as recommended by the IEC 61850-90-5 standard for PMUs. The RPI runs the operative system Raspbian, which can operate the open-source libraries libiec6850 for applying the IEC 61850 standard. The messages are also sent via Open VPN to ensure encryption and authentication features. Another possible implementation is performed via MQTT, where the PMUs act as clients communicating measurements to a broker (an MQTT server) that collects the data. The LOCO PMU can exchange measurements via Ethernet, WIFI and wireless adapters such as 3G/4G modem devices. The choice of components of the PMU, its assembling, testing and installation has been refined and upgraded with support of Avacon's vocational training unit in order to conform industry standards for a safe and reliable operation in the field.

Figure 8: PLMulti II - measurement device

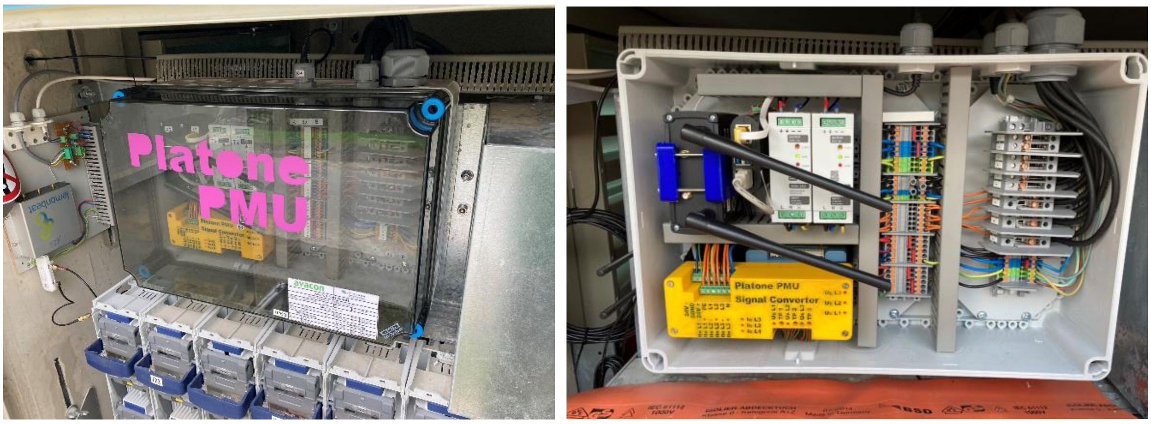

Figure 9: Phasor measurement unit with LTE communication device

3.3. Flexibility in the Field Test

3.3.1. Community Battery Storage System

The CBES shown in Figure 10 is a large-scale battery energy storage system based on lithium nickel manganese cobalt oxid (NMC) technology. The storage provides storage capacity and flexible power for the application of UCs and testing of the EMS (ALF-C) features. In an aggregated manner considering the storage capacity, the CBES simulates storage potentials provided by future residential household batteries and electric vehicles that provide bi-directional power through charging and discharging. Technical properties of the CBES have changed during the project duration affecting the usable storage capacity. The maximum state of energy (SOE) at a stage of charge (SOC) of 100 % was equal to 850 kWh at the point of time of delivery. However, after 3 years, the usable (net) capacity and the corresponding SOE (SOC = 100%) equals 774,5 kWh.

Figure 11 shows the CBES as a system integrated into a 20-foot container. The system is divided into 2 separated rooms, one battery cell room and a "dirt room" that houses a transformer and technology for cooling and heating.

Figure 10: CBES in the field test site Abbenhausen (Twistringen)

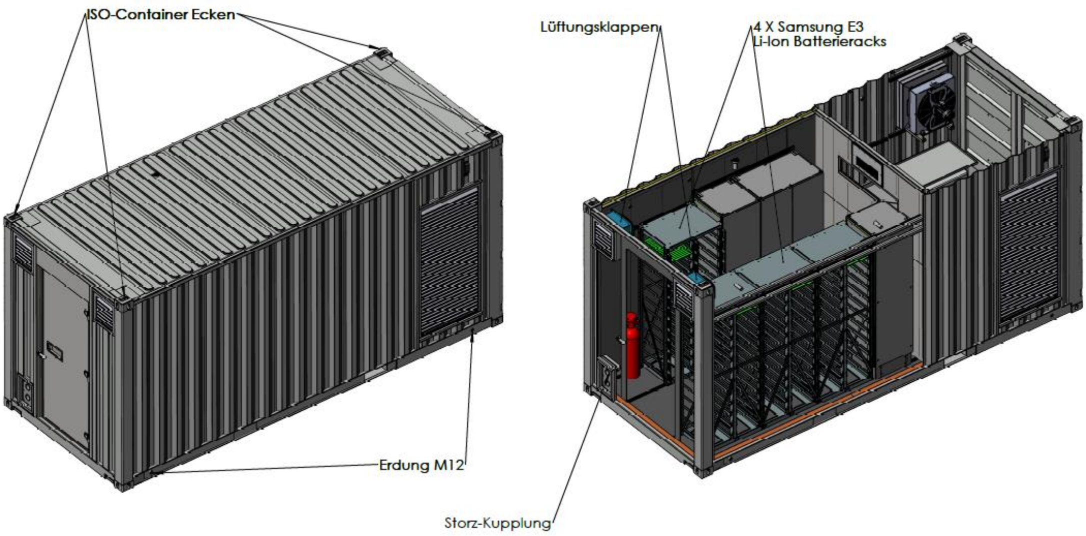

Figure 11: CBES - schematic sketch

3.3.2. Household Battery Energy Storage System (HBES)

In the demonstrator field trial, 5 households are equipped with a HBES to participate in the project and provide one directional flexibility. Each HBES is operated in combination with a roof-top PV system and are primary used for the increase of PV self-consumptions. During the field test phase, HBESs steering is limited to the interruption of battery charging to be in line with the current regulation and legislation which is set in §14a of the Energiewirtschaftsgesetz (EnWG) [18]. Due to ongoing regulation and legislation, the flexibility that can be provided by a HBES operated with a PV-system is limited to the interruption of load demand used for HBES charging. In this context, the load demand of HBES for charging can be interrupted. Since the EMS of the PV system only charges HBES during times of PV generation, for project intentions the HBES can only be interrupted during times of PV generation. Table 4 gives an overview of the technical properties of the HBESs that have been implemented in the demonstrator. HBESs implemented in the field and a HBES prototype are illustrated in Figure 12.

Table 4: Overview of HBESs located at customer premises

	Alias	HBES Storage Capacity (kWh)	HBES Max Charging Power (kW)
Customer 1	Einstein	7,7	4
Customer 2	Pascal	7,7	4
Customer 3	Tesla	5,2	2,7
Customer 4	Kelvin	5,2	2,7
Customer 5	Heisenberg	5,2	2,7

Figure 12: Residential HBES system and HBES system prototype

4. KPI Results

This chapter is dedicated to UC performance analysis based on the defined KPIs. In subchapter 4.1, a second round of KPI analysis for KPI_DE_01 “Reduction of of Energy Exchange” and KPI_DE_02 “Reduction of Power Peaks” is performed for UC 1 with RTO and SBO modes. Subchapter 4.2 summarizes and consolidates the results of KPI analysis provided in previous deliverables of WP 5 [1] [2] and [3] for a final evaluation.

4.1. KPI Results of UC 1.0 and 1.1

A first evaluation of UC 1.0 has been evaluated in Deliverable 5.4 [1]. After the submission of the demonstration report, additional testing of UC 1.0 and first applications of UC 1.1 have been performed. The control logics of UC 1.0 and UC 1.1 are described in subchapter 2.5. The results of both UC 1 versions are evaluated and compared in this section.

The performance analysis of the balancing algorithms is based on 35 and 53 test days featuring PV generation for UC 1.0 and 1.1, respectively. The tests were conducted to cover various weather conditions, i.e., PV generation scenarios. Each test day starts at midnight and runs for 24 hours. All $P_{M,PCC}$ - and P_{CBES} measurements are aggregated to 15-minute mean values.

The performance of UC 1.0 and UC 1.1 are evaluated separately by comparing the respective changes in exported and imported energies as well as export and import power peaks. The change of each quantity $\Delta\varphi$, e.g., export energy, is computed by taking the difference between the quantity φ_m measured during the test and the computed value of this quantity if no test had been conducted, φ_c:

$$\Delta\varphi = \varphi_m - \varphi_c \,.$$

To evaluate the significance of each change and to aid comparison between both modes of control, the difference $\Delta\varphi$ is further normalised by the average value of the quantity itself, φ_{ave} for UC 1.0 and UC 1.1 respectively, defining the relative change $\Delta\varphi_r$:

$$\Delta\varphi_r = \frac{\Delta\varphi}{\varphi_{ave}}.$$

The test days in all upcoming figures are sorted in descending order by their change of export energy. Test day numbers are kept consistent across all figures for UC 1.0 and UC 1.1. The limits of the y-axis are identical for each quantity to aid comparison between both UC operation modes.

4.1.1. KPI_DE_01 – Reduction of Energy Exchange along MV feeder

KPI Calculation

The performance of UC_DE_01 is evaluated by comparing the respective changes in exported and imported energy for both UC 1 versions presented in subchapter 2.1, UC1.0 and UC1.1. The change of each quantity $\Delta\mathrm{E}$, e.g., export energy, is computed by taking the difference between the quantity E_m measured during the test and a baseline, E_c,:

$$\Delta\mathrm{E} = \mathrm{E}m - \mathrm{E}c$$

The baseline, E_c, describes the energy exchange at PCC if no UC with UC 1.0 and UC 1.1 would have been applied. It is a computed value by applying following equation for each 15-minute interval, i, of a 24-hour period (96 intervals) for each day:

$$\mathrm{E}_{c,\mathrm{i}} = (P_{M,PCC,i} - P_{CBES,i}) * \ 0{,}25\ hours$$

Where $P_{M,PCC}$ and P_{CBES} are measured 15-minute mean active power values at PCC and the charging power of CBES, respectively.

E_m is computed for every time interval with the equation:

$$\mathrm{E}_\mathrm{m} = \sum_{i=1}^{96}(P_{M,PCC,i}) * 0{,}25\ hours$$

To evaluate the significance of each change, and to aid comparison between both algorithms, the difference $\Delta\mathrm{E}$ is further normalised by the average value of the quantity itself, E_ave for UC 1.0 and UC 1.1 respectively, defining the relative change $\Delta\mathrm{E}_\mathrm{r}$:

$$\Delta\mathrm{E}_\mathrm{r} = \frac{\Delta\mathrm{E}}{E_{ave}}$$

The KPI has been computed for energy import and export for UC 1.0 and 1.1 and SBO control approach respectively. Here n is the number of test days for each respective UC.

$$E_{ave} = \frac{1}{n}\left(\sum_{i=1}^{n} E_i\right)$$

Energy Export Reduction

Figure 13 shows the relative change in energy exported, $\Delta E_{\mathrm{r,ex}}$, from the community to the MV grid when using UC 1.0. As previously defined, export of energy, E_{ex}, is denoted with a negative sign. Thus, positive values of ΔE denote a reduction of energy export, E_{ex}. The UC 1.0 reduces energy export for all but one test day. The average reduction is 48% of $E_{\mathrm{ave,ex}}$ with a maximum of 112%.

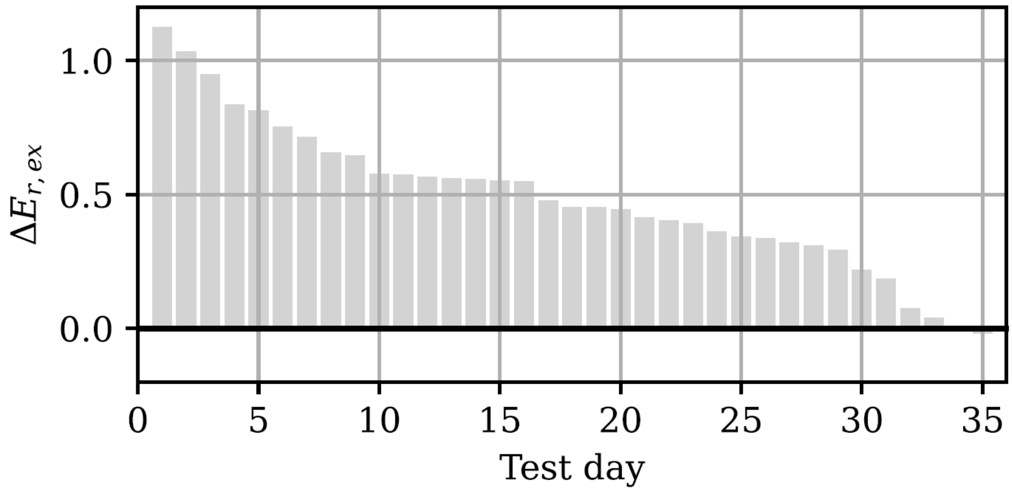

Figure 13: Energy export reduction for UC 1.0

Figure 14 shows $\Delta E_{r,ex}$ when executing UC 1.0. Energy reduction is achieved for all but three test days. Mean reduction is only 32% and maximum reduction at 77% is significantly lower than for the UC 1.0. The explanation for this difference is a bias in the UC 1.1 test days towards winter and early spring days with less solar generation, i.e., less energy export reduction potential. This must be considered when comparing UC 1.0 and UC 1.1 performance. This bias could be removed in future analysis by simulating the behaviour of the algorithms on historic time series of P_c and using the actual field test measurements for validation of the results. This would further allow direct performance comparison between UC 1.0 and UC 1.1..

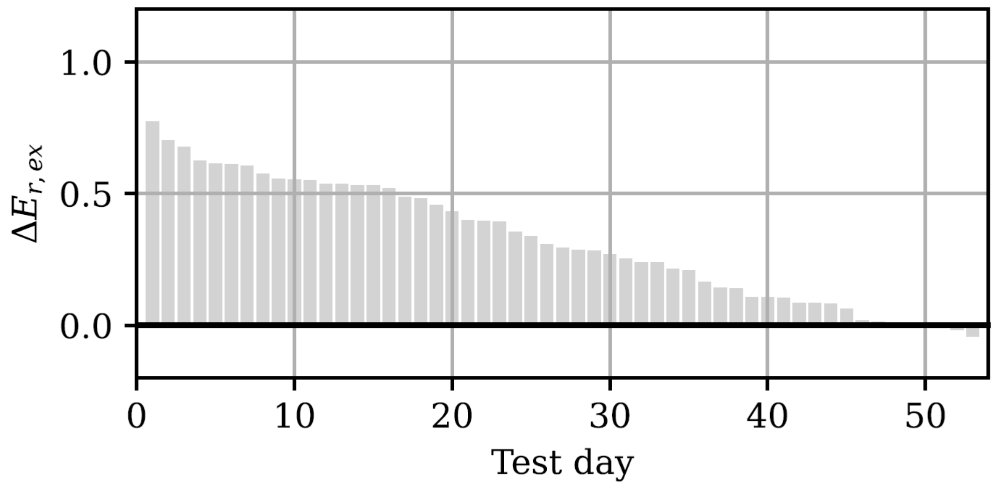

Figure 14: Energy export reduction for UC 1.0

Energy Import Reduction

Figure 15 shows the relative change in energy imported, $\Delta E_{r,im}$. Negative values denote an improvement, i.e., reduction of energy imported, E_i. UC 1.0 reduces energy import on all test days except test day no. 34. The average reduction is 53% and its variation is spread evenly across all test days. Figure 15 shows $\Delta E_{r,im}$ when executing UC 1.1. A reduction is achieved on many test days with signification deteriorations on some test days where only a low reduction of energy export was achieved. The average reduction is just 28%. This is likely caused by an overestimation of PV generation in the forecast, causing the CBES to charge itself with energy from the MV grid instead, thus increasing energy import. Test day no. 44 has the highest increase and will be discussed in detail later.

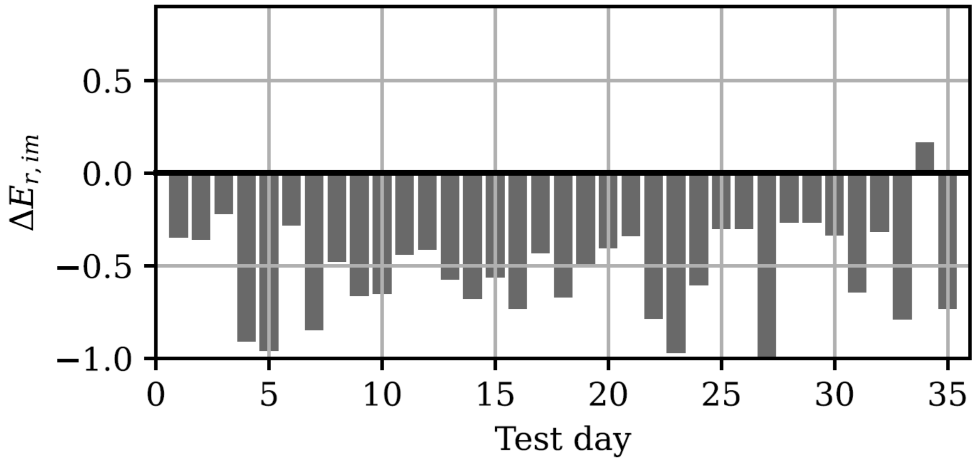

Figure 15: Energy import reduction for UC 1.0

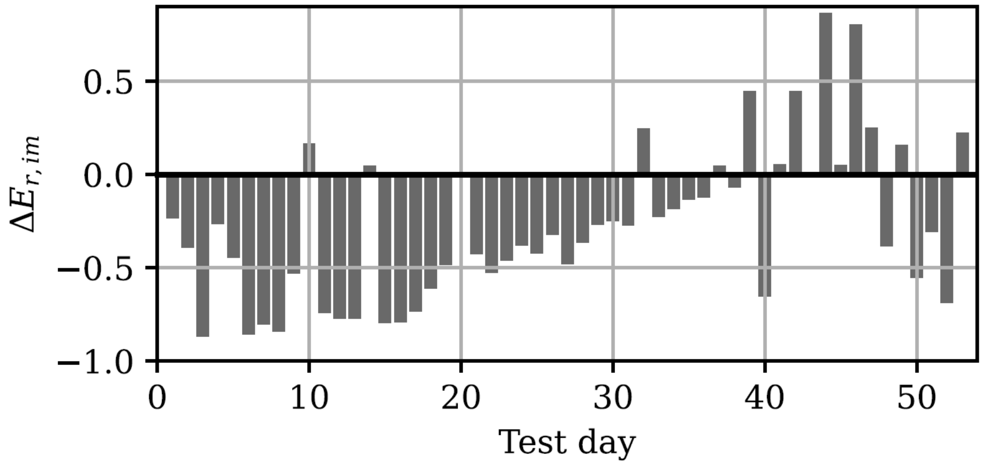

Figure 16: Energy import reduction for UC 1.1

4.1.2. KPI_DE_02 – Reduction of Power Peaks

KPI Calculation

The KPI computes the mean value of the relative change in power peak for export and import, $\Delta P_{p,r,ex}$ and $\Delta P_{p,r,im}$, for a 24-hour interval for all testing days. Being an export quantity, positive values denote a reduction of export power peak, $P_{p,ex}$. The power peak mean value for each testing day is computed with the formular:

$$\Delta P_{p,r} = \frac{1}{96}\left(\sum_{i=1}^{96} \frac{|P|_{C,PCC,peak,i} - |P|_{M,PCC,peak,i}}{|P|_{C,PCC,peak,i}} * 100\right)$$

Where:

$|P|_{C,PCC,peak,i}$ is the absolute value of the computed power peak at PCC of the 15-minute interval i. The value indicates the baseline.

$|P|_{M,PCC,peak,o}$ is the absolute value of the measured power peak at PCC of the 15-minute interval i.

Export Power Peak Reduction

Figure 17 shows the relative change in export power peak, $\Delta P_{p,r,ex}$. Being an export quantity, positive values denote a reduction of export power peak, $P_{p,ex}$. The reduction of export power peaks, $\Delta P_{p,r,ex}$, is distributed independent of energy export reduction with an average reduction of 19%. Test day no. 4 in Figure 17— which has almost no export peak reduction despite a large export energy reduction—will be discussed in detail later. Figure 18 shows $\Delta P_{p,r,ex}$ when executing UC 1.1. The average reduction of 43% is larger compared to the UC 1.0. Thus, by taking the complete day ahead net active power forecast into consideration, UC 1.1 is better compared to UC 1.0 as the SBO finds the optimum schedule for CBES to control taking into account the whole timeseries of a day ahead forecast of P_{PCC} and not only single values of a measured value of P_{PCC}, i.e. $P_{M,PCC}$. An optimum solution is achieved avowing high peaks more effectively compared to UC 1.0 in which the flex thresholds are achieved earlier without the consideration of a horizon for decision making. Obviously, the accuracy of forecast profile is significant for UC1.0 to find the optimum schedule.

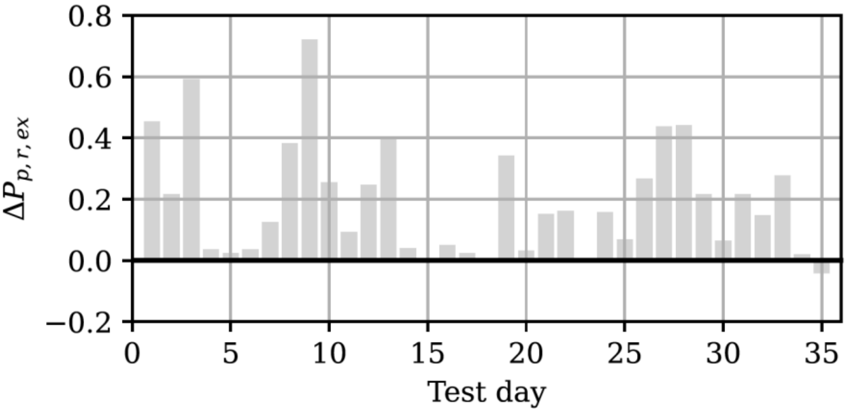

Figure 17: Export power peak reduction for UC 1.0

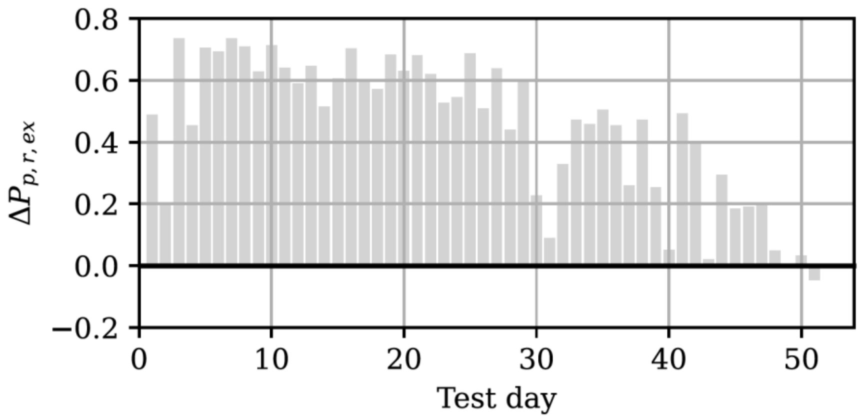

Figure 18: Export power peak reduction for UC 1.1

Import Power Peak Reduction

Figure 19 shows the relative change in import power peak, $\Delta P_{p,r,im}$. Being an import quantity, negative values denote a reduction of $P_{p,im}$. On average, there is an increase of the import power peak by 39% with a maximum increase of 200%. As a detailed discussion of test day no. 19 will show, this is caused by unsteady PV generation due to moving cloud coverage. Figure 20 shows $\Delta P_{p,r,im}$ when executing the SBO. Like the UC 1.0, $P_{p,im}$ was increased by 40% on average.
This increase is likely the result of overpredicting PV generation, which causes the CBES to store more electricity than generated locally, thus charging the CBES from the MV grid. A more detailed analysis would require a disaggregation of $P_{M,\ PCC}$ and $P_{C,\ PCC}$ at the PCC into consumption and generation to calibrate more accurate consumption profiles as well as analysing the PV generation forecast accuracy in more detail.

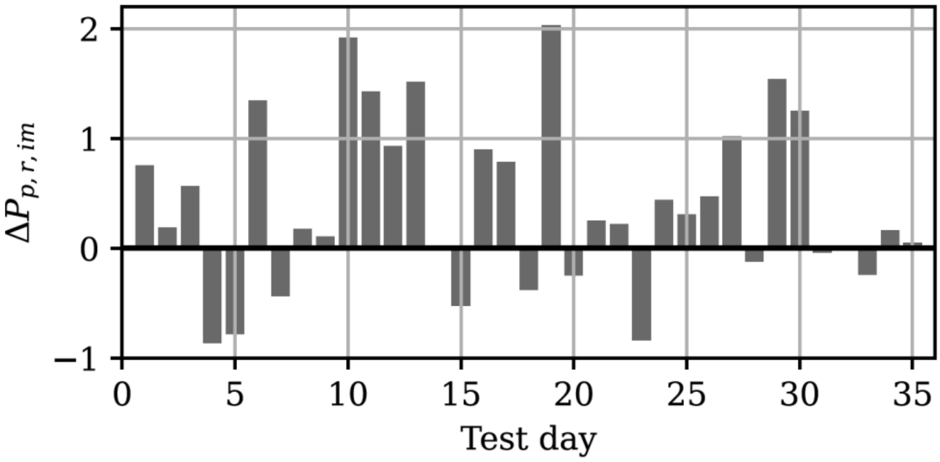

Figure 19: Export power peak reduction for UC 1.0

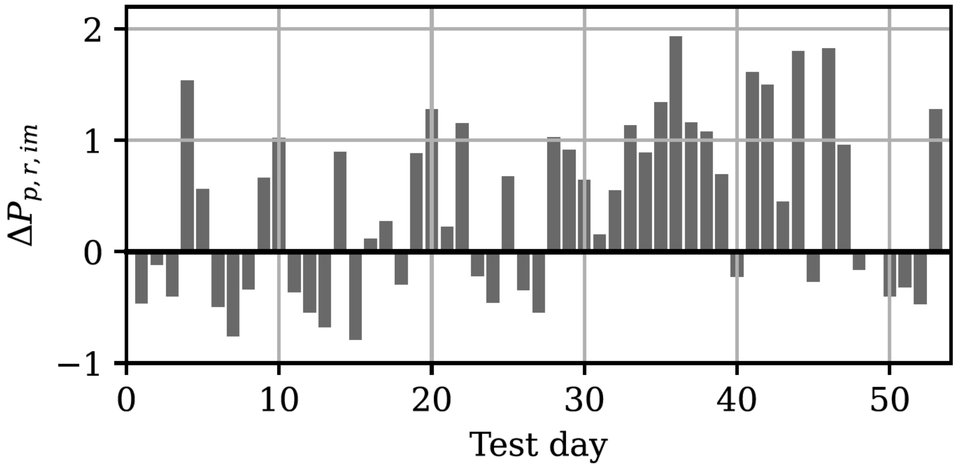

Figure 20: Import power peak reduction for UC 1.1

4.1.3. Discussion on results

It should be first mentioned that the evaluation of bothversions of UC1 is based on different test datasets. This is basically due the limitation associated with the operation of the grid which allows for only one-at-a-time implementation of UCs. This limitation leads to different sizes of datasets with the corresponding different times and weather conditions.. Therefore, the comparison provided in subchapter 4.1 is not fully free of discrimination However, the aim of the demonstrator is not to evaluate UC performance in an artificial environment, e.g., simulation, but rather in the operational grid business. Therefore, keeping in mind the above-mentioned limitation and consideration, it has been tried to analyse the performance of UC1 in as much as possible indiscriminate way but at the same time in real grid operational scenarios to capture the effect of all factors that can potentially impact the performance of UC1.

On the bright side, the results presented in subchapter 4.1.1 and 4.1.2 showed that both, UC 1.0 and UC 1.1, achieve a significant reduction of energy exchange at PCC on almost all testing days. This was specially recognized for the reduction in the amount of exported power and energy of the community which is of great importance for the field trial equipped with large amount of PV installations and the corresponding considerable PV feed-ins. In a nutshell, it can be definitely stated that the PV-self-consumption within the community was increased significantly according to the obtained results. However and for a few days, UC 1 performance displays some increasing energy exchange at PCC (and mainly in form of power imports)

In light of the above-mentioned facts, the following paragraphs will delve into the factors that negatively impact the performance of UC1 and hinder the full potential release of the developed solutions. For a detailed discussion of the underperformance of both UC versions, three test days are selected. Each test day is represented by two power curves for its 24-hour test run divided into 15-minute intervals. The measured power, when executing the UC 1.0 or UC 1.1, $P_{\mathrm{M,\,PCC}}$, and the computed power exchange at PCC if UCs would not have been applied, $P_{\mathrm{C,\,PCC}}$. Power values are normalised with respective UC 1.0 or UC 1.1 mean export power, $P_{\mathrm{ave,ex}}$, giving P_{r}.

<u>CBES Storage Limits (UC 1.0)</u> – Test day no. 4 of UC 1.0 shows great performance on power peak and energy exchange reduction. Figure 21, $P_{\mathrm{C,\,PCC}}$ illustrates that this day was clear and sunny with large PV generation. UC 1.0 balances consumption and generation with CBES control until noon. At noon, during peak export power, the CBES is fully charged already and balancing halts—halfway through peak generation. Once energy consumption exceeds local generation again, ALF-C balances power by discharging energy from the CBES. A CBES with more storage capacity would improve UC 1.0 performance, but this might not always be technically or economically viable. Alternatively, starting the UC with a lower SOC can improve the performance of UC 1.0.

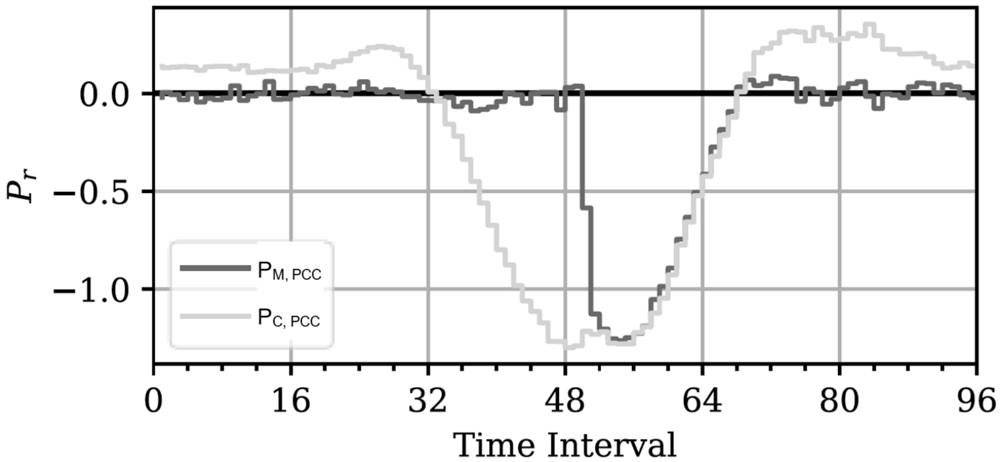

Figure 21: Relative power on test day no. 4 (UC 1.0)

On this day, UC 1.1 applying optimization on a day ahead forecast would have likely yielded a better result. Alternatively, instead of aiming zero power exchange at PCC, UC 1.0 could be configured to achieve a higher threshold at PCC. Then, charging of CBES is triggered only once this new threshold is exceeded and not before that. Thus, CBES control would only be active during phases of large PV generation, requiring less storage capacity of the CBES. This example also illustrates that during summer days the CBES should be discharged purposely during night-time hours for a maximum of flexibility during daytime.

Unsteady Weather (UC 1.0) - Test day no. 19 of UC 1.0 shows moderate improvement, but a significant increase of the import power peak. In Figure 22, $P_{M,\ PCC}$ indicates that this day featured moving clouds periodically covering the sun, i.e., reducing PV generation.

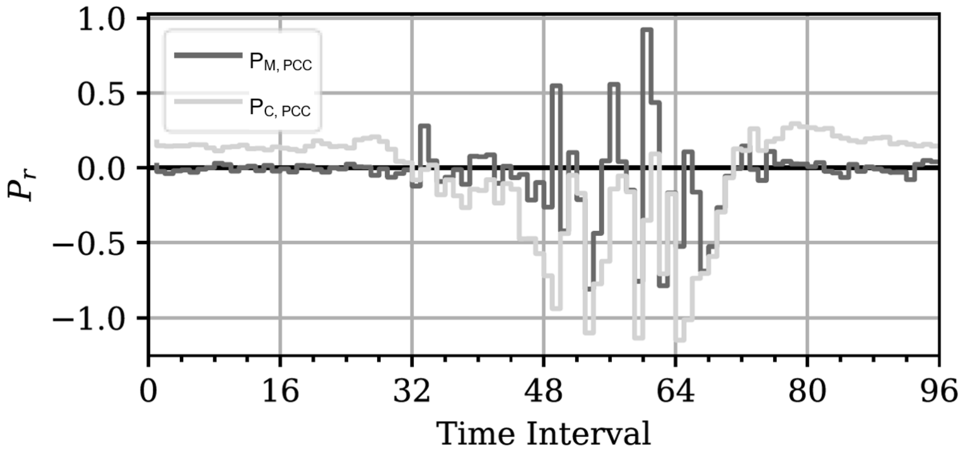

Figure 22: Relative power on test day no.19 (UC 1.0)

For this test day, the value of $P_{C,\ PCC}$ was computed to illustrate the baseline. $P_{M,\ PCC}$ illustrated the measured results after UC 1.0 application. The curves of $P_{C,\ PCC}$ and $P_{M,\ PCC}$ indicates that during phases of sunshine multiple times right after adaptation of CBES charging power according to the rule-based logic, clouds rolled in, reducing solar radiation. The sharp drop in PV generation resulted in the CBES charging from the MV grid instead, increasing the import power peak. In order to react to volatile PV feed-in, the measurement-and-control cycle associated with UC 1.0 could have higher frequency of the measurement-control-cycle. However, increasing the frequency from 15 minutes to higher requires a investigation considering the performance of hardware components, communication infrastructure and latency of the EMS (ALF-C) in the Platone Open Framework. See subchapter 4.2.5.

A solution to react to such unpredictable changes in PV generation would be increasing the frequency of the UC 1.0 cycle up from the current once per 15 minutes. This example further illustrates the volatility of PV generation and the steep gradients in power generation caused by moving clouds.

Inaccurate Weather Forecast (UC1.1) - Test day no. 44 of UC 1.1 set shows poor performance overall. In Figure 23, $P_{C,\ PCC}$ shows a day with very little PV generation. However, large positive values of $P_{M,\ PCC}$ highlight that the PV generation was overpredicted.

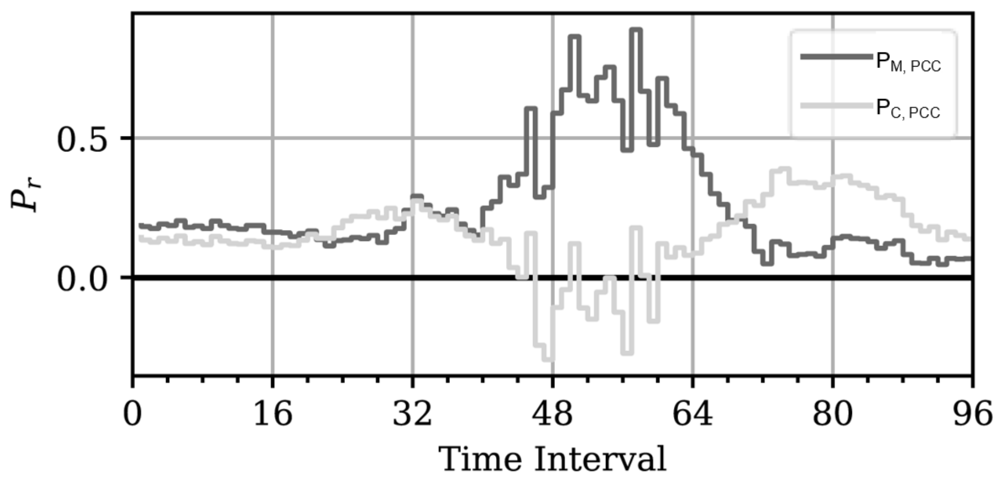

Figure 23: Relative power on test day no.4 (UC 1.0)

Lacking any feedback loop, UC 1.1 continues compensating PV generation that never materialised, thus charging the CBES via the MV grid. The UC 1.1 performance in the field could be improved by sing more accurate day-ahed forecast of P_{PCC} as input for the optimization. Another possible solution would require an extension of ALF-C that checks whether the forecast input into UC 1.1 meets reality intraday. If the forecast error is significant intraday, UC 1.1 should stop or change to UC 1.0 as the schedule is no longer optimal.

4.2. Overview of Demo KPIs

This section summarizes the KPI results that have been achieved in the German demonstrator. A consolidated summary, with additional information on KPIs computation, related objectives, baselines and data collection as well as insights are described in Deliverable 1.7 [19].

4.2.1. KPI_DE_01 – Reduction of Energy Exchange along MV Feeder

KPI_DE_01 evaluates the achieved reduction of the energy exchange along the MV/LV grid-connecting transformer during the application of UC 1 with a near real time mode of operation (UC 1.0). This KPI evaluates the ability of the developed solution to reduce the energy consumption from the feeding grid by measuring the deviation of energy consumption in times of UC DE 1 application and times UC DE 1 is not applied.

The results of KPI_DE_01 for UC 1.0 for different days and periods are summarized in Table 5**.** Testing in 2022 have been applied on different days in 2022 to include a mixed type of days (sunny, overcast and mixed days). The results of KPI_DE_01 for UC 1.0 and UC 1.1 are presented in section 4.1.1.

Table 5: KPI_DE_01 results of UC 1.0

Date/Period	Time	Duration [t]	KPI
[d/m/yyyy]	[CET]	[h]	[%]
1 / 7 / 2021	0.00 am – 01.59 am	2	88.51
1 / 7 / 2021	0.00 am – 05.59 am	6	89.86
1 / 7 / 2021	0.00 am – 11.59 am	12	81.64
1 / 7 / 2021	0.00 am – 11.59 pm	24	61.31
1 / 7 / 2021 - 2 / 7 / 2021	0.00 am – 11.59 pm	48	49.27
1 / 7 2021 - 4 / 7 / 2021	0.00 am – 11.59 pm	96	42.51
06 / 2022 – 12 / 2022	0.00 am – 23.59 pm	35 test days	Import: 53 % Export: 48 %

4.2.2. KPI_DE_02 – Reduction of Power Peaks

This KPI_DE_02 evaluates the target of UC DE 1 to minimize the power peaks of power flows along MV/LV grid-connecting transformer. This KPI determines the relative reduction or increase of the highest measured peak in a defined interval. The results of the first KPI analysis of UC 1.0 are described in D5.4. The results of this analysis are summarized in Table 6**.**

The table provides an overview of KPIs that have been evaluated for different periods during UC 1.0 application. In the table periods and times consider for the KPI evaluation are indicates. The UC was active for the hole period from June 1st, 2021, until June 4th, 2021.

Because the evaluation of the KPI in this first analysis is based on a relatively small data set from a limited number of UC 1 testing days and to have a better understanding of UC 1 performance for this KPI additional tests have been applied on different days in 2022 that include a mixed type of days (sunny, overcast and mixed days). The results of KPI_DE_02 for UC 1.1 and a comparison with UC 1.0 are presented in section 4.1.2.

Table 6: KPI_DE_02 results of UC 1.0

Date	Time	Period [t]	KPI
[d/m/yyyy]	[CET]	[h]	[%]
1 / 7 / 2021	0.00 am – 02.00 am	2	73.65
1 / 7 / 2021	0.00 am – 06.00 am	6	73.98
1 / 7 / 2021	0.00 am – 11.59 am	12	44.02
1 / 7 / 2021	0.00 am – 11.59 pm	24	32.37
1 / 7 / 2021 - 2 / 7 / 2021	0.00 am – 11.59 pm	48	36.05
1 / 7 2021 - 4 / 7 / 2021	0.00 am – 11.59 pm	96	5.78
06 / 2022 – 12 / 2022	0.00 am – 23.59 pm	35 test days	Import: 39 % Export: 19 %

4.2.3. KPI_DE_03 – Increase in Self-Consumption

The KPI_DE_03 evaluates the capability of UC DE 1 to reduce energy export from the LV grid into the MV grid. Therefore, the KPI evaluates the capability of UC 1.0 to maximize the consumption of locally generated energy by intermediate storage of generation surplus in local CBES and withdrawing energy at high load time to serve the demand. Table 7 summarizes the results of KPI_DE_03 for UC 1.0 for different days and periods. Additional information on KPI computation is provided in Deliverable 5.4 [1] and 1.7 [19].

Table 7: KPI_DE_03 results of UC 1.0

Date	Time	Duration [t]	$E_{C,TEI}$	E_{TEI}	KPI
[d/m/yyyy]	[CET]	[h]	[kWh]	[kWh]	[%]
1 / 7 / 2021	0.00 am – 02.00 am	2	0	-2.06	n.a.
1 / 7 / 2021	0.00 am – 06.00 am	6	0	-2.59	n.a.
1 / 7 / 2021	0.00 am – 11.59 am	12	-0.55	-14.0	2,434.34
1 / 7 / 2021	0.00 am – 11.59 pm	24	-162.21	-51.20	-68.44
1 / 7 / 2021 - 2 / 7 / 2021	0.00 am – 11.59 pm	48	-725.75	-222.13	-69.39
1 / 7 2021 - 4 / 7 / 2021	0.00 am – 11.59 pm	96	-2,980.11	-1,733.16	-41.84

4.2.4. KPI_DE_04 – Maximization of Islanding Duration

This KPI_DE_04 measures the ability of UC 1.0 to maximize the duration of time at which a power exchange along the MV/LC grid connection point is reduced close to zero and to energetically uncouple the LV grid from MV grid. Table 8 summarizes the results of KPI_DE_04 for UC 1.1 for selected days and periods**.** Additional information on KPI computation is provided in Deliverable 5.4 [1] and 1.7 [19].

Table 8: KPI_DE_04 results of UC 1.0

Date	**Time**	**Duration [t]**	**KPI**
[d/m/yyyy]	[CET]	[h]	[%]
1 / 7 / 2021	0.00 am – 02.00 am	2	2.00
1 / 7 / 2021	0.00 am – 06.00 am	6	6.00
1 / 7 / 2021	0.00 am – 11.59 am	12	10.00
1 / 7 / 2021	0.00 am – 11.59 pm	24	12.38
1 / 7 / 2021 - 2 / 7 / 2021	0.00 am – 11.59 pm	48	25.33
1 / 7 2021 - 4 / 7 / 2021	0.00 am – 11.59 pm	96	64.98

4.2.5. KPI_DE_05 - Responsiveness

A key requirement for unlocking the full potential of any EMS is its responsiveness to flexibility requests. ALF-C and the connected CBES, must process and carry out a request deterministically within five minutes. The faster flexibility can be provided, the more valuable and effective it will be for grid-related issues. This KPI evaluates the precision of balancing consumption with the generation of a whole energy community in order to achieve a given active power setpoint defining the load exchange at the MV/LV grid connection point. Table 9 summarizes the results of KPI computation. Additional information on KPI computation is provided in Deliverable 5.5 [2] and 1.7 [19].

Table 9: KPI_DE_05 results of UC 1.0

Period	Time	Number of cycles	KPI
[yyyy/mm/dd]	[UTC]	[kW]	[minutes]
from 2021/11/29 11 a.m. to 2021/12/21 11 a.m	0.00 am – 11.59 pm	1,126	5

4.2.6. KPI_DE_06 - Accuracy of the achievement of a given setpoint

The accuracy of reaching and maintaining a defined setpoint is a quality feature of flexibility that can be provided by local networks and communities. The ability to achieve and maintain a setpoint exactly helps to avoid power fluctuations in the LV and MV network. KPI_DE_06 evaluates the accuracy of UC1.0 with RTO to balance consumption with the generation in LV community, by CBES control, to achieve a requested power exchange at the PCC. For the period under investigation, the mean value of KPI_DE_06 was 5.2 kW with a standard deviation of 6.3 kW. The average absolute value of P' for the period investigated was 64.8 kW. This means that on average an accuracy within 8% of the requested power was achieved. Table 10 summarizes the result of KPI computation. Further information on KPI computation are provided in Deliverable 5.5 [2] and 1.7 [19].

Table 10: KPI_DE_06 results of UC 1.0

Period	Time	KPI	KPI
[d/m/yyyy]	[CET]	[kW]	[%]
2021/11/19 to 2021/12/31	0.00 am – 11.59 pm	5.2	8

4.2.7. KPI_DE_07 - Reduction of load peaks in MV grid

A strategic goal of energy management in the low-voltage grid, i.e., the community level, is the alleviation of load spikes on the medium-voltage cables and transformers from peaks in local generation and consumption. Hence, KPI_DE_07 evaluates the decrease of power peaks on the medium-volte cable that supplies Abbenhausen when UC DE 3 and UC DE 4 with RBC were active in the field test.

Figure 24 shows the maximum 15-minute average power value, P_peak, during each of the 24-hour use case runs. Additionally, the respective power peak had the use case not been active, P_(peak,c), is computed. The scatter plots relates both power peak values for each day either UC DE 3 or UC DE 4 were active. A diagonal y=x divides the diagram. Given P_peak, if the corresponding P_(peak,c) is higher than P_peak, i.e., the application of the use case reduced the peak power on the medium voltage line, the symbol on the diagram will be above the dividing line. Conversely, if the use case increased the power peak on the medium-voltage line, the symbol will be below the dividing line. Lastly, if the use case had no effect, the symbol will be on the dividing line.

Overall, the ALF-C was able to reduce the power peak on the medium-voltage line by up to 200 kW. Except for one instance, where the peak power was increased slightly, on every other day there was either a reduction in cable load or no change at all. The load reduction on the medium-voltage cable is larger when UC DE 4 was applied compared to UC DE 4. This is the result of the combination of the impact the significant rooftop PV generation of Abbenhausen has on this medium-voltage line and the application of UC DE 4 on sunny days, with a bulk export. Hence, the impact potential in load reduction is larger for UC DE 4.

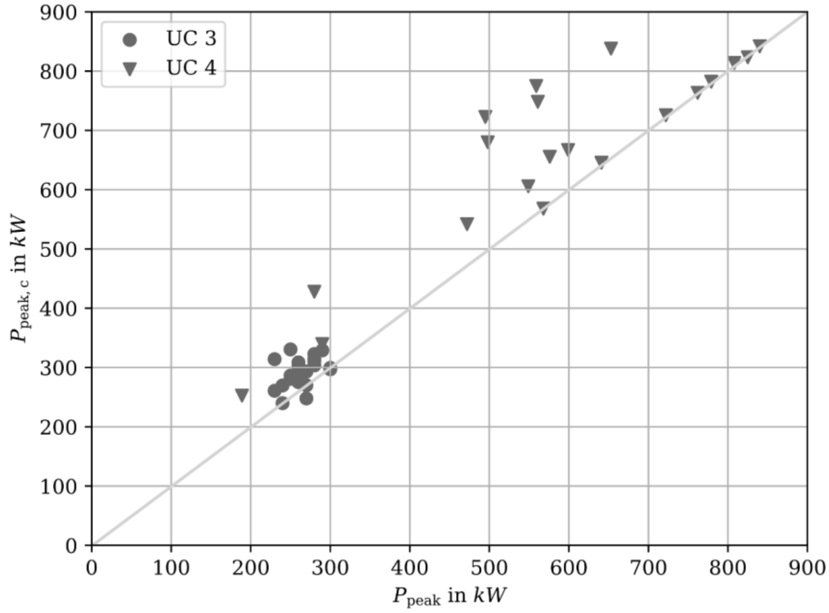

Figure 24: KPI_DE_07 results of UC 3 and 4 with RTO

More information on KPI computation are provided in Deliverable 5.6 and [3] 1.7 [19].

4.2.8. KPI_DE_08 - Forecast of LV grid Energy Demand

The advantage of a schedule for an energy management system is that the overall goal, in Platone the reduction of peak loads and energy exchange, can be achieved efficiently when activation of— generally limited—flexibility can be optimised. This schedule-based operation (SBO) requires accurate prediction of electricity consumption and generation in the community, from which the residual power curve at the secondary substation can be computed for the subsequent optimization in the ALF-C. Large forecast deviations result in potentially detrimental schedules for the ALF-C and subsequently the goal of power and energy reduction is not achieved. Additionally, the forecast is used to compute the amount of bulk energy in UC DE 3 and UC DE 4 which is to be imported and exported respectively in the designated timeframes.
The KPI_DE_08 evaluates the ability of the ALF-C to forecast by taking the difference of the forecasted energy export of Abbenhausen for the upcoming day, computed from the residual power forecast, with the actual energy export. This difference, ΔE_{ex}, is plotted in Figure 25 for around 200 days in 2022, sorted an ascending order.

Given the sign convention in the ALF-C—export energy and power are denoted with a negative sign—a negative value of KPI_DE_08 means that a higher energy export was forecasted than realised. Vice versa, a positive value for KPI_DE_08 means that more energy was exported on that day than was forecasted. It becomes clear that the forecast algorithm tends to overpredict energy export, given that KPI_DE_08 is negative on 75% of days. While underprediction of exported energy happens less often, the maximum error of 750 kWh is comparable to the maximum error for overprediction. In comparison, the storage capacity of the community battery energy storage in the field test is 770 kWh. Thus, these errors can have significant impact on the performance of the ALF-C with SBO, see KPI_DE_01 and KPI_DE_02.

There are two possible causes for these large deviations: errors in forecasting local electricity consumption or errors in local electricity generation. A more detailed analysis presented in deliverable 5.6. [2] indicates that the main source of error is the generation forecast by comparing the forecast with measurements at a customer rooftop PV system. Thus, to improve the performance of the ALF-C schedule-based control algorithms a better understanding of forecast errors is required, ideally supported by real measurements of PV generation in the field. Additionally, the ALF-C need to detect intolerable deviations and react accordingly, e.g., intra-day update or switching to RBO.

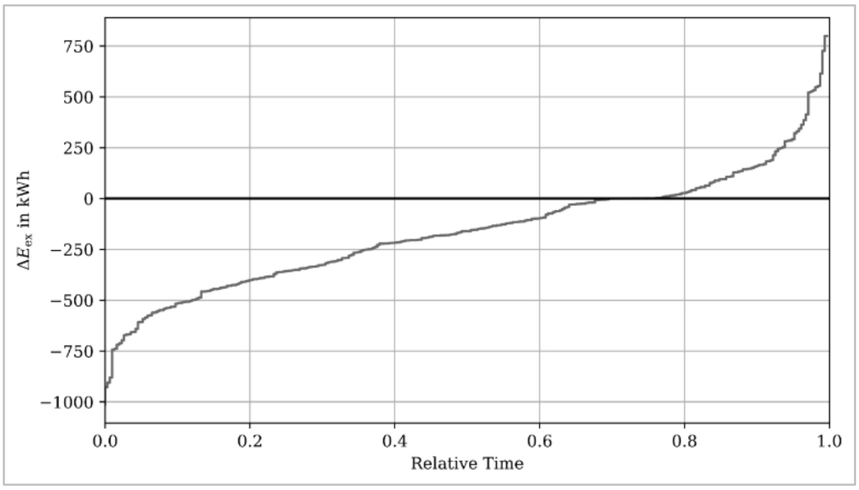

Figure 25: KPI_DE_08 - Difference in energy export between forecast and occurrence

5. Lessons Learned and Implication on Future Operation

This chapter gives an overview of lessons learned collected during the project. The lessons learned described in this deliverable provide a summarization of UC-related and general lessons learned covering both UC-specific lessons and the ones related to all aspects of implementing and operating a demonstration project in a research project. A detailed description of UC-related lessons learned are provided in the UC demonstration reports of WP 5, Deliverables 5.4 [1], 5.5 [2] and 5.6 [3].

5.1. Overview

The implementation of the German demonstrator covers a very broad spectrum of tasks and topics which lead to several lessons learned by investigating them. This deliverable shall highlight some of these lessons and related implications on future operation of a comparable demonstrator. To collect and consolidate lessons learned, a workshop has been conducted, for which topic clusters have been defined in advance. An overview of defined topic areas and related content is listed in Table 11. A Miro-Board, as result of the workshop from the 8th of June 2023, is shown in Annex 14.1.

Table 11: Overview of topic areas for lessons learned

No	Topic Area
1.)	Project Management and Tools
2.)	Public Relation and Customer Engagement
3.)	Development and Implementation
4.)	Field Test Setup and Operation
5.)	Evaluation and Dissemination
6.)	Deliverables and Reports
7.)	Regulation and Legislation
8.)	Community Load Demand Characteristics
9.)	UC Results

5.2. Project Management and Tools

Table 12 gives an overview of lessons learned related to "Project Management and Tools" that have been collected during the project duration of the demonstrator.

Table 12: Lessons learned related to project management and tools

Topic	Lessons Learned	Implication on future Operation
Project Management for IT development	The development of the IT solution in the German demonstrator (ALF-C) has been managed orientated on the agile principles according to SCRUM [20]. For this reason, the scope of the development task was separated into several segments (Epics) that would realise different functions of the IT solution. In order to implement the functions respective storys were created with tasks that could easily be assigned to developers. The scrum cycle implies a specific workflow of refinement, planning, review and retro which have been performed with the help of the tool Jira [21]. A bi-weekly meeting was hold to plan and review a sprint. In the intermediate weeks the refinement of new Storys and retrospective took place. Along with the scrum cycle, a core-team meeting was held weekly, in which product owner, scrum master and the development lead harmonized the objective and planned releases of the IT solution. Furthermore, a short daily-call was set up to clear questions quickly that occur while working on the stories. Necessary workshops resulted from stories were planned and organized. With the agile approach, the development work could be advanced in a structured and targeted manner. The agile approach also enabled problems that arose spontaneously to be prioritized at short notice and solved quickly. Furthermore, this approach helped to respect the deadlines according to the team members availability. A major learning was associated with the implementation of the project. In the context of a classic waterfall project with the creation of an implementation concept, it would have been delayed or only insufficiently possible to run through the learning curve. The agile method proved to be very effective here. Adaptations as well as new UCs could be designed and implemented efficiently. The sprint duration of 2 weeks and the cycle rate for the sprint meetings were chosen purposefully to keep the total number of stories that needed to be worked on low but with rich results and beneficial impact on the team's motivation. For evaluation of the agile workflow the retrospectives took place. It is important to find the right time interval for retrospectives. While a two week interval is too short for no new findings to emergge, an interval more than 8 weeks is too long due to the fact that the development of the IT solution requires slight allignements in the agile components of the project, such as user story writing, definition of readiness and	Based on the positive experience gained, agile project management orientated on the SCRUM method will be continued for the expansion and higher scaling of ALF-C.

	acceptance criteria, depending on the content of functions that need to be developed. Beside all the benefits of the agile working method there is one disadvantage that the time required to develop different functions and features cannot be planned accurately in advance, which has an impact when it comes to defining deadlines.	
Cost, Resource and Budget Planning	At the beginning of the project, resource and cost planning was constantly monitored. In retrospect, it became apparent that the initial assumptions of the cost planning were realistic and accurate for the majority of cost positions (e.g., material, service costs and hardware components). Individual adjustments only had to be made due to internal accounting practises. However, in the case of individual cost items, such as for external services, e.g., for the operation of infrastructure, it became apparent that the allocation to "expense" or "investment" depends on the design of contracts.	For future grant projects, efforts will be made to clarify the type of contract at an early stage in order to correctly allocate cost items to "other direct costs" or "equipment costs".
Involvement of Education Department	Within the scope of project objectives, households needed to be equipped with household battery storage systems that enabled a communication interface with the developed IT solution and met the project budget. Due to the complexity and scope of the customer equipment process, the training department of Avacon has been involved to compile the household storage system, including inverter and communication devices, and installation in the households. This proved to be a lifeline for the successful retrofit process due to the motivation, expertise, technical know-how and flexibility. Lessons Learned gained during the installation process are described in section 5.5.	Based on the positive experience gained, the possibility of the involvement of the internal training department will be proved as alternative to commissioning of external service providers.
Documentation	An IT project with the dimension of the German demonstrator covers a very wide range of complex tasks that have to be described, outlined and continuously revised. In the course of the project work, it became clear that the instant documentation of results is important. Especially for the forthcoming IT implementation and changes to be made in the IT landscape on a later stage. The structuring of the documentation and the ongoing follow-up is documented on confluence which facilitated structural rearrangements with the growing complexity and amount of topics. This was done to avoid missing information in the documentation and limiting the consequent technical discussions for the missing information. Therefore, the documentation should be continuously updated and, if possible, automated.	The documentation of results is prioritized even more and included as a regular task in the agile workflow.
Service Providers	Already at the beginning of the project, the risk management identified the uncertainty about the functionality, technical suitability of individual assets (CBES, HBES, service provider for communication connection) as a potential risk for the successful	Due to the positive experience, it is recommended to work

	implementation of the demonstrator, and its associated UCs. In retrospect, it has been shown that all contracted service providers have worked in a very goal- and solution-oriented manner and that the procured equipment and services have fulfilled the intended purpose and contributed to the desired goal and success.	with the contracted service providers.
Atlassin Jira and Confluence	For agile project management of development topics, Atlassian's Confluence [22] was used for documentation. Atlassin's JIRA was used for the definition, planning and monitoring of open work topics in sprints. Both software solutions are established solutions in agile project management in the industry. They also proved to be very helpful and supportive during the implementation of the demonstrator. With the interface of both software solutions it becomes possible to refer to respective documentation on confluence during the planning phase in the agile workflow which was done with the software Jira. This supports and simplifies the story description with Jira and enables a valuable documentation of results. Confluence is also a suitable tool for documentation outside of agile project management.	Due to the positive experiences, Atlassian’s Confluence use is also recommended in future projects.
Microsoft Word, Power Point, Excel	For the usual project management activities, such as planning, monitoring, and reporting, the common Microsoft (MS) Office products are very well suited. The PowerPoint extension tool "ThinkCell" has proven to be very helpful for scheduling activities such as the creation of chart-based evaluations via Gantt charts. However, for detailed evaluations, e.g., for deliverables, it has become apparent that MS Excel is no longer suitable for the evaluation of demonstrator results of a project with the size and complexity of Platone The large amounts of data to be processed (e.g., 1-minute, 15-minute measurement data of several measurement points for several years) are not manageable for Excel. Separate programs must be procured to process such data (e.g., Anaconda - Python) and experts are needed to operate them.	For future implications, it is recommended to use programs as Anaconda for evaluation of measurement results.

5.3. Public Relation and Customer Engagement

Table 13 summarizes lessons learned and related implication on future operation related to Public Relation and Customer Engagement

Table 13: Lessons learned related to public relation and customer engagement

Topic	Lessons Learned	Implication on future Operation
Involvement of Municipality	The involvement of the municipality resulted in a great learning since the involvement simplified the process of asset installation, customer integration and community acceptance for the demonstration. In case of asset installation, the involvement of the municipality helped to identify a larger number of suitable lots for placing the community storage and accelerated the process of obtaining relevant permissions. In terms of customer engagement, technical integration and creation of community acceptance, the involvement of municipality caused a higher awareness for the demonstrator and highlighted the advantages for households to participate in the demonstrator.	In future demonstrations or in case of an expansion of an existing demonstrator with additional participants, the involvement of the municipality is highly recommended to mitigate the risks of the implementation of hardware components and customer engagement.
Involvement of Local Council	The local council was involved to discuss strategies for customer engagement in the demonstrator. They provided great inputs on how to approach households to find demonstration participants. In this regard and since the local council is familiar with the interests and needs of the community, identifying incentives for households in the frame of the project intentions of the demonstrator was simplified. With the local council, key messages of the demonstration have been spread, too.	In case of a demonstrator expansion, the involvement of the local council would simplify the process of customer involvement.
Involvement of Politics	Climate goals and challenges that DSO face with the increased share of RES along with the Platone demonstration objectives and achievements were presented to politicians, which enabled a higher media exposure of the demonstrator. With the respective broadcasting of the demonstration objectives and achievements in different media, a higher awareness of the project was ensured.	To create a higher visibility of demonstrator outcomes, results will be presented to politicians.
Involvement of Installers	Regional installers were invited to an information event in which they were informed about the project before starting	In the course of building a new demonstrator or expanding the demonstrator in another area, it

	the customer equipment process to avoid misunderstandings among installers about the role of German network operators regarding electrotechnical conversion work in private households. Furthermore, the exchange with local installers offers the opportunity for technical exchange in terms of technical systems of the different manufacturers on the market, e.g., inverter, storage, heat pump, technical characteristics (,e.g., interfaces, controllability, measurement, etc.). This approach contributed with identifying suitable systems for the demonstrator.	is recommended to involve installers at an early stage to create transparency to the project and to identify potential service providers for installation service.
Customer Engagement Workshops	Customer engagement workshops were organized to obtain more insights about regarding the interests of the customers, which contributed with creating suitable incentive models to achieve a greater customer involvement and a higher number of project participants. Also, the customer engagement workshops realised the clear understanding of the project intentions and enabled the room for individual questions.	For future implications it is recommended to organize customer engagement workshops, since they have beneficial impacts on the customer involvement during the project phase.
Materials for Visualization	The demonstrator set up and project intentions were explained more comprehendible with the help of flyers, roll-ups, videos and graphics. Depending on the target group materials used for visualization created a better understanding about challenges for the grid with the increasing share of renewables.	For future implications it is highly recommended to use material for visualization on workshops, fairs, conferences and meetings to create a better understanding of presented topics.

5.4. Development and Implementation

Modularization of developed solution

The selection of a suitable IT architecture of ALF-C was of great significance for the subsequent course of the development. Already at the beginning of the development phase, it became clear that the requirements for an ALF-C can be supported by a microservice-based architecture. Therefore, many components of the overall solution can be viewed in isolation and thus designed optimally. With the use of RESTful APIs, the possibility of using services both, synchronously and asynchronously, was supported in the best possible way. The main focus was on the principle of statelessness. This creates the need to connect the services to a higher-level controlling instance that controls communication between the services and serves as a timer for the overall process. With the selection of the cloud platform MS Azure Logic Apps, the requirements for the decisive control process could be implemented easily and reliably. The possibility of mapping the overall process on a low-code basis and by means of visual support made it possible to integrate the microservices successfully right from the start.

Development and Implementation on MS Azure Power Apps

ALF-C was implemented in a MS Azure environment in which several features were created with PowerApps. For the configuration and monitoring of UCs a Graphical User Interface (GUI) was implemented, which is be able to trigger new UCs, display the status of the flexibility (CBES and HBES), monitor running UCs, and link to Grafana dashboards to observe the status of the grid and UC effects. Since the architecture of ALF-C relies on handling *.json files and uses Azure Logic Apps to communicate with all the components, the Microsoft Power Platform fits perfectly in this environment.

Using PowerApps as component of the Microsoft Power Platform enabled a straightforward approach for rapid application development. For experienced developers the underlying concepts are different, but the learning curve for developers with a classical background and people that are new to that topic is flat.

The required environment for UC application to realise demonstration objectives, foresees a configuration for upcoming UCs to ALF-C as a *.json document in a blob storage container. Since writing to a blob storage is not possible with plain PowerApps code, an additional layer in the PowerAutomate (formerly known as Microsoft Flow) regime was created. The flows consume data sent by the PowerApps and save it to a blob storage or get data from the storage and return it to the PowerApps. Even though complexity is increased with this layer, a higher level of flexibility is ensured regarding handling data stored in Azure subscription.

The PowerApps permit the display and the manipulation of data stored in local variables directly bound to an underlying data architecture. The control (i.e., GUI elements interacting with data) is identical to data acquisition in Excel cells with a formula, which eases the development of Power Apps.

The speed of development is comparably high – in an agile development process a quick adaption to changed environment is possible and was proven successfully throughout the whole project.

By ensuring new features of ALF-C GUI to rely on interacting with the runtime environment regarding storing *.json files to a blob storage or by communicating with logic apps via REST API calls, future enhancement poses no issues. Increased complexity bloats a no-code-app as well as a classical app. The need of a planned approach and well-designed architecture exists in both alternatives.

A design phase allowing named developers to change the GUI in the PowerApps web editor environment was used for development. New features are able to be tested or challenged in online sessions. As soon as a new GUI is saved, it is accessible by other users that have access to the app which makes the development available in the productive environment.

5.5. Field Test Setup and Operation

Household Battery Energy Storage System (HBES)

In the course of setting up the field test environment, it became apparent that flexibilities were not available in the households of acquired participants or did not have the technical prerequisites for measurement and control (e.g., interface for connecting IoT gateways). Therefore, the communication connection and measurement and control capability were to be established by retrofitting inverters and storage systems as well as gateways. For the procurement, installation, and commissioning of suitable inverters and other devices, local solar companies in the region were invited to a workshop. The aim of the meeting was to explain the project and the objective for integrating households into the ALF-C. It quickly became apparent that the solar installers were not available for commissioning, which would have led to delays in the implementation of the field test setup in the project. In addition, in general solar installers only install devices of contracted manufacturers. Most manufacturers possess large scale, manufacturing systems that are technically capable to provide system state data, e.g. charging power, state of charge, in close real time. Many systems also provide an interface to a manufacturer backend system to enable external control. However, large scale service providers in many cases do not offer access to their backend systems to access these systems or charge high prices for the access to the backend system. To examine an alternative approach, Avacon's training department was involved to handle the customer equipment process of WP5. The department have necessary technical experiences, certifications and technical equipment to carry out such a project themselves. Thus, the training was entrusted with the task of planning, procuring, installing, commissioning and technically accepting a suitable HBES system, including inverters and gateways for the households. The customer equipment process was successfully carried out by trainees of Avacon’s training department. The lessons learned gained during the activities of the training department are described below.

In summary, the implementation of HBESs went very well under the given circumstances. The installation of the field test components took place without any significant delays or unplanned problems despite the problems in the supply chain, which was relevant in the year of installation, 2021. Only the communication link between the EMS operating the inverter for the PV and battery system at customers premises and the backend system of the ALF-C experienced some stumbling blocks and delays. This was primarily due to vendor-specific software implementations. Much of the time spent setting up the communication link between the PV system and the project's server environment was dedicated to working on the associated documentation. In particular, the planning, installation, and registration of the PV systems was managed entirely by the project team; only the roof superstructures for the rooftop PV panel were installed by external specialized installers. This rather unusual structuring of the work provided insights and experience that would likely have been lost by interfacing with service providers. Furthermore, the close contact enabled a higher frequency of exchange about project objectives and contributed making participants feel more as part of the project. It should be noted that the project participants were very positive about the project and shared its overall interests.

HBESs Installation Workload

Due to lack of installers in the setup phase of the field test environment Avacon has decided to install HBES at customers premises with qualified personnel and trainees from the internal education department.

An ambitious time frame was set for the installation of HBES and related components, e.g., inverter, router, cable laying, at customer premises to stick to the timeline for the demonstrator. Most of the systems were installed within a time window of one day, but required comprehensive rework due to the commissioning of the system. In total, three full working days were spent on site for each installation. This included one day of work for the installation of the rooftop system performed by external service providers. Installation cannot be performed on every day of the week, as works on rooftops can only be carried out in almost complete windless conditions and weather temperatures above 10-15 degrees Celsius. Otherwise, the potential for accidents due to slipping, wind forces on the PV modules and moisture from rain or condensation is high. In addition, approximately one day of work for planning and inspection and two days for documentation and registration of PV system with the responsible grid operator were planned. In summary, for the installation of one HBES system one week was required. Main unpredictable time-consuming issues within the construction of the system were the spatial conditions between the PV roof system, inverter, main power line and HBES. Due to spatial distances between components, unpredicted costs occurred for cable laying.

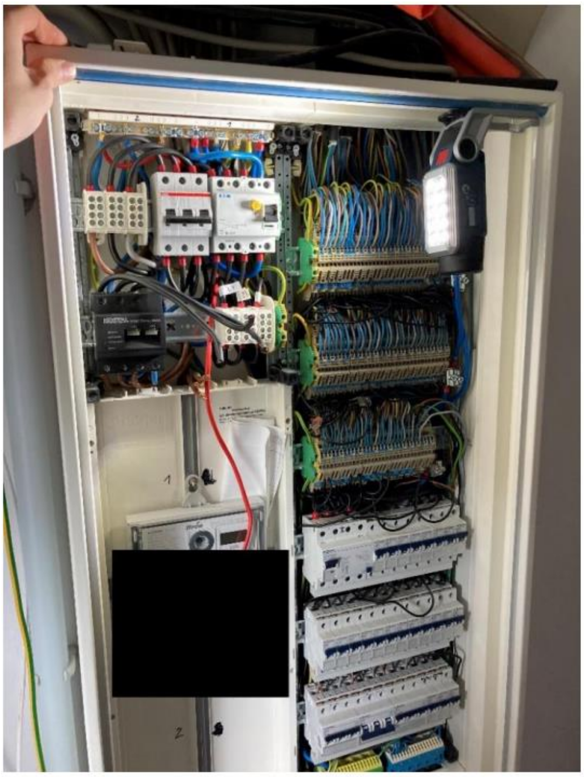

Figure 26: Electrical main distribution box with high packing density of a customer household

The installation of cable management systems was time-consuming, since it not only involves a huge amount of manual work with many individual parts but also includes difficulties in finding compromises between simple feasibility, structural requirements and visual demands on the installation. Furthermore, electrical distribution boxes often require a considerable wiring effort, since the distribution boxes are often completely covered with installation material (see Figure 26). Requirements set by the Verein Deutsche Elektrotechniker (VDE) [23] according to the latest regulations are difficult to be met. Otherwise, they require an allocation of the distribution box which resulted in negative impacts on the economic efficiency of retrofit, economic efficiency of PV system and economic efficiency of self-consumption optimization or economic efficiency of smart home systems. In particular, during the installation in some cases it was difficult to comply with the standard "DIN 18015-1:2020-05", as it requires a maximum of two circuit breakers per residual current circuit breaker and per phase conductor. In case of some households retrofitting a PV system led to difficulties in accommodating the system. In some cases, it was not possible to perform a conversion or extension according to the standards, e.g., DIN 18015. In these cases, the conversion or extension of the electrical wiring had been carried out with reference to an electrotechnical inventory protection, after ensuring that at least no safety-relevant standards were circumvented.

Project Participant Feedback after HBES installation

In summary, customers were very positive and satisfied with the project and its progress. All customers have continuously dealt with the characteristics of their PV system during the project and reported conspicuous features and observations. According to project participants after analysing smart meter data it became clear that household consumption behaviour changed partly after the installation process. Since project participants did not have access to manufacturer's web and app interface of the HBES’s EMS to view their system data, some customers helped themselves by regularly monitoring generation output, weather, and battery state of charge resulting in adjusting their consumption patterns to match the performance of their system. For example, customers reported manually operating powerful household appliances such as washers, dryers, and electric charging stations during periods of high PV power generation on purpose. In addition, some customers reported manually turning on a fan heater during the transition period, in the fall months of September through November 2022, during periods of high PV generation to reduce heating energy costs. So far, no negative impact on the power grid was noticed, however, this change in behaviour was not reported by all project participants.

Implication on future operation

The involvement of Avacon's education department turned out to have more beneficial impact on the project compared to assign manufacturers. For future project it is recommendable to prove weather installation at customer premises can be performed with internal qualified personnel. However, the installation process is time and therefore resource extensive. The technical equipment of a larger number of households need to be planned and weighed over commissioning of external installers or service providers. Advantages for the field test implementation and customer equipment process were:

- motivated trainees looking for a challenge,
- availability of technical know-how and expertise,
- employee with certification for electrical work and installation in the grid and households

Table 14: Lessons learned related to the field test setup and operation

Topic	Lessons Learned	Implication on future Operation
Location of a Field Test Area with a CBES	The location of a field test area in which a CBES implementation would result in performing innovative grid supply strategies to meet project objectives requires to fulfil a handful criteria, e.g. characteristics of Avacon's forecasted future grid (rural area, high PV generation, residential loads) and a variety of smart grid components (Smart Secondary Substation, measurement devices such as PMUs, LTE or other communication, etc.)During the search process, following elements emerged to be fulfilled by the field test area for a successful realisation of project objectives: **CBES footprint**: A floor space is required for the installation of the CBES. Due to grid connection requirements, a 300 kW storage, should be located with maximum 150 m distance from the secondary substation. Furthermore, due to fire requirements, a fire hydrant must be available in the immediate vicinity <150m. To ensure compliance with emission and fire protection requirements, the distance to the nearest residential building needs to be 100 m. The compliance with these requirements limits considerably the selection of suitable field test sites. **Characteristics of the field test environment**: The objective was to locate the demonstrator in a low-voltage grid area that has a regional grid with single-family	Generous time (at least 6 months) should be planned for the identification and selection of a suitable field test area. For the construction of a demonstrator with large-scale battery storage (CBES), legal requirements from the Federal Emission Control Act, fire protection specifications and building regulations from the building code must be taken into account [24]. Planning offices and construction service providers should be involved in the project at an early stage due to the low availability (high order situation, shortage of skilled workers). Planning offices and construction service providers should be involved in the project at an early stage. The installation of a large-scaled storage facility is subject to approval by the building authorities. The conditions imposed by the approval process can represent considerable time and cost risks. It is also advisable to involve and inform the locally responsible building authorities in the project at an early stage. This can accelerate the approval process minimize risks for the successful implementation of the project and allows technical adaptions on the large-scaled storages facility. It is also important to establish contact with local landowners at an early stage in order to acquire a suitable site for the CBES footprint.

	homes and a high penetration of rooftop PV systems. In order to cover the "excess generation" scenario by the community, the installed PV capacity should be at least 150 kW per 100 households. However, to ensure that the LV municipality has a surplus production, test measurements were carried out for a period of one week. This procedure has proven to be very effective, as collected measurement data provided evidence of fulfilling technical requirements.	
PMU	**Installation**: The first PMU, developed by RWTH Aachen, was adapted to be placed at the secondary substation and successfully connected to it as a reference measurement device. For the current and voltage conversion, a circuit board was laid out and an appropriate housing that fit in the secondary substation was built. During the evaluation of measurement data, knowledge has been gained about the composition and functionality of the PMU by drawing a schematic diagram for the signal converter and a PMU system structure diagram. The identification of suitable current and voltage converters was challenging, since there are almost no sensor available on the marked that convert a current or voltage signal from 15 kV (MV) into a 5 V signal that is processable for the Raspberry PI component of the developed PMU. To solve this issue, the point of measurement has been shifted to the LV bus bar (400 V) for which the market offers appropriate sensors. A challenging aspect was the fitting of the PMU into the secondary substation. Such substation has been implemented with larger sizes in the past. As spaces for substations in populated areas decreases, substation have to fit in more narrow places, e.g., between streets and neighbouring properties. As results substation are built mor compact, offering less free space for retrofit solutions.	For future implications it is recommended to investigate the availability of converters that are able to convert current or voltage signals from 15 kV (MV) into 5V signals on the market since the market offers expands steadily. Alternatively, measurements on the LV bus bar (400V) are feasible. Furthermore, the PMU providers should improve how the solution could be betters designed to fit as retrofit solution in existing secondary substation with narrow spaces.

5.6. Data Analysis and Dissemination

Automation of Evaluation

The evaluation of UC application requires the passage of several processing steps and is complex due to the large amount of data. To ensure a reliable evaluation, the measurement data must be examined for completeness, consistency and persistence. In the course of creating several evaluations, the following items had to be considered for a concrete evaluation of the implemented solutions:

1.) Missing measurement data in timestamps or in baseline data set. UCs performance evaluations, require the evaluation of measurement data for completeness, e.g., measured data from PCC and CBES, Measurement data from 2 measurement points on the medium voltage line.

2) Plausibility check of measurement data: During the field test phase, the metering device in the secondary substation has been updated. As unwanted consequence, the transformer ratios of the voltage dividers of voltage and current measuring sensors were incorrectly changed. The misinterpretation of the voltage signals led to an exaggeration of the generated current and power values by a factor of 1.6. The inclined measurement data suggested a twice as high consumption of the community in the night hours.

3) Successful execution check of a UC. In the course of UC evaluations, it is important in general to exclude sources of interference or error that are not attempted by the UC algorithm. This includes a break in communication links that lead to an interruption in the control of flexibilities in the field.

During the first UC evaluations, the data was manually examined for the items above. In course of the field test phase, the process has been automated. For this purpose, test criteria were defined and a Python script to automate the data testing process. The following test steps were defined for the script:

- Does the data set contain 96 15-minute cycles per day (24h)?
- Does each 15-minute cycle contain at least 10 measured values from PCC?
- Does each 15-minute cycle contain at least 10 measured values from CBES?
- Was the UseCase set to "active"?

  In case all 4 criteria are met, the time-period of the data set is taken into account for the UC evaluation.

In future UC evaluation should be automated. The process of automated-evaluation should be improved to perform additional plausibility checks to avoid extensive manual work on large data sets.

The UC evaluation was published in a paper for the cired 2023.

5.7. Community Power Profile Characteristics

In the subchapter 5.7.1 and 5.7.2, individual lessons learned on generation and consumption characteristics are exemplified by individual key values and illustrative examples. The lessons learned are explained with each example. The data and results shown are based on the measurement data taken from the LV busbar of the LV/MV grid connecting feeder at the PCC, which indicate the residual load demand of the community Abbenhausen (Twistringen) of the German demonstrator. The data were collected during the field test phase and publicy uploaded on zenodo. The results can be considered representative of the load response characteristics of PV-driven low-voltage grids in regional electricity distribution power grids.

5.7.1. Peak Load Demand of a PV-driven LV community

Table 15 summarizes the annual maximum peak load import (consumption) and export (surplus of generation) of each field test year. The import peak load (consumption) values (consumption) occurred on December 24th in the period from 2 p.m. to 5 p.m. in all years. The values indicate the maximum peak value with 115 kW load demand in 2020 and the lowest with 99 kW in 2022. The values indicate a steady reduction of the yearly maximum load demand peak (import) over the years. The maximum export power peaks are steadily increasing. The maximum export peak, which describes the export power flow from the LV grid into the MV grid (surplus of generation after consumption), in 2021 equals -308 kW. Until 2023, the values have increased up to 384 kW. The highest export power peaks occur in the months from April to June. This could be due to a more optimal solar incidence angle or a higher efficiency of the roof-top PV system as result of lower temperatures compared to summer months.

Table 15: Annual peak load value of LV community (Abbenhausen) at winter times

Year	Import Peak Load (kW)	Export Peak Load (kW)
2020	115	
2021	106	-308
2022	99	-348
2023	-[1]	-384

[1] The value is missing, since the report has been created in July 2023

5.7.2. Daily Load Profile of a PV-driven LV community

This section shows representative 24h-load profiles for sunny and overcast days of different seasons of the year.

Clear Sunny Summer day

Figure 27 illustrates the load profile of the LV community on a clear sunny summer day and taking the example of June 9, 2023. The import peak load (consumption) is 38 kW max. The imported energy during this period (positive values) amounts 170 kWh. The export peak power (net surplus of generation) is -300 kW max. The exported energy quantity is 2,330 kWh.

The present example illustrates the large disparity between generation and consumption (power and energy) within a 24-hour period. The high surplus quantity due to the high installed PV capacities leads to very high max peak power values and high energy quantity which must be exported to the higher MV grid. Similar load behaviour of other local LV grids allocated along an MV line would result in additional load on the MV line.

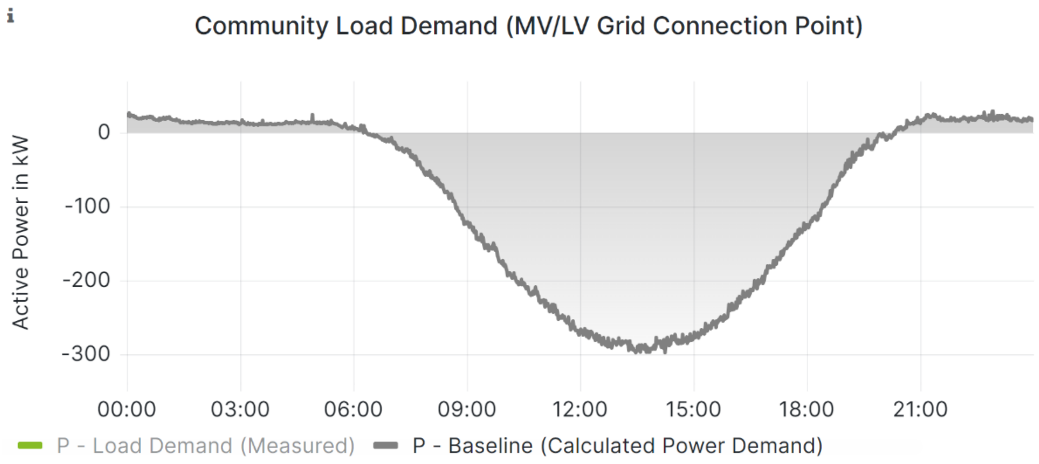

Figure 27: LV community load profile on a clear sunny summer day (9th June 2023)

Overcast Sunny Summer Day

Figure 28 illustrates the load profile of the LV community on an overcast sunny summer day, (July 3rd, 2023). The maximum import peak load (consumption) is approx.. 35 kW max. The imported energy during this period (positive values) still amounts approx. 170 kWh. The max export peak power (net surplus of generation) is -384 kW max. The example illustrates the effect that the rapid changes of light and shadowpassing clouds have on the PV feed-in and thus the power exchange profile at PCC:

- volatile power exchange fluctuations during day light hours,
- power drops at times of surplus-generation of up to 100% in a few minutes,
- Even power imports at day times during volatile fluctuations.

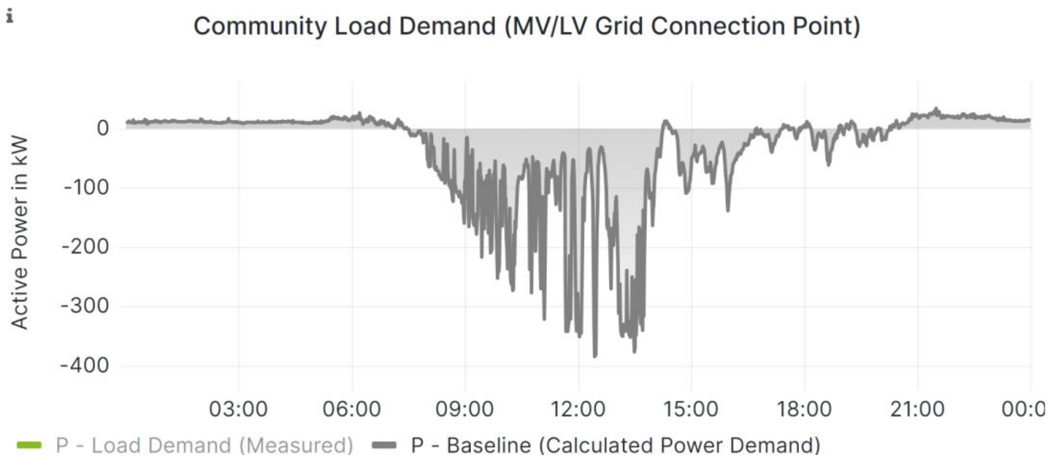

Figure 28: LV community load profile on an overcast summer day (3rd July 2023)

Sunny Winter Day

Figure 29 illustrates the load profile of the LV community on a clear sunny winter summer day (example of January 17th, 2023. The max import peak load (consumption) is 68 kW. The import energy is 683 kWh. The export peak power (net surplus of generation) is -131 kW max. The exported energy quantity is 143 kWh.

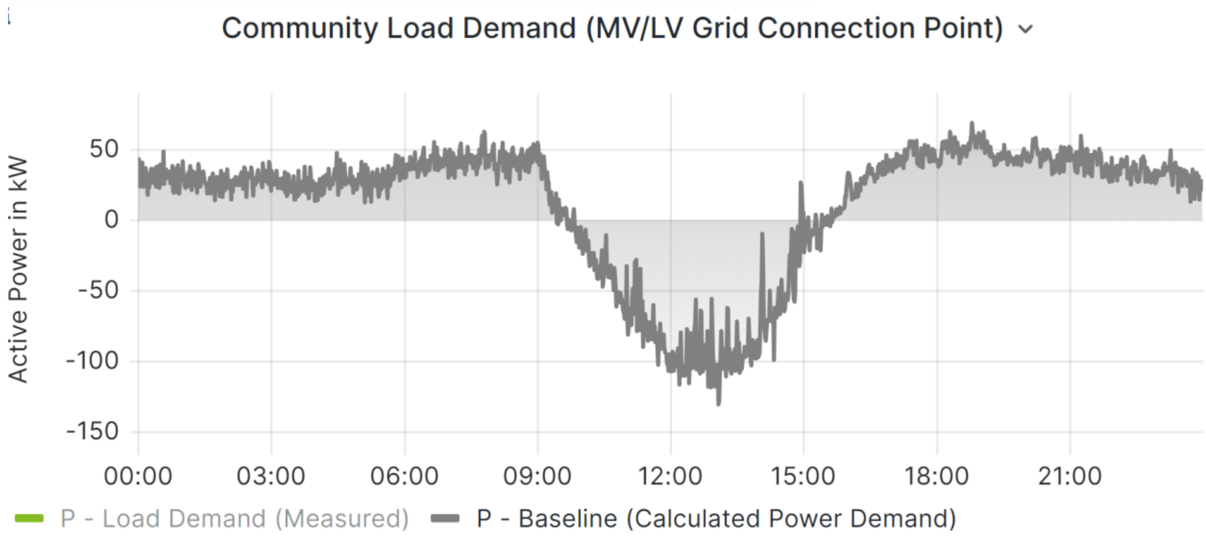

Figure 29: LV community load profile on a sunny winter day

Christmas Eve Winter Day

Figure 30 illustrates the load profile of the LV community on the German Christmas Eve (December 24th, 2022). In all years of the field test phase Christmas Eve has been the day of the year with the highest load demand peaks. The import peak load (consumption) is 99 kW max. The import energy is 1.056 kWh. The export peak power (net surplus of generation) is -131 kW max. The exported energy quantity is 12 kWh.

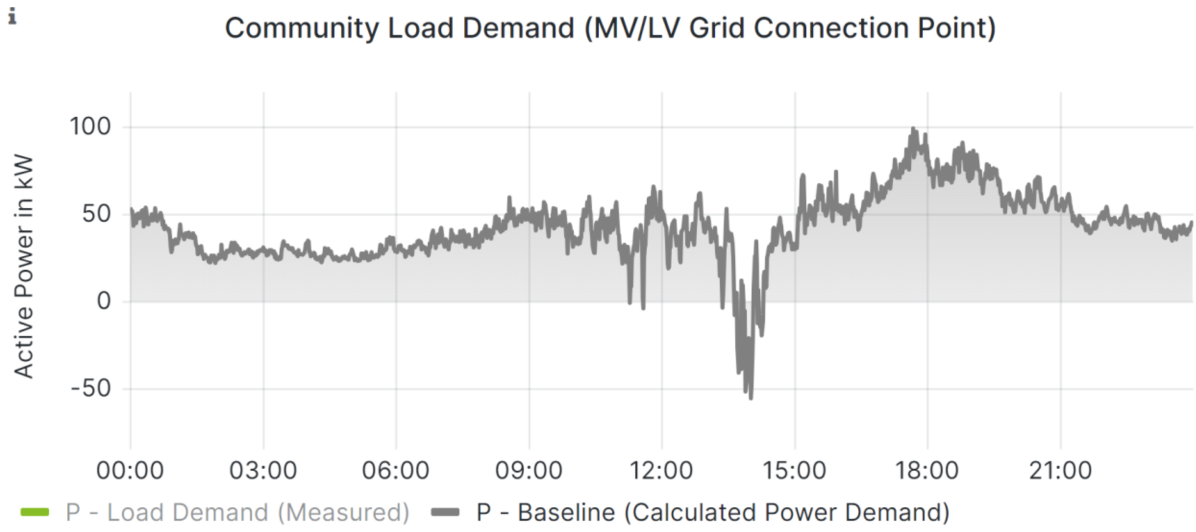

Figure 30: LV community load profile on Christmas Eve (24th December 2022)

Cold Winter Day

Figure 31 illustrates the load demand of the community of Abbenhausen on a cold winter day (17th June 2022) with a daily average temperature of -6,3°C and 99% humidity. The import peak load (consumption) is 89,5 kW max. The import energy is 1.076 kWh.

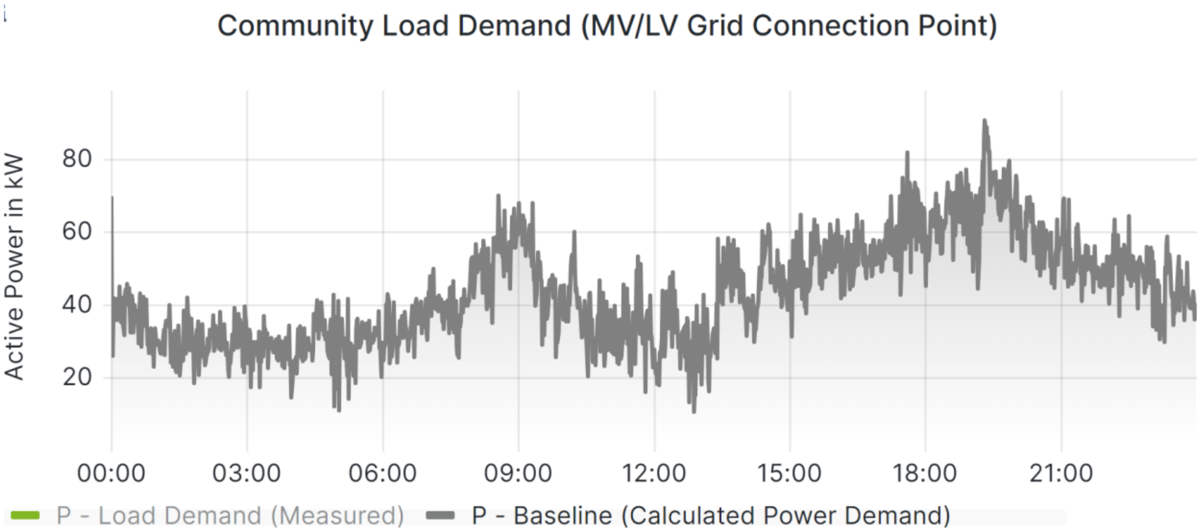

Figure 31: LV community load profile on a cold, overcast winter day (17th December 2022)

5.8. UC Results

This chapter summarizes major lessons learned that have been collected during the demonstration phase of the German demonstrator under lead of Avacon. The following lessons learned are grouped per each UC.

5.8.1. UC 1

This UC has been applied with a near real time control (UC 1.0) and SBO mode (UC 1.1). Both approaches are described in section 2.5. and results are evaluated and compared in 4.1.

Lessons Learned from UC 1.0:

The UC has been applied with a near real time measurement-control cycle with a repetition interval of 15 minutes. The results clearly showed that ALF-C with a UC 1 with is able to minimize the power and energy exchange at PCC on sunny summer days as long as CBES in the field provides flexible power and storage capacity for charging and discharging. Therefore, the UC 1.0 is able to reduce the power exchange at PCC close to zero and temporary energetically uncouple the LV-grid of the community from the MV-grid. However, in case of overcast days, the results showed that high-frequency fluctuations in PV generation in the community in conjunction with the inertia of the 15-minute measurement-control-cycle can result in a contradictory impact on the target of minimizing the power peaks and energy exchange at PCC. Especially during midday, UC 1.0 can have no effect no effect on power exchange peaks reduction at the MV/LV feeder. Furthermore, in case of a 24h boundary condition, the maximum daily power exchange value is neither reduced on clear sunny days, nor unsteady overcast day. This is the result of a lack of unused storage capacity and the use of near real time measurement data as input.

Example days of each scenario are illustrated in Figure 32 and Figure 33. The green curve “P – Load Demand (Measured)” indicated the measured power exchange at PCC during the UC 1.0 application. The grey curve “P – Baseline (Calculated Power Demand)” is a computed baseline, which indicates the power exchange over time at PCC, if no CBES control with UC 1.0 would have been applied. Figure 32 shows that the UC 1.0 is able to reduce the maximum peak power value of a 24-hour interval. In night-time the approach reduces the power exchange closer to zero. At day-time, as soon as PV generators begin with renewable feed-in, fluctuations occur. These fluctuations are results of by-passing clouds, reducing solar radiation on the PV panels. Due to the 15-minutes control cycle of the RTO, the CBES charging cannot be adapted to the measured power changes fast enough. As a result, the CBES continues charging with energy from the MV grid, which leads to import power peaks at PCC. Figure 33 illustrated an example for a sunny day. This figure shows less fluctuations and resulting power exchange at PCC closer to zero. However, at about 11.30 a.m. local batteries reach their maximum states of charge and stop providing flexibility for balancing, see Figure 34 for CBES and Figure 35 for HBESs. The missing availability of unused capacity of batteries for control lead to a power exchange increase up to the baseline. Further lessons learned from UC 1.0 are described in the Platone Deliverable 5.4 [1], RTO chapter 4.1.

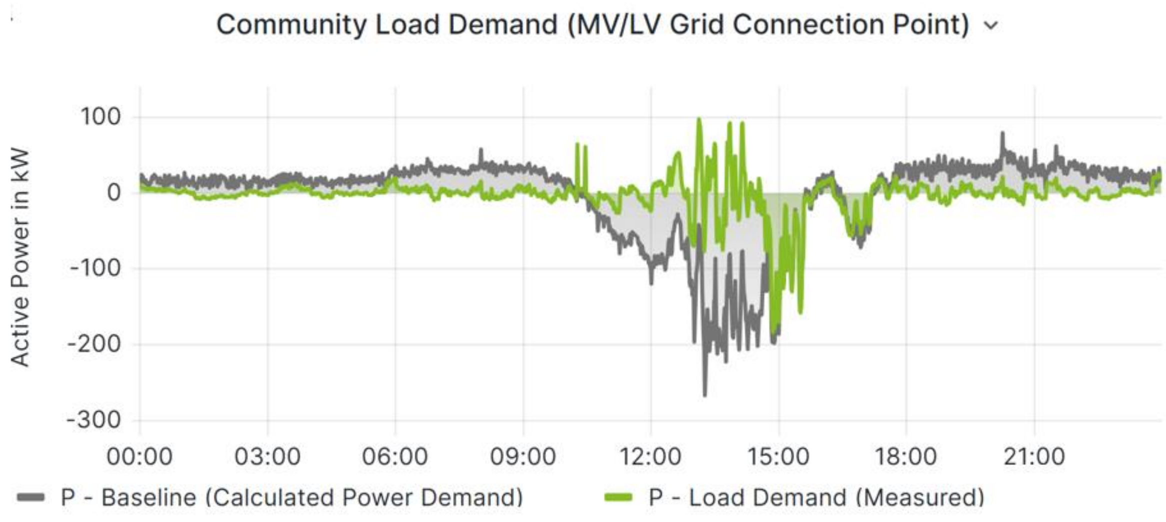

Figure 32: LV community load profile during UC 1.0 application on a sunny, overcast day (10th September 2021)

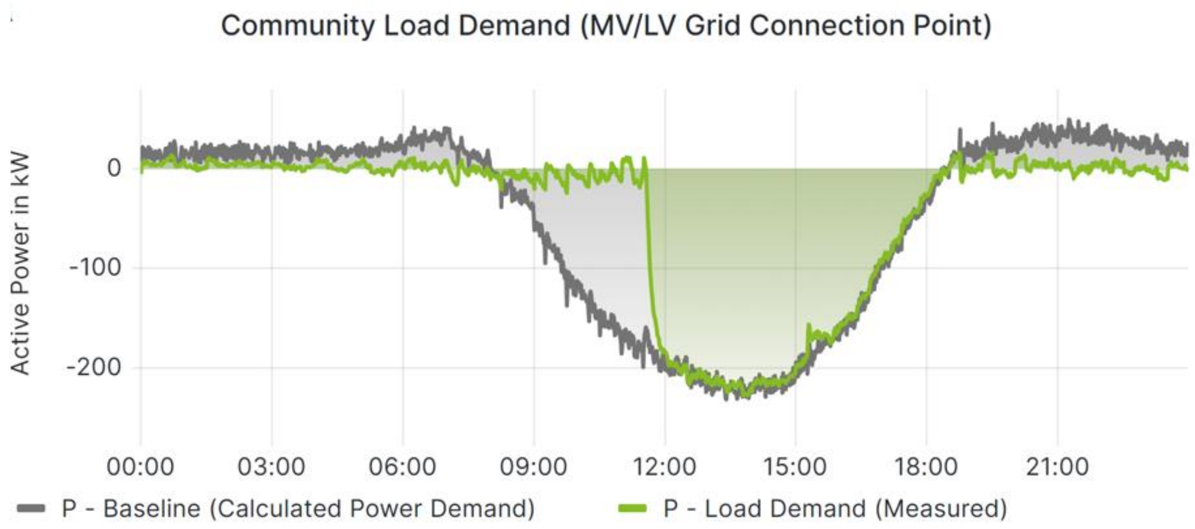

Figure 33: LV community load profile during UC 1.0 application on a sunny day (8th September 2021)

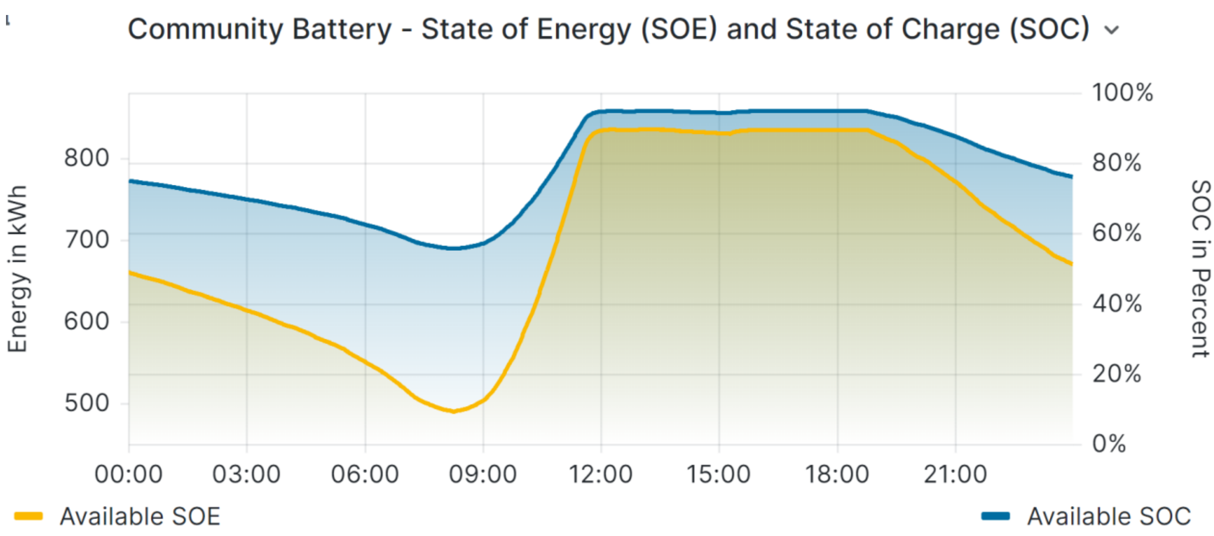

Figure 34: CBES SOE and SOC over time during UC 1.0

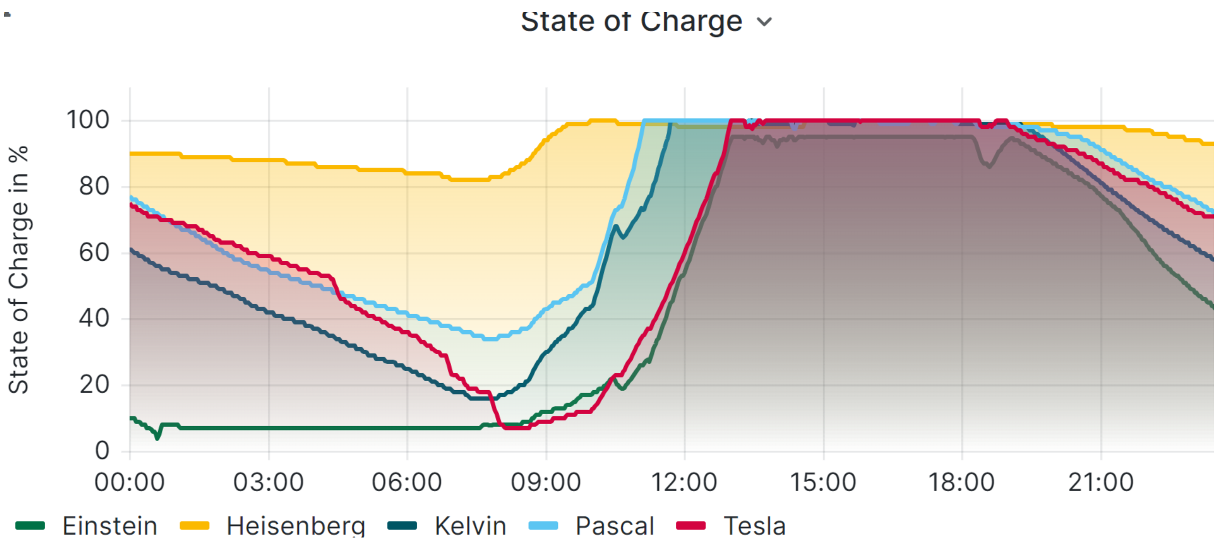

Figure 35: SOC of HBES of a 24 hours period during PV self-consumption

In summary, measured data indicate that on clear sunny summer days, UC 1.0 with the near real-time control with 15-minutes measurement-control cycle is reducing the energy exchange between community and MV grid at the PCC. Thus, this UC is able to increase self-consumption of a renewable PV-driven community and increase duration of virtual islanding. Furthermore, on sunny summer days this UC is able to decrease the power exchange at PCC as long as storage capacity is available. When a 24 h time window is defined as boundary condition UC 1 in the given field test setup is able to compensate peaks until 11 a.m. on sunny summer days. However, due to the 15-minutes control intervals the near real time operation mode of UC 1 is not reducing the daily maximum power exchange peak. On unsteady overcast days the control mode can cause to even higher power exchange peaks, as the 15-minutes control cycle can adapt battery control not fast enough with the volatile feed in. Shortening of UC time window increases probability of power peak compensation.

This UC is able to energetically uncouple the LV grid from the MV grid and reduce peak reduction, but due to fluctuating performance that depends on weather condition and external factors, the reliability is not sufficient to meet requirements to replace flexibility control with conventional grid expansion and reinforcement. In such a case the UC applied in the operational grid has to display a constant value of performance. For example, in case of power exchange peak reduction underperformance on a single 15-minute interval of a year can result damages on the physical components of the infrastructure, e.g., transformer. Same applies for unsteady weather conditions, which display periodically covering of PV generators that leads to reduction of generation in LV communities and high gradients in the residual power demand at PCC. Resulting implication are described in the following.

Implication on future operation for UC 1.0

Based on the lessons learned from UC 1.0 evaluation, following implication on future operation is derived as solution for evaluation to avoid the power peak increasing effects during CBES control with an RTO mode:

Direct-Charging Approach (Measurement-Control-Cycle) - In case of the given field test environment the near real time operation mode is reducing the daily maximum power exchange peak at the MV/LV grid connection point within a 24-hour on sunny non-overcast summer days. The cause is the limited available storage capacities in the given interval field test setup and the fact that the near real time mode of operation at each point of time uses all available flexibility resource(es) at each point of time without the consideration of future measured values and purely based on the measured value at each 15-min timestamp. On sunny days the storage reaches its maximum SOC already early in the morning. Volatile power exchange peaks and maximum power exchange peaks of 24h intervals caused by PV feed-in, cannot be compensated for all days with a near real time control with 15 minutes measurement-control cycles and limited flexibility (storage capacity). The approach therefore only has a limited grid friendly and positive system related effect for the DSO. But it has a positive effect on the contribution of maximization of collective self-consumption. Therefore, different approaches have been derived in theory that address the limited availability of flexibility to improve the effect during 24-hour intervals. For example, increasing the frequency of the control cycle, e.g., from 15 minutes to 3 minutes, can increase the effect of power peak compensation at PCC, even in times of high fluctuation with high gradients. Alternatively, the limitation of charging and discharging power of local flexibility (e.g., CBES, P_{TCB}) e.g., to 50 % (150 kW), might avoid or reduce positive (consumption) power peak at the substation during day times.

Delayed Charging Approach - With this approach the starting time of UC application will be shifted to a later point of time of the day, closer to the point of time at which the PV-generators achieve their peak values. This approach supports the reduction of large power flows as result of high generation peaks. This delay assures that during peak generation, storage capacity is available to countermeasure load peaks. To maximize the effect of peak power reduction (export peaks) at PCC, the point of time of the beginning of this UC has to be determined such in a way that in the afternoon, at time of sunset and before the local consumption of the community exceeds local generation, the CBES is fully charged with surplus of generation from PV generation at daytime. The starting point for charging the CBES can be determined empirically or based on a forecast of net generation and consumption in conjunction with an optimizer in order to ensure that CBES storage capacity is optimal used for power peak reduction at PCC. This approach supports the maximization of collective self-consumption and relieve the MV-network from additional stress.

Peak-Shaving Approach - With the Peak-Shaving approach a threshold is determined for the power exchange at the LV/MV feeder. When the threshold is exceeded, control of the storage begins. The charging power of the storage should also result from the difference of the measured power value and the threshold value. The control of the CBES reliefs the MV-grid from additional stress caused by the peaks in generation and increases hosting capacity for additional PV generators or other RES. This approach has a grid-friendly and positive system related effect for the DSO. However, this approach does not contribute to maximize collective self-consumption of energy generated locally.

Lessons Learned from UC 1 with SBO:

The lessons learned from UC 1 with SBO set with a boundary condition of 24 hour for optimization are described using two example days. Figure 36 displays UC 1 effects on a sunny day and Figure 37 on an unsteady weather day. The green curve "P – Load Demand (Measured)" indicated the measured power exchange at PCC during the UC 1 SBO application. The grey curve "P – Baseline (Calculated Power Demand)" is a computed baseline, which indicates the power exchange at PCC, if no CBES control with UC 1 SBO would have been applied. Figure 36 illustrates that the UC 1 SBO mode is able to reduce the power peak exchange at PCC of a 24-hour interval. The reduction of the daily maximum power exchange peak is significant. In case of unsteady weather import power peaks occur that don't happen in baseline. This is the result of an inaccurate weather forecast. However, these peaks have minor effect on the target of daily max power peak reduction. As the RTO approach, also SBO is able to energetically uncouple the LV grid from the MV grid, to increase self-consumption of a renewable, PV-driven community and increase duration of virtual islanding.

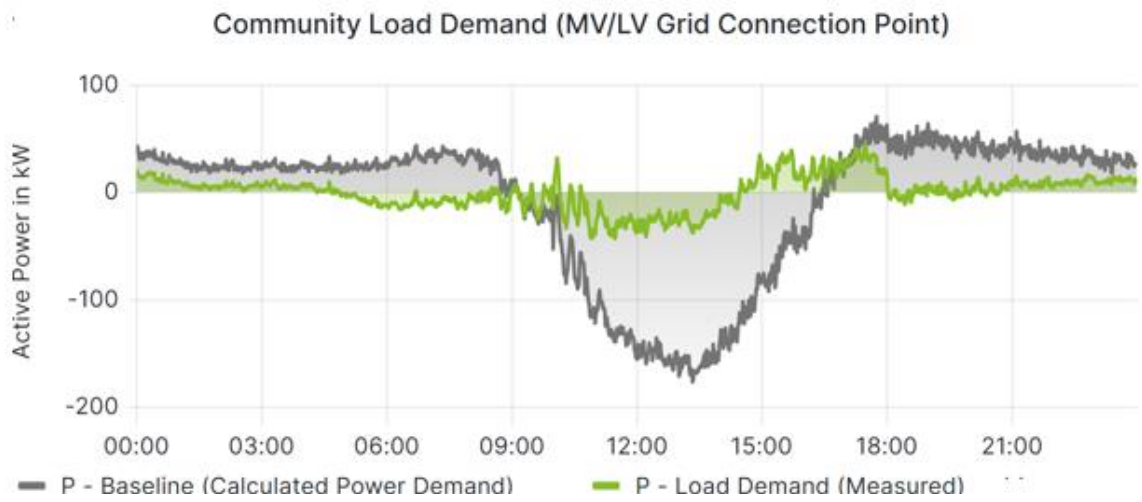

Figure 36: LV community load profile during UC1 SBO application on a clear sunny day (12th February 2022)

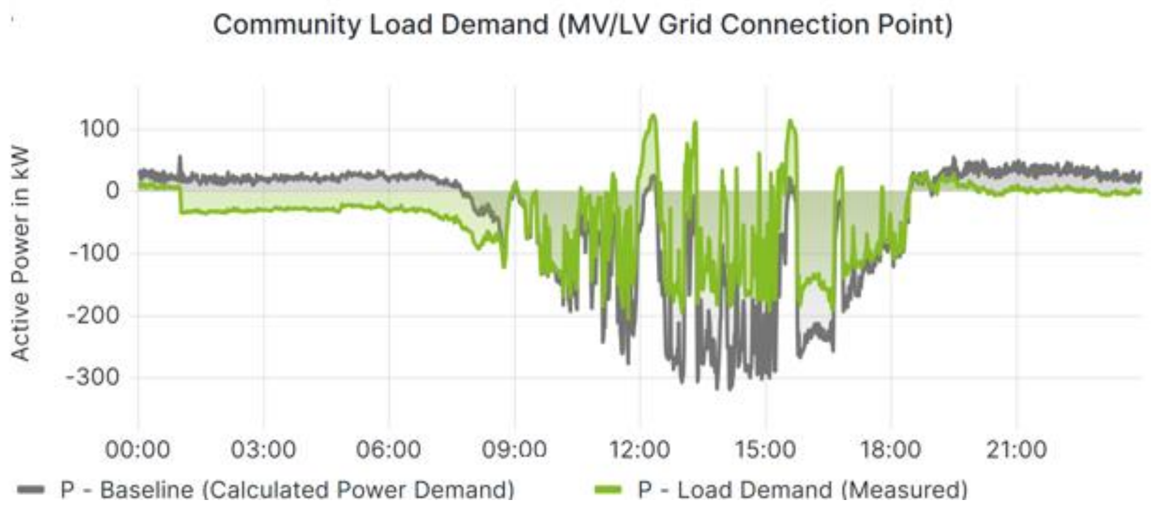

Figure 37: LV community load profile during UC1 SBO application on a day with unsteady weather (3rd April 2022)

5.8.2. UC 2

The evaluation of the KPI performance of UC 2 showed that:

1) An achieved 99% of flexibility availability (KPI_PR_03) indicates that the implemented field-test setup provides a high availability. The KPI thus confirms that the implemented field test set setup is sufficient for the evaluation of UC algorithms.
2) The KPI_DE_05 shows that the responsiveness of the ALF-C balancing scheme in combination with the field-test setup has a short latency and meets the requirements of the initially targeted 5 minutes. The dispatching of flexibility request into a measurable power flow value at the MV/LV grid connecting feeder, confirming the execution, takes places in under 2 minutes. The quick responsiveness meets the requirements for prequalification for the participation on secondary control power markets.
3) The main difference between requested setpoint and achieved setpoint of 5.3 kW (8%) measured with KPI_DE_06 shows that the balancing scheme based on a 15-minute control cycle is sufficient for the UC application. However, deviation between requested and measured load exchange at MV/LV grid connecting point during UC 2 application is the result of stochastic and highly dynamic changes of the community load demand and PV generation, especially during daytime. The performance of the ALF-C balancing scheme might be increased through a shorter duration of the control-cycle.
4) The KPI target values for UC 2 have been achieved and prove the success of the implementation of the ALF-C balancing scheme and the field-test setup. In addition, it has been shown that the set KPI target values were realistic and appropriate.
5) Automation of test runs can save a significant amount of resources and time and improve repeatability. For UC2 testing, the ALF-C interface for triggering requests from external market participants (DSO, TSO, aggregators) was simulated and automated by implementing a so-called runbook. As a result, the testing of the ALF-C prioritization algorithm was considerably simplified and less error-prone than manual input via a GUI.
6) Incoming flexibility requests can only be executed when there is sufficient flexibility storage capacity in the community/LV-grid. When flexibility requests from higher grid management instances (DSO, TSO, market) cannot be fulfilled due to a lack of available flexibility, it would be efficient when a second level (regional) EMS would manage these requests and dispatch them to other energy communities on the same MV feeder.

5.8.3. UC 3

Lesson Learned from UC 3 and 4 with RTO

Bulk Window - The result of load profile analysis of an MV line feeding the field test community (Abbenhausen) pointed out that the best time for bulk-based energy delivery in a 24h interval in a generation driven Scenario (UC 4) is the period from 8 p.m. to 0 a.m. in order reduce peak power on the MV line. In case of demand driven scenario (UC 3) and on sunny days, the most beneficial period for bulk exchange (import of predicted energy deficits) is in the period from 0.00 a.m. to 4 p.m. However, in case of days with unsteady weather and overcast days with less PV generation, the period from 0.00 a.m. to 9 a.m. is most beneficial for power peak reduction in the MV grid (feeder and line) for bulk energy import.

Power and Energy Demand Forecast for LV grids -The evaluation of the developed and implemented power and energy forecaster for LV communities pointed out, that the residual load demand forecast can be very accurate on sunny days. On overcast days, the forecast is still accurate at night-time (no PV generation). However, on daytime of days with unsteady weather during overcast days, the forecast can be very imprecise from morning to noon. In many cases, the forecaster is too optimistic in terms of PV feed-in compared to the actual occurred PV feed-in, which results in an imprecise generation forecast on overcast unsteady days.

Bulk-Based Energy Supply and Export - The results of UC 3 and 4 with RTO have shown that the bulk-based energy delivery and export principle has potential to uncouple LV communities from the MV-grid. Furthermore, the results pointed out that UC 3 and 4 with RTO reduce power peaks on the MV line in most cases. However, the evaluation did not show significant improvements of MV line peak power reduction by applying UC 3 and 4 compared to UC 1. However, it must be taken into account that the majority of the days considered for the UC 3 and 4 evaluation are overcast days, which are calendrically located in the transition period from summer to winter. The evaluation should therefore be carried out again for a larger number of days in order to take into account a better mix of sunny, non-overcast days and overcast days.

Example Days for UC 3

Example days of UC 3 with SBO are illustrated in Figure 38 and Figure 39. The green curve “P – Load Demand (Measured)” indicated the measured power exchange at PCC during application of UC 3 with SBO. The grey curve “P – Baseline (Calculated Power Demand)” is a computed baseline, which indicates the power exchange at PCC, if no CBES control with UC 3 SBO would have been applied. Figure 38 shows a significant peak power reduction in a 24-hour interval of an almost clear sunny winter day. In night-time, the approach reduces the power exchange closer to zero. At 0.30 a.m. to 3.00 a.m. the import of the energy bulk takes pace, which displays the energy deficits that has been computed based on the load and generation forecast for the present day. At daytime, as soon as PV generators begin with renewable feed-in, minor fluctuations occur. Fluctuations do not cause higher power peaks.

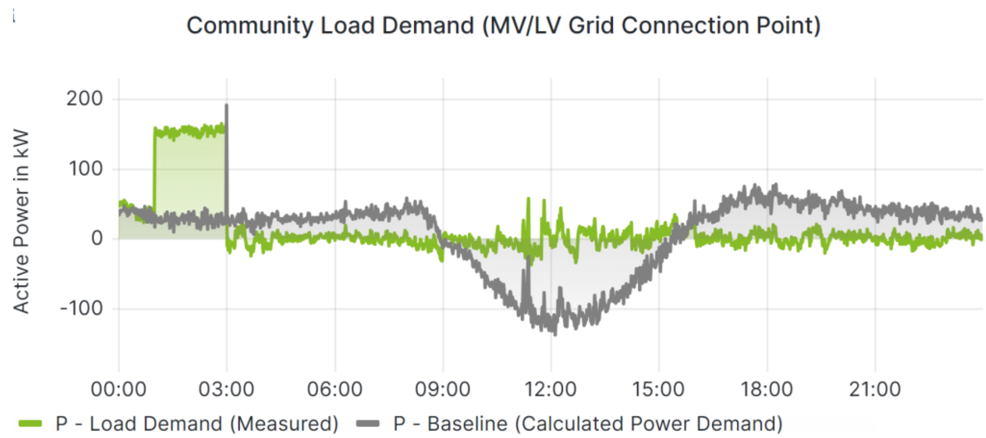

Figure 38: community load profile during UC 3 SBO application and with sufficient storage capacity

Figure 39 shows the effect of an underpredicted energy demand of the community on a demand driven day that displays no surplus of generation. The predicted energy deficit of 245 kWh for the illustrated day (19th November 2022) has been imported as bulk from 0.30 a.m. to 3.a.m. At 10.30 a.m. the bulk is completely depleted. The storage is not available for additional balancing in the grid. Thus, the peak load of the 24-hour interval is not reduced.

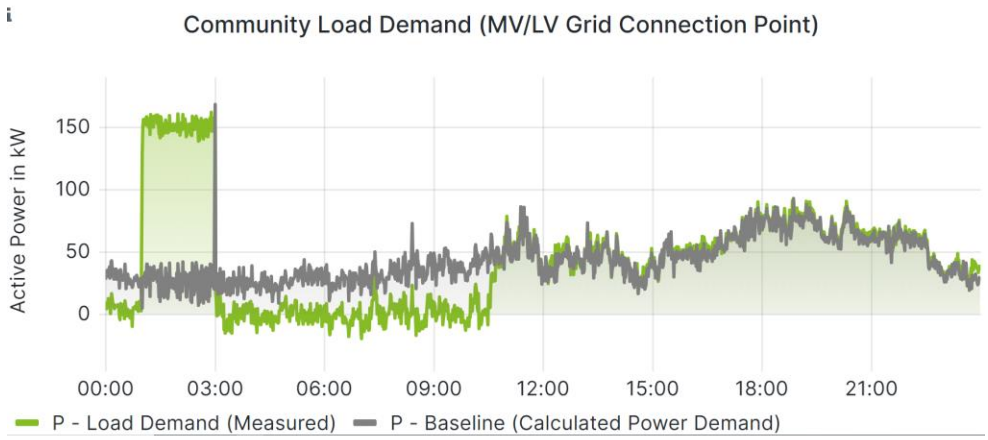

Figure 39: community load profile during UC 3 SBO application and without sufficient storage capacity

5.8.4. UC 4

Lessons Learned from UC 4 with SBO will be illustrated on example days in Figure 40. The meaning of the curves is identical to the figures in the previous section. The figure shows an example for a sunny clear summer day (7th April 2023). The example illustrates the bulk energy export at 00.30 a.m. to 04.00 a.m. and reduction of export peaks in the period from 10.00 a.m. to 17.00 a.m. The example makes illustrates that in the 24-hour period a reduction of the absolute peak power value from 300 kW to approx. 150 kW was achieved. The measured power exchange curve (green curve) shows almost a straight line in bulk export period. Same applies at times of generation peak times, but with small fluctuations around the value of 150 kW. As soon as the consumption exceeds local generation the power exchange decreases almost to zero as the load demand of the LV community is served by the CBES.

The example shows that UC 4 with SBO applied on a clear sunny day and using an accurate generation and consumption forecast is able to a.) to reduce the peak power value within 24-hours, b.) to increase the local self-consumption, c.) export surplus of generation at suitable time for the MV grid.

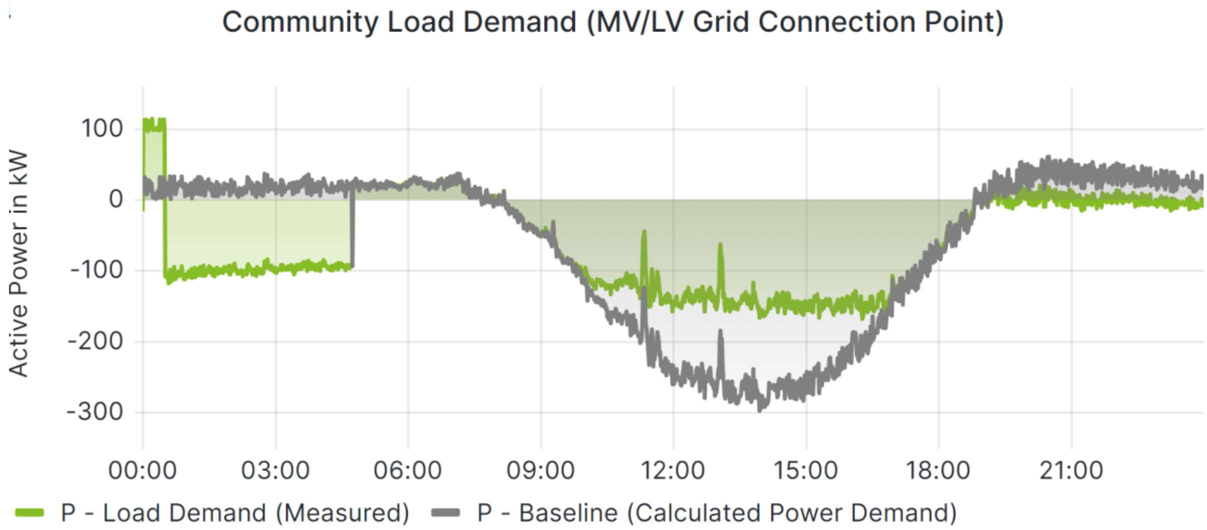

Figure 40: community load profile during UC 4 SBO application and with sufficient storage capacity

5.8.5. Forecast of Generation and Demand in LV Grids

The SBO balancing approach as well as the determination of energy amount to be imported as bulk package in UC 3 or exported as bulk package in UC 4 is based on a power exchange forecast that predicts the residual load exchange at PCC. A detailed description is provided in section 2.5. Results of evaluation are described in section 4.1. Gained lessons learned will be described on the example of Figure 41 and Figure 42. The blue curve indicates the residual power exchange at MV/LV grid connecting feeder, determines 24-h ahead and the grey curve indicates the measured power exchange (baseline). The lessons learned are:

- The factor of scaled generation and demand forecast must be continuously adapted according to the changes of the technical characteristics of the grid, e.g., increase of installed generation capacity of PV or loads.

- On clear sunny days, the forecast is able to predict the residual power exchange with moderate accuracy (see Figure 41)

- The implemented forecast leads to over prediction and underprediction of PV generation on unsteady and/or overcast days (see Figure 42).

- The generation forecast is not able to predict rapid power fluctuations (see Figure 42).

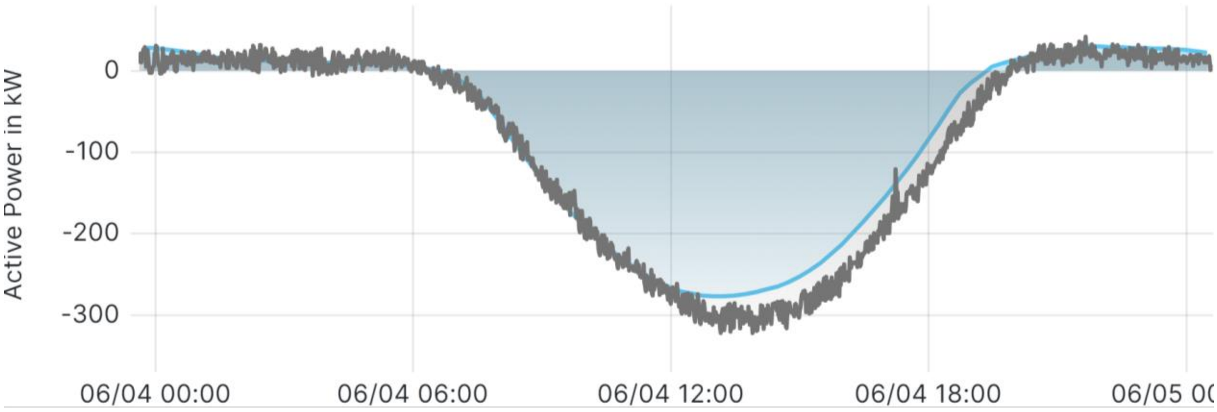

Figure 41: Power exchange forecast on clear, sunny Days

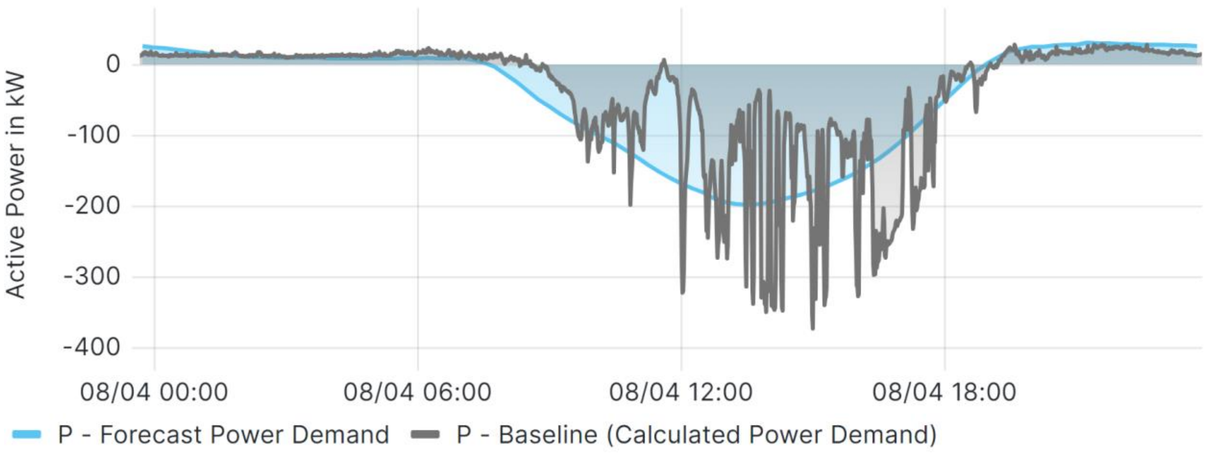

Figure 42: Power exchange forecast on unsteady, overcast days

6. Open Issues and Potential Areas of Further Research

This chapter provides an overview of open issues and areas of further research on 1.) related to the UCs and 2.) general topics.

6.1. UC related Open Issues and Areas of Further Research

Improvement for RTO Mode

The results of power peak reductions with a RTO mode with a measurement-control cycle of 15-minutesintervals showed, that power the in case of rapid feed-in fluctuations from PV contradictory effects may occur leading to even higher power peaks. These contradictory effects might be solved by increasing the frequency of the control cycle, e.g., up to 5-minute. It is necessary to investigate which cycle length is required to eliminate the observed negative effects and evaluate the ratio of cost and benefit.

Feedback Loop for SBO Mode

The conclusion of SBO evaluation pointed out that a feedback loop for SBO balancing is required to improve grid beneficial effects (e.g., power peak reduction). In many cases on unsteady, overcast days the SBO continuous CBES control in LV grid to compensate day ahead predicted PV generation that never materialised, which lead to charging batteries with energy from the MV grid. A possible solution would be an extension of ALF-C with a second-level control algorithm that continuously checks whether the forecast used as input for the SBO meets reality (e.g., measured data from local weather station). If the forecast error is significant, the SBO should stop or change to the RTO as the schedule is no longer optimal.

Load Forecast Accuracy

The SBO mode in the present demonstrator is based on a generation and load forecast. The load forecast is based on a calibrated standard load profile (see chapter 2.5). However, the accuracy of the load demand forecast for low-voltage grids as applied in the German demonstrator can be improved by applying additional analysis (e.g., DeepLearning). For example, historic measurement data of the load demand could be analysed to identify time-depending scaling factors to be applied to SLP to put respect to seasonal load demand characteristics. Furthermore, the load forecast could be improved by adding sensitivity factors that put respect to different weather forecast data. For example, analysis could be applied to identify the sensitivity of the load demand on the weather, by determine the sensitivity of the load demand on,e.g., temperature, precipitation, wind and other, varies. Additionally, other temporal influencing factors could be analysed for relevance e.g., social behaviour and thus the characteristics of energy consumption in LV grids, such as vacations, public holidays.

Generation Forecast Accuracy

The PV feed-in in low-voltage grids is not only influenced by global radiation values and cloud cover. Temperature and irradiation angle on the panels of residential roof-top PV systems also have an effect on the feed-in. An analysis and evaluation of the sensitivity of the residual PV feed-back on these data could provide factors as outcome that could improve the accuracy of PV forecasts.

Storage Capacity Drop of CBES

One learning gained during the field test phase is the drop of storage capacity of CBES. During the 3 years of the field test phase the storage capacity has decreased by 9% from about 850 kWh to 774,5 kWh. This is a relevant aspect to be considered, when applying UC with SBO mode as the reduction of storage has a negative effect on the UC performance. Future application of the control mode may be improved by putting respect to this effect, which is not a characteristic effect for the CBES, but for most storage technologies, that will be allocated in households has resident PV storage system or electric vehicles.

7. Conclusion

The German demonstrator under lead of Avacon has implemented an EMS that enables monitoring and optimal control of battery storage in low voltage grid levels to relieve the electric distribution grid from additional stress caused by residential PV systems. Four UCs have been formulated to implement a local balancing scheme to coordinate flexibility control, to allocate flexibilities for maximising the benefits of DSO and customers, and to demonstrate informational and temporary uncoupling of LV and MV grids by handling energy supply and export in bulk energy packages. The developed EMS and the corresponding IT and communication infrastructure have been implemented from the scratch and integrated into the Platone Open Framework to utilize services provided by DSO TP and BAL relevant for performing the defined UCs. For the validation and evaluation based on sets of predefined KPIs, UCs have been applied in a future-relevant and scalable environment that consists of a community located in the LV grid level that displays high generation capacities from rooftop PV systems. The field test setup has been added by the installation of sensors, e.g., a PMU in a secondary substation, a CBES to provide flexibility for control, and residential HBESs operated in combination with the corresponding rooftop PV systems.

What has been recognized at an early stage of the project is the importance of the informational involvement of the municipality, local authorities and customers to mitigate risk for the implementation of a demonstrator that consist of hardware components, e.g., CBES that requires official permission, free space considering fire prevention and other safety limitations, grid connections, etc. Furthermore, the involvement of customers at an early stage has been proven to be beneficial for the engagement as technical hurdles at customers premises could be identified soon and individual technical requirements in regard to the HBESs taken into account.

UC algorithms have been successfully formulated in 62559-2 which supported and simplified the process for identification and documentation of relevant UC steps, actors, systems and services. Considering that the whole system was built from the ground up, UCs were operable with limited data, i.e., active power measurement from a secondary substation bus bar and MV line, active charging power and state of charge data of the CBES, external generation forecast and SLP. For all UCs, a near real-time RTO with a 15-minutes measurement-control cycle has been designed for balancing the overall PV generation and consumption of the community. A second mode for balancing has been applied for UC 1 with an SBO that applies optimization on a day-ahead forecast of the community residual power demand.

The decision to implement the developed EMS in MS Azure with PowerApps simplified the development activities as it allowed the use of standardized interface, e.g., API via MQTT protocol. This decision allowed the implementation of the developed local balancing mechanisms and simplified the integration of services provided by the Platone Open Framework, proprietary services used for data acquisition, e.g., from PMUs, and external services providers. Additionally, it facilitated the dispatching of setpoints for controlling CBES and HBESs necessary for the successful implementation of the above-mentioned balancing mechanisms.

The results of data collected during the project phase gave valuable insights of great UC performance and the power and energy demand characteristics of the community. Measurements data analysis of power exchanges at PCC showed that the selected community displays significant surplus of generation, high export peaks and amounts of exported energy as well as volatile energy exchanges with the MV grid. Thus, PV generators are significantly shaping the residual load profile of the community and the decisive factor for obtaining a peak reduction for most of the days during the year. UC 1 with RTO, especially on clear sunny days, has demonstrated that an export peak reduction and an increase of local PV self-consumption can be clearly achieved and adds benefit to the DSO and the community. Indeed, UC 1 with RTO and SBO achieved an effective uncoupling of the LV grid from the MV grid, while the forecast-based SBO also allows an informational uncoupling for at least 24 hours. On the other hand, on several days with unsteady overcast weather and by applying UC 1 with both, RTO and SBO, the measured power peak values indicated higher peaks compared to baseline (non-control). A comparison of both modes based on average daily showed that neither algorithm showcased superior effects to the other. However, the RTO performance limiting factor is the limited storage capacity of CBES and the control cycle of 15-minutes, which cannot balance volatile PV feed-in rapid enough. A closer to real-time, e.g., 3 minutes, could improve peak reduction. In case of SBO, underperformance is the result of non-accurate forecast inputs and the lack of consideration of external factors that influence the power exchange at PPC. Increasing the forecast accuracy could improve peak reduction and could strongly illustrate the advantage of SBO. Identifying grid shaping factors and analysis of sensitivity has been identified as topics for further research.

UC 2 has successfully demonstrated the ability of the proposed EMS to coordinate flexibility control with centralized grid operation and the ability to balance the CBES with volatile generation and demand in the community to provide a requested value of power exchange at PPC, e.g., for grid stabilising purposes. Analysis of UC 3 and 4 have highlighted the potential of reducing power peaks in the MV grid by applying of an ex-post energy supply in bulk on demand driven days of the community (UC 3) and ex-ante export of surplus of generation on PV-generation driven days. Both UCs showed potential for significant improvement by applying a more accurate day-ahead forecast of the community energy demand.

In conclusion, the developed EMS in conjunction with the Platone Open framework demonstrated excellent results and showcased its great potential for the DSOs to improve grid operation and facilitate the energy transition. The results and lessons learned gained added great value in all areas of Avacon business department from the education depart over legal, IT, gird operation and installers in the field.

8. List of Tables

9. List of Figures

10. List of References

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11. List of Abbreviations

Abbreviation	Term
ALF-C	Avacon Local Flex Controller
API	Application Programming Interface
BAL	Blockchain Access Layer
CBES	Community Energy Storage System
D	Deliverable
DER	Distributed Energy Resources
DSO	Distribution System Operator
EMS	Energy Management System
EnWG	Energiewirtschaftsgesetz
GUI	Graphical User Interface
CBES	Local Battery Energy Storage
LV	Low Voltage
MV	Medium Voltage
KER	Key Exploitable Result
KPI	Key Performance Indicator
P	Active Power
PCC	Point of Common Coupling (MV/LV grid connection point)
PMU	Phasor Measurement Unit
PV	Photovoltaic
RTO	Real Time Operation
REC	Renewable Energy Community
RES	Renewable Energy Sources
SBO	Schedule-Based Operation
SCADA	Supervisory Control and Data Aquisition
SLP	Standard Load Profile
SO	System Operator
SOC	State of Charge
SOE	State of Energy
T	Task
TSO	Transmission System Operator
UC	Use CaseUC
VDE	Verein Deutscher Elektroingenieure
WP	Work Package

ANNEX

A.1 Workshop on Lessons Learned - Results