Platone

PLATFORM FOR OPERATION OF DISTRIBUTION NETWORKS

Platone

PLATform for Operation of distribution NEtworks

D5.6 v.1.0

Use Case 3 and 4 Demonstration Report

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Abstract

This document contains a demonstration report on use case 3 and 4 applied in the German demonstration trial of the H2020 Platone project. The report contains a description of motivation, a description of the updated field test setup and algorithms. The use case evaluation is based on Key Performance Indicators (KPI). This deliverable assesses energy and power demands of a photovoltaic driven community, puts it into relation to the residual net load demand of multiple communities connected to a single MV line, with and without the application of UC 3 and 4 algorithms. Further, this report assesses the forecast for the residual load and energy demand for a low voltage community and the reduction of peak loads of a bulk-based energy supply on the MV grid.

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.

Platone is using blockchain technology to build the Platone Open Framework to meet the needs of modern DSO power systems, including data management. The Platone Open Framework aims to create an open, flexible and secure system that enables distribution grid flexibility/congestion management mechanisms, through innovative energy market models involving all the possible actors at many levels (DSOs, TSOs, customers, aggregators). It is an open-source framework based on blockchain technology that enables a secure and shared data management system, allows standard and flexible integration of external solutions (e.g., legacy solutions), and is open to integration of external services through standardized open application program interfaces (APIs). It is built with existing regulations in mind and will allow small power producers to be easily certified so that they can sell excess energy back to the grid. The Platone Open Framework will also incorporate an open-market system to link with traditional TSOs. The Platone Open Framework will be tested in three European demos and within the Canadian Distributed Energy Management Initiative (DEMI).

In WP 5 of the Platone project, Avacon with the support of the consortium, has conceptualized, implemented and successfully integrated a decentral Energy Management System (EMS) prototype, named Avacon Local Flex Controller (ALF-C) to control small scale flexible assets located in local low-voltage grid section. The ALF-C applies SCADA / ADMS functionalities to provide services to DSO, TSO and grid customers (communities). Its functionalities create more transparency on generation, consumption and the status of the grid. It applies a local balancing scheme that integrates small scale flexible assets and enables monitoring and control features. In a wider concept of grid operation by system operator (SO), the ALF-C displays a prototype of an automized, semi-autonomous edge computing energy management instance, as part of a decentral flexibility management mechanism that follows the edge computing paradigm. It enables SO to extend the flexibility portfolio by building a bridge to the increasing number of untapped dormant flexible assets located in LV-networks in order to increase the grid hosting capacity for renewable energy and reduce power peaks in distribution network.

The implemented energy management system, ALF-C is tested in a community with 89 households that has a significant volume of roof top photovoltaic (PV) generation that often exceeds local generation. This community is representative of future generation and consumption characteristics. A large community battery energy storage (CBES) is installed in the community to model future flexible power and storage potential provided by domestic battery storages operated by households.

With Use Case (UC) 3 and 4, Avacon implements a balancing scheme that supplies communities with energy in advance of the demand by making use of available storage capacity to buffer forecasted deficits for later withdraw by the low voltage community. Bulk delivery and the withdraw of energy from storages are scheduled in such a way, that the feeding MV/LV transformer will be released from peak load penetrations and self-consumption of generated energy from photovoltaic will be increased.

The UC balancing applied and evaluated in this report is based on a Rule-Based Control (RBC) and according to a day-ahead forecast to determine the residual load and energy demand of the low voltage community in the trial. The scheduling of bulk windows is based on historical measurement data taken from the feeding MV line. This report also describes a second UC control approach involving a Schedule-Based Control (SBC) with optimization, which targets to improve the peak load reduction at PCC considering the technical limits of available storages capacities in the optimization.

As the forecast of the power exchange at the PCC can provide accurate results that benefit UC 1 (Islanding-Mode) [1], UC 2 (Flex-Share-Mode) [2], UC 3 and 4. The accuracy of this forecast along with the KPI associated with the performance of the applied logics for UC3/4 are presented, too to draw the final conclusion about lessons learned and define the path for future developments.

Authors and Reviewers

Main responsible		
Partner	**Name**	**E-mail**
Avacon Netz		
	Benjamin Petters	benjamin-georg.petters@avacon.de
	Navreet Dult	navreet.dult@avacon.de
	Christoph Jätz	christoph.jaetz@avacon.de
Author(s)/contributor(s)		
Partner	**Name**	
RWTH Aachen		
	Amir Ahmadifar	aahmadifar@eonerc.rwth-aachen.de
Reviewer(s)		
Partner	**Name**	
Siemens		
	Brunella Conte	brunella.conte@siemens.com
	Carlo Arrigoni	carlo.arrigoni@siemens.com
APIO		
	Alessandro Chelli	alessandrochelli@apio.cc
	Mattia Alfieri	m.alfieri@apio.cc
Approver(s)		
Partner	**Name**	
RWTH Aachen		
	Amir Ahmadifar	aahmadifar@eonerc.rwth-aachen.de

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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 aims to removing technical and economic barriers to the achievement of a carbon-free society by 2050 [3], 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. The Platone platform will be tested in three European demos (Greece, Germany and Italy) and within the Distributed Energy Management Initiative (DEMI) in Canada. The Platone consortium aims to go for a commercial exploitation of the results after the project is finished. Within the H2020 programme “A single, smart European grid” Platone addresses the topic “Flexibility and retail market options for the distribution grid”.

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 called 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 low-voltage networks and local balancing mechanisms to foster the integration of renewable energy generation an increase the efficiency of existing grids.

This report is dedicated to UC 3 and 4 of the German demonstrator. In these UCs, the balancing scheme applied by the ALF-C prototype controls the community battery energy storage (CBES) in such a way that a community is energetically uncoupled from the MV grid. Energy deficits of an LV community shall be provided ex-ante (UC 3) and surplus of generation exported ex-post (UC 4). The algorithm aims at reducing the stress in the MV grid and the MV/LV feeder and increase the local PV self-consumption. The UC algorithms follow rules-based control (RBC) and schedule-based control (SBC) with optimization logics, both operating in conjunction with forecast profiles of MV line and the MV/LV feeder.

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 performed 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 5.3.3 “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 low voltage grid.

1.2 Objectives of the Work Reported in this Deliverable

The objective of this deliverable is to exemplify the implemented scheme for supplying energy to communities located in low voltage grids ex-ante (UC 3) and export surplus generation in bulk ex-post at suitable times. Further, this deliverable evaluates the demonstration results of the UC 3 and 4 implemented in the demonstrator performed based on demonstrator specific KPIs. Based on the collected results, lessons learned and the implication on future operation are described.

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 outlines the motivation for implementing an ex-ante energy supply and ex-post energy export. Chapter 3 gives an overview of the field test setup and changes of technical properties since the last reports, relevant for the UC evaluations. Chapter 4 describes details on the UC algorithm. Chapter 5 provides technical evaluation of UC 3 and 4 applications in the field. Chapter 6 outlines the lessons learned, conclusions and implications on forthcoming applications.

1.4 How to Read this Document

This report provides a detailed explanation in the motivation for the UC 3 and 4 approaches, the latest specification of assets located in the field test environment. A detailed description of all assets implemented in the demonstrator is provided in Deliverable 5.4 [1]. This report provides a description of UC 3 and 4 algorithms, which have been described as a first version in D5.3. The Rule-Based Control balancing approach described in this report has been also applied in frame of UC1 and UC 2. The demonstration report on UC 1 is provided in D5.4 and the report on UC 2 in D5.5 [2].

2 Motivation

In the past years the number of distributed energy resources in rural electric distribution grids is constantly increasing. Recent geopolitical developments, the resulting energy crisis and inflation as result motivates households to invest in roof-top photovoltaic system and heat pumps in order to improve energetically independency from the public energy supply and increasing energy market prices. As consequence rural distribution grids are facing a rising number of Distributed Energy Resources (DER) consisting of Renewable Energy Sources (RES) feeding energy into the grid, e.g., roof-top photovoltaic systems, and consuming electric energy for generating heat, e.g., heat pumps, or for charging of electric vehicles. The increasing number of PV generators located in communities in Low Voltage (LV) grids are about to generate energy surplus that exceeds local demand even within 24-hours periods. Communities with high number PV generators and relatively low power demand, the generation excess leads to reverse power flows on the medium voltage (MV)/LV grid connection point from the LV grid towards the MV grid. A substantial volume of reverse power flow can affect the distribution feeder's voltage profile and increase distribution feeder voltages beyond the technical limits. Further, high power flows can lead to thermal violation of the transformer and LV line branches, which at the current stage can only be solved through conventional grid reinforcement or expansion. Voltage violations can be avoided through implementation of tap-changing transformer in secondary substations as alternative.

Among the biggest challenge for DSO operating rural distribution grids with high shares of distributed energy resources (DER) is the stochastic nature of a network demand that is interfered with by local production. While demand-only communities in the LV grid voltage level can be planned and operated rather reliably, high shares of DER, e.g., roof top photovoltaic systems of residential households, charging stations for electric vehicles, introduce an element of uncertainty that makes it difficult to plan and design networks efficiently. Uncertainty in the planning process must lead to over-dimensioning of assets to account for the risk of unexpected load configurations. One possible way to reduce uncertainty, and hence increase efficiency and reliability in distribution grid planning and operations, is to leverage flexibility and smart control algorithms to uncouple the low-voltage network from its MV-feeder by employing a packet-based approach to power supply. The residual demand of a network after local production can be forecasted and be delivered to the network in bulk in advance. The energy can be stored in local batteries from which customers can withdraw energy as they please without affecting the MV-feeder. The same approach can be applied to a scenario at which the local generation from photovoltaic exceeds local consumption. Generation and consumption of a community can be forecasted, and the residual surplus of generation can be stored in local batteries from which the community can withdraw renewable energy (collective self-consumption) in night times. The remaining surplus of energy can be exported ex-ante at a suitable time for higher level distribution grid.

Further reasons for UC 3 and 4 implementations are the results, experiences and lessons learned collected during the application of UC 1 and UC 2. The load and energy demand characteristics of the field test community and the results and lessons learned from UC 1 application are described in Platone Deliverable 5.4 "Use Case 1 Demonstration Report" [1]. The evaluations have pointed out that the PV-driven community on average summer day displays a high surplus of generation, which exceeds the total demand withing 24-h period by factor eight. The community battery energy storage system (CBES) with a capacity of 850 kWh was not high enough for compensation in the 24h-period either. Consequently, a control scheme aiming to reduce peak loads in MV-level on a longer term (>24h) requires a pro-active ex-post discharging of the CBES. To address this issue rule-based control scheme of UC 1.0 has been further developed to a schedule-based control scheme with optimization (UC 1.2), aiming to minimize load peaks at the MV/LV feeder by taking into account the available storage capacity and forecast of PV generation. The results and a comparison of both control approaches in PV-driven rural distribution grids are described in [4]. However, both control schemes do not consider the load situation in the feeding MV-grid level nor the grid operating DSO has the possibility to influence point of time and duration of export of generation surplus (UC 4) or import of energy in bulk (UC 3). This lack of control shall be addressed in UC 3 and 4.

3 Field Test Design

In the following subchapter relevant components will be described that have been involved in the UC 1 demonstration.

3.1 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 homes that hosts about 89 households. About 23 houses are equipped with roof-top photovoltaic systems. Further, 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, are sent to a cloud database. For more details see [1].

The community is representative for future communities in distribution grids 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 system to increasing PV self-consumption.
4.) displays increasing share of sector coupling technologies, using electric energy for generating heat, e.g., heat pumps.

Figure 1 displays a picture of the community Abbenhausen selected for the field test trial of the demonstrator.

Figure 1: Picture of the Community Abbenhausen selected as Field Test Region

3.2 Relevant Actors and Components of Use Case 3 and 4

Deliverable D5.3. provides an overview of relevant actors and components of the demonstrator. 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 the following.

Community Battery Energy Storage (CBES)

The CBES 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. The CBES simulates storage potentials provided by future residential household batteries and electric vehicles providing bi-directional power through charging and discharging. Technical properties of the CBES have changed. The changes affect the 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 2 years, the usable (net) capacity and the corresponding SOE (SOC = 100%) equals 779,5 kWh. The changes are summarized in Table 1.

Table 1: CBES Changing Storage Capacity

	Date of Delivery 1. February 2021	Date of UC 3 and 4 Demonstration Report 28. February 2023
SOC	100 %	100 %
SOE (SOC)	880 kWh	779,5 kWh

Residential Roof-Top Photovoltaic Systems

The community of Abbenhausen is characterized by a high share of residential customers with roof-top photovoltaics system. 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 feed into the grid, which effects the load flow in the LV and MV grid. Also, the installed generation capacity has changes during the field test phase, following the trend of towards a steady increase of PV systems observed in the grid service area of Avacon.

On the political developments starting in 2022, the resulting energy crisis and the commitment of the German Federal Government to stronger promote the expansion of renewable energies, the demand in private sector for technologies improving self-consumption and the degree of self-sufficiency is 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 2 summarizes the changes of the installed PV generation capacity during the demonstrator phase.

Table 2: 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 28. February 2023
PV Installed Generation Capacity	410 kWp	445 kWp
Number of roof-top photovoltaic systems	26	30

At this point, it has to be mentioned that the number for installed generation capacity for roof-top PV system allocated in the field test region of the demonstrator reported in Deliverable 5.3 (302 kWp in [5]) was not correct and the correct value was indeed 410 kWp which is reported now in this report. The information provided in Deliverable 5.3 was based on entries in databases. However, the entries in the system do not always reflect the real state of the network. The update of databases after the confirmation of officials and after of the addition of new PV grid connections typically takes place with a delay of several months.

Household Battery Energy Storage Systems (HBES)

In the demonstrator field trial, 5 households participate in the project, which provide one directional flexibility from HBES. The HBES are 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 HBES steering is limited to the interruption of battery charging to be in line with the current regulation and legislation, which is set in §14a EnWG. Due to ongoing regulation and legislation the flexibility, that can be provided by HBES operated with PV-systems 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, the HBES can only be interrupted during times PV generation.

Table 3 gives an overview of the technical properties of HBES that have been implemented in the demonstrator.

Table 3: Overview of HBES 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

3.3 Definition of Data for UC 3 and 4

An overview of measurement data and the sign conventions sign relevant for UC 3 and 4 is listed in Table 4.

Table 4: Measurement Data Definition and sign Conventions

Data	Definition	Convention of Sign
$P_{M, PCC}$	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.	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.
$E_{M, PCC}$	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.	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.
$E_{F,PCC}$	Forecasted Energy Exchange at PCC The data are forecasted in kilowatt hours (kWh) on the LV busbar of the MV/LV feeder. The values indicate the forecasted net energy demand of the community of Abbenhausen considering its total local generation and consumption.	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.
$E_{C,PCC}$	Computed Energy Exchange at PCC The data is calculated in kilowatt hours (kWh) and indicate what would be measured on the LV busbar of the MV/LV feeder when no use case was applied. The values indicate the computed net energy demand of the community of Abbenhausen	Positive values indicate the amount of energy that would have been provided by the MV grid (to meet the LV grid local consumption) when no use would be running and negative values indicate the export of the

	considering its total local generation and consumption	excess of energy from LV to MV grid when no use case was applied.
E_{ave}	Average Energy Exchange at PCC The data is measured in kilowatt hours (kWh) on the LV busbar of the MV/LV feeder and averaged. The values indicate the net energy demand of the community of Abbenhausen considering its total local generation and consumption.	Positive values indicate a load flow from the MV grid into the LV grid (consumption) and negative values indicate export power flows.
$P_{C, PCC}$	Computed Active Power Exchange at PCC Computed data in kilowatt (kW) indicating the net load demand of the community of Abbenhausen considering its total local generation and consumption., that would have been measured, if no UC control would have been applied (baseline)	Positive values indicate a load flow from the MV grid into the LV grid (consumption) and negative values indicate export power flows.
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	Positive values indicate battery consumption/charging and negative values indicate discharging of battery.
$P_{F,PCC}$	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.	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.
P_{peak}	Peak Power Exchange at PCC The data is measured in kilowatt (kW). The value indicates the peak load of the community of Abbenhausen.	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.
$P_{peak,c}$	Computed Peak Power Exchange at PCC The data are computed in kilowatt (kW). The value indicates the computed peak load of the community of Abbenhausen.	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.
UC_{st}	Use Case Start Time This value indicates the start time of a use case	Only positive values are considered.
UC_{end}	Use Case End Time This value indicates the end time of a use case	Only positive values are considered

BW_{st}	Bulk Window Start Time This value indicates the start time of the bulk	Only positive values are considered
BW_{end}	Bulk Window End Time This value indicated the end time of the bulk	Only positive values are considered.
SOC	State of Charge This value indicates the state of charge of the battery and is measured in %.	Only positive values are considered.

4 Use Case 3 and 4 Description

The target of UC 3 is to uncouple the load and energy demand of the LV community from its feeding MV-line by employing a packet-based approach for energy supply. The UC shall be applied in a demand driven scenario in an LV community, in which the residual energy demand in a given period of time is higher than the local generation. The residual demand of the community of Abbenhausen (considering the total local generation and consumption of the community) shall be forecasted and supplied to the community (imported from the MV grid) in advance of high times of power demand by charging of local storages. The community later can withdraw energy from the storage as requested without creating additional peak loads on the MV feeder or MV line. An example of such a demand-driven scenario and further explanations are provided in section 4.2.1

The opposite principle applies to UC 4. It is applied in a generation driven scenario, in which the residual surplus of generation in a given period of time, e.g., 24 hours, exceeds the local demand. In this scenario, the battery located in the LV community is prepared to store the generated surplus, to be delivered to the MV-feeder at a fixed time window at non-critical times. An example of a gen[eration-driven scenario and further explanations are provided in section 4.2.2.

The bulk time and bulk energy will be input parameters for the ALF-C that are received by an external instance. For the fieldtest trial, a work around for these parameters are defined. In order to achieve the objectives of use case 3/4, the time window of the use case, i.e, 24 hours is divided in three windows. Figure 2 shows such a division for an exemplary day of May 30th 2021. The grey curve displays the net load demand of the community after generation ($P_{M,PCC}$) measured in the 24-hour use case time window. The three time windows of *W1, W2, W3* are defined as follows:

- W1 [$UCst$, $BWst$] is the period of time from UC Start ($UCst$) to the Beginning of the bulk window ($BWst$)
- W2 [$BWst$, $BWend$] is the period from the start of the bulk window ($BWst$) to the end of the bulk window ($BWend$)
- W3 [$BWend$, $UCend$] is the period from the end of the bulk window ($BWend$) to the end of the UC ($UCend$).

The above-mentioned use case time window division leads to two main time periods within the use case 24-hour time period:

Uncoupling Period – The uncoupling W1 and W3 are the periods of energetical uncoupling of the LV community. In this period the load and energy demand of the community is served by discharging of CBES in times of local demand exceeds local generation or by charging of battery in times local generation exceeds local consumption. In times of battery charging or discharging the load exchange at the MV feeder and lines as well as MV/LV feeder are reduced. For the CBES control in this period different balancing schemes, a Rule-Based Control (RBC) or Schedule-Based Control (SBC), have been implemented. Both control algorithms are described in [4] and [6]. The RBC is less complex since it doesn't require optimization. However, the control logic of RBC purely decides about battery setpoints based on measurements at each instance of time. This is done without taking into consideration the future forecast values and therefore the battery boundaries, i.e., maximum and minimum allowable SOCs are reached. On the contrary, SBC takes into consideration an optimization horizon and decides about the optimum setpoints of the battery based on the forecast of $P_{M,PCC}$ ($P_{F,PCC}$).

Bulk Period – The bulk period is covered by window W2. In this period the energy bulk is imported or exported. In UC 3 the energy will be imported, since this UC is applied in a demand driven scenario in which the community displays energy deficits in a 24-hour period, to be imported in advance of the occurring demand. In UC 4 the energy will be exported, since this UC is applied in a generation driven scenario, in which surplus of generation has to be exported pro-actively. The amount of energy is determined based on a forecast ($P_{F,PCC}$), which predicts for each 15-minutes the average load exchange on the PCC. The forecast of residual energy demand or surplus of generation for UC period [$UCst$, $UCend$] is computed with the forecasted residual load demand ($P_{F,PCC}$) (total forecasted consumption after total forecasted generation) for the period ($P_{F,PCC}$) $[UCst, UCend]$.

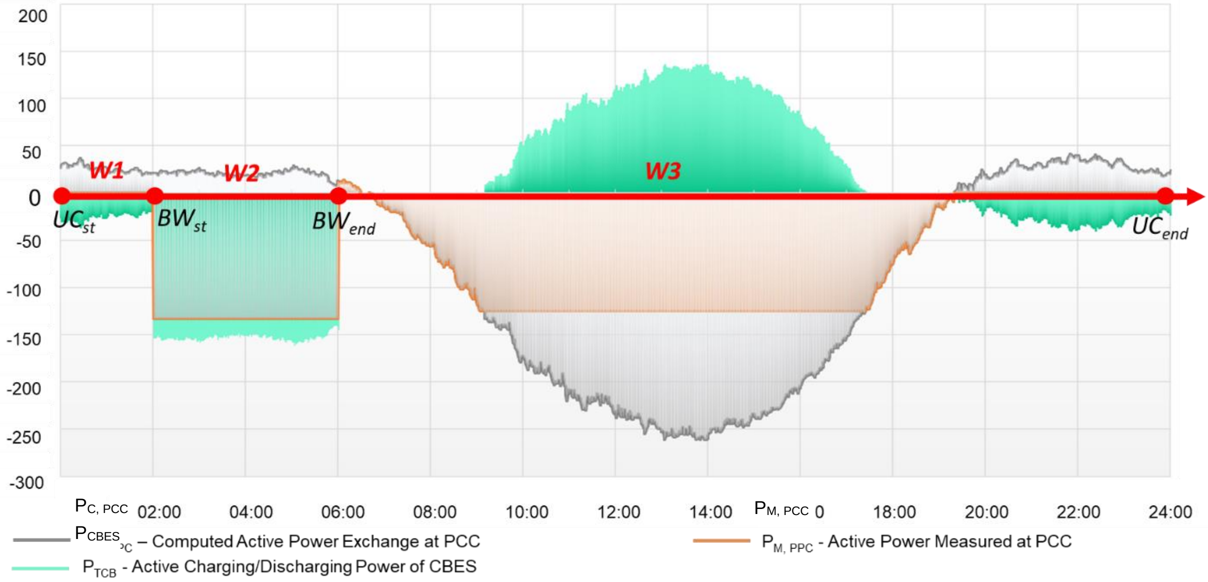

Figure 2: Use Case Time Window division into three time windows

Use Case 3/4 bulk inputs

Both UCs require a set of input data related to the bulk delivery/reception of energy as described below:

1.) Bulk window: The best time of bulk energy delivery for the MV-line and High Voltage (HV)/MV-transformer, taking into account the load on the transformer (see section 4.1.1 for more information)

2.) Bulk energy: The appropriate amount of energy to be scheduled for delivery (import or export) as bulk which is computed based on a residual net load demand forecast of the LV community. (see section 4.1.2 for more information)

Use case 3/4 control approaches

Once the bulk energy and window are calculated, two control approaches of rule-based control (RBC) and scheduled-based control (SBC) which are described respectively in sections 4.2.1 and 4.2.2 are applied to achieve the above-mentioned targets of UC3/4. It is noteworthy that in this report, the intermediate results of UC 3 and 4 demonstration field trial by implementing only the RBC will be presented and evaluated based on the presented KPIs in section 5. As it will be described in section 4.2.1, the RBC logic is applied on the (near) real time measurements of the residual power of the LV community leading to (near) real time setpoints of the storage unit(s). On the contrary and as described in section 4.2.2, the SBC logic is applied on the residual forecast of the LV community. The results associated with the application of SBC approach for UC3/4 are going to be presented in the Final Report. As SBC control approach decides about the schedule of the battery based on the forecast of residual power of the LV community, the schedule (setpoints) are prone to uncertainty in the residual forecast of power at PCC ($P_{F,PCC}$). To avoid the impact of this uncertainty, this report focuses on the intermediate set of results associated with the application of RBC. The results related to the application of SBC will be reported during the final phase of the project and the corresponding deliverable D5.7. Furthermore, both of these control approaches will be released as open source services via the respective channels as approaching the project end.

In the following sections 4.1.1 and 4.24.1.2, the above-mentioned use case bulk inputs and control approaches are going to be discussed in more details.

4.1 Bulk inputs

4.1.1 Bulk window identification (W2)

The aim of UC 3 and 4 is an energetic uncoupling of the low-voltage grid of the test site (Abbenhausen) from the medium-voltage by storage control allocated in the community. Furthermore, the UC concept foresees to reduce power peaks in the medium-voltage grid by avoiding the simultaneous power demand or export of power in times of surplus of generation from multiple local LV grids (communities) allocated along a medium-voltage line. In UC 3, residual energy deficits are determined by means of a forecast and imported into the local grid in advance of the demand by temporarily storing energy in local storages. In times of high demand, the required energy of the LV community is served through the storage. In UC 4, the opposite approach is used for the delayed export of surplus generation. The energy is imported or exported as bulk in a specific time window. The aim of the overall concept is to relieve the HV/MV feeder at the substation or the feeding medium-voltage network in times of high load peaks. Therefore, the period for the bulk exchange (W2) must be placed in periods that have the lowest load (power flows).

To make the results and effects of UC 3 and 4 measurable and assessable for KPI evaluations, the measured results are put into relation to the residual power and energy demand supplied by the feeding MV-line. The residual load profile of the MV line is computed based on the measurement data taken from the MV distribution stations "Weisse Riede" (WR) and "Beckeln" (B). The measurement takes place at the measuring points P_{WR} and P_B indicated in red in Figure 3. The measurement data provided are available as 15-minutes averaged values in 15-minute intervals. The computation of both measured values with the correct sign describes the residual power demand of all secondary substation 1 to 9 (power demand after generation).

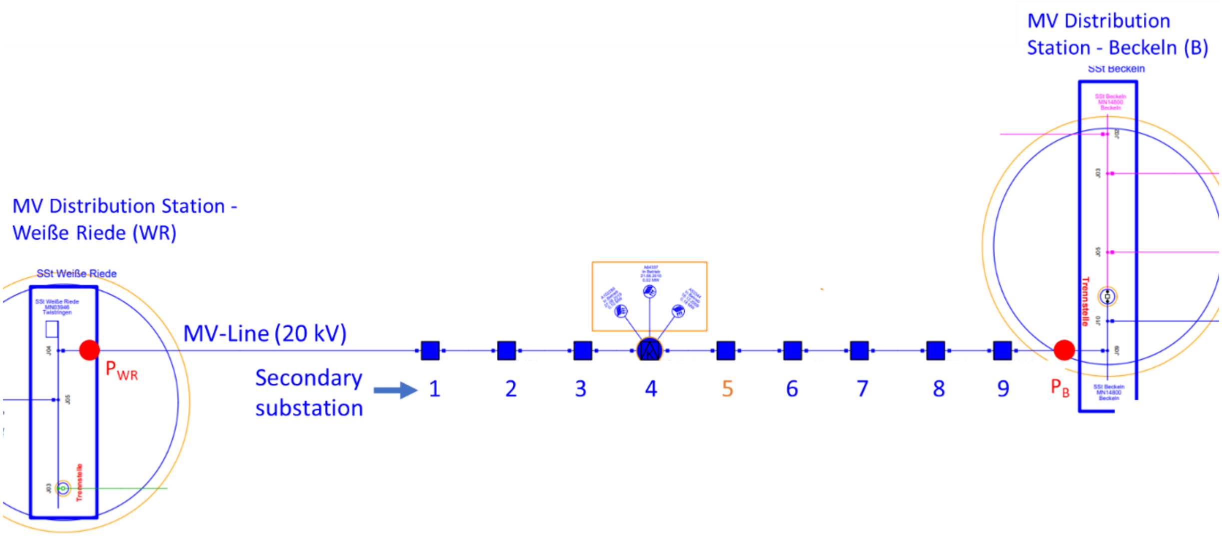

Figure 3: Grid Model MV-Line of Field Test Region

Bulk Window in a Demand Driven Scenario (UC3)

An example of the residual load demand of all communities on the MV line for 4 winter days is illustrated in Figure 4. The large red circles in this figure highlight the periods of time at which residual load reaches the highest magnitude in positive values representing peak consumption period. The yellow circles highlight the periods at which the residual load reaches the smallest magnitude in positive values, representing lowest consumption. Negative values indicate a residual surplus of generation. Figure 4 shows that on winter days, demand driven scenarios, the highest load demand peak values are achieved in the period from 2 p.m. to 10 p.m. The lowest load demand peak are achieved in the period from 0 a.m. to 9 a.m. on overcasted winter days and 0.a.m. to 4 p.m. on sunny winter days.

Instead of an uncontrolled power import, Use Case 3 aims at deploying a packet based approach, where deficit of energy in a given LV network is supplied by the stored energy in a battery, which has been imported from the MV-feeder at non-critical times. The MV line shall be relieved from additional stress from LV grid levels during times with highest load demand peak (2 p.m. to 10 p.m.). Therefore, the bulk energy should be delivered in a time window within the period of lowest demand in the period from 0 a.m. to 9 a.m. on predicted overcasted days or 0 a.m. to 4 p.m. on predicted sunny winter days. If done and coordinated properly, the highest peak demand times on the MV line will be reduced and the MV line is relieved.

Therefore, the yellow indicated periods in Figure 5 are most beneficial for MV-feeder and line when used as bulk window (W2). The periods in red cycles are most beneficial for MV- feeder and line, when used as period of battery discharging to serve the demand in the LV community.

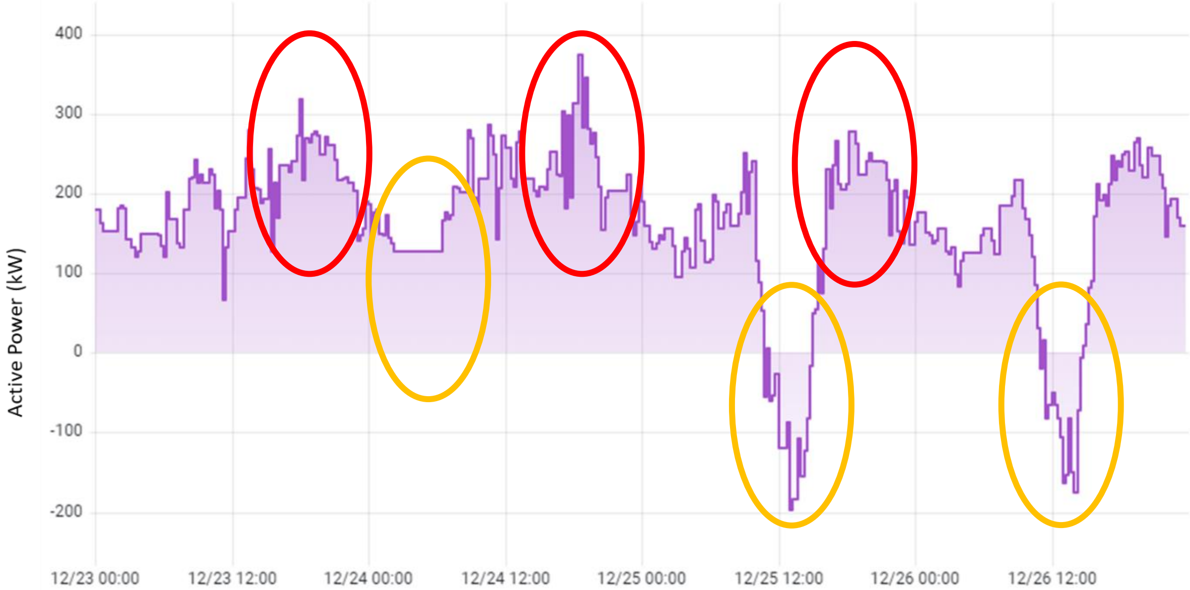

Figure 4: Residual Load demand MV Line (23 - 26.12.2021)

Bulk Window in a Generation Driven Scenario (UC 4)

An example of the residual load demand of all communities on the MV line for 2 days in summer is illustrated in Figure 5. The large red circles in this figure highlights the periods of time at which residual load reaches the highest magnitude in negative values representing peak generation period.

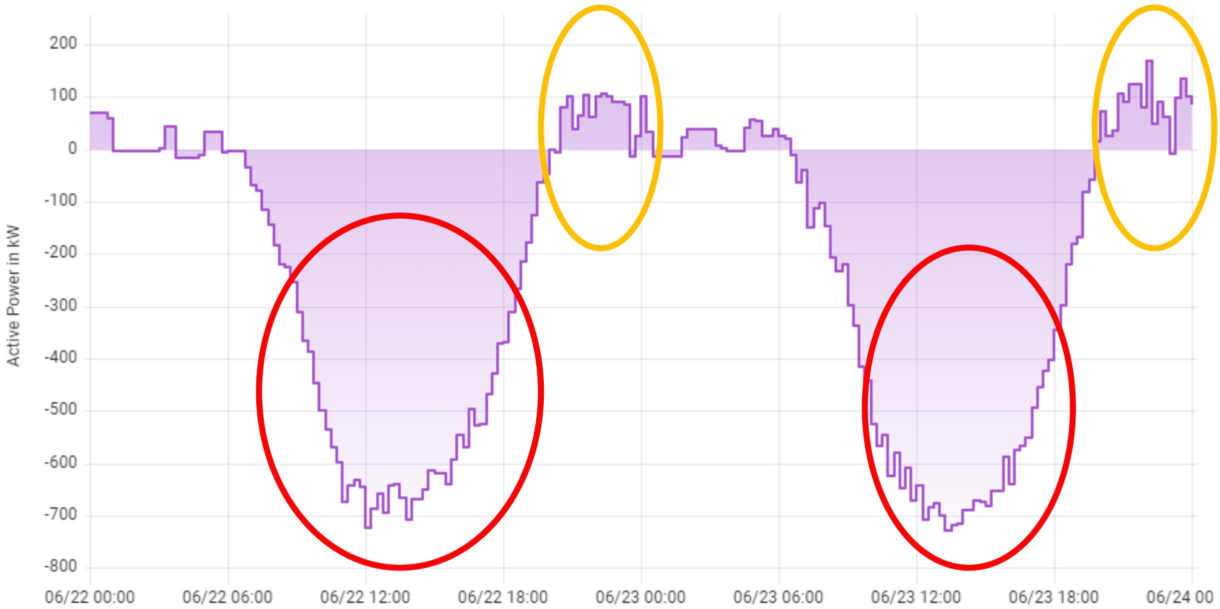

Figure 5: Residual Load Demand on MV Line (22/23 June 2022)

Figure 5 shows that on sunny summer days, generation driven scenarios, the highest peak values are achieved in the period from 6 a.m. to 7 p.m. on these days the highest load demand peaks are achieved at 8 p.m. to 0 a.m. In a demand driven scenario in winter, illustrated in Figure 4, the highest load demand peaks are achieved in the period from 3 p.m. to 0 a.m.

An additional statistical evaluation for the residual power demand characteristics on the MV line has been performed based on a dataset of measurements taken from a 2-year period. The data set consists of 15-minutes total active power values summarized for all 3 phases. Each 15-minutes interval is the average of the measured value. For this analysis, the median, mean and standard deviation has been determined at each of the 96 intervals across all days. The results are shown in Figure 6.

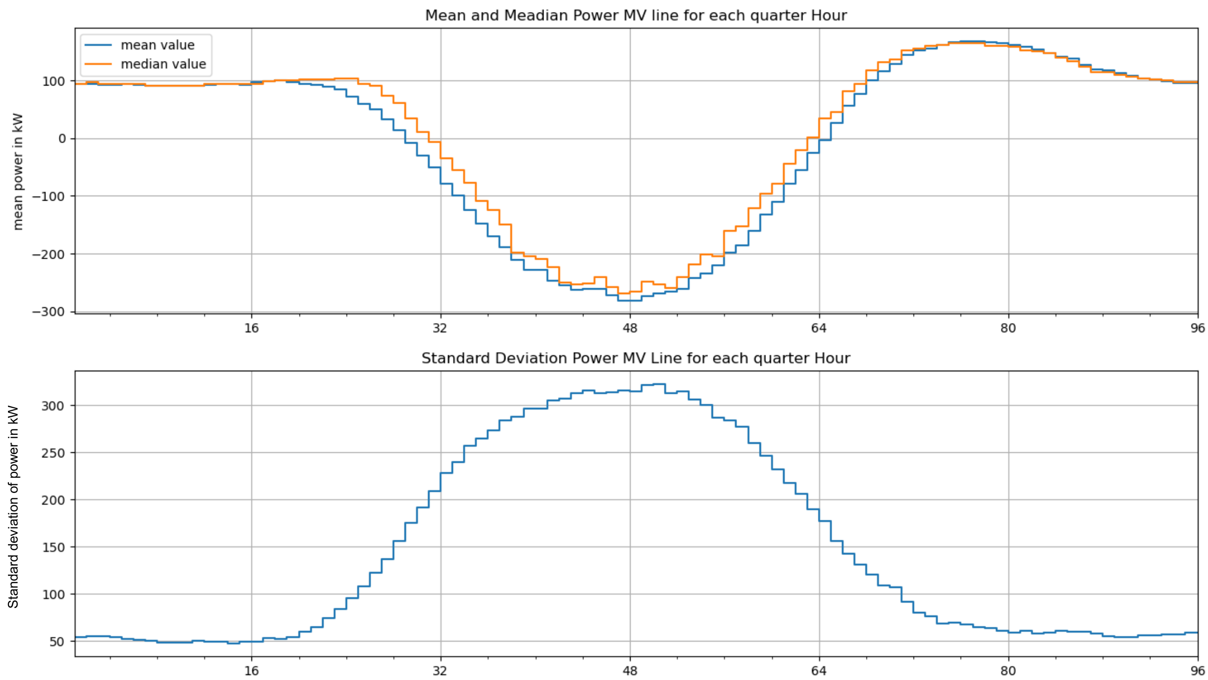

Figure 6: Statistical Evaluation of Power Demand Characteristics on the MV Line Feeding the Field Test Region

Figure 6 illustrates that during night-time from 0.00 a.m. to 5.30 a.m. and 11.00 p.m. to 12 p.m. the mean and median power exchange at PCC are each 100 kW. During these periods the load exchange at the

PCC is only driven by the demand of the communities and not interfered by PV generation. Additionally, the standard deviation is at its lowest level and very stable. This means the deviations from the average are very small compared to daytime, especially during noon. Instead of uncontrolled power export of generation surplus, a packet-based approach, where surplus energy in a given LV network is stored in a battery, to be delivered to the MV-gird level at non-critical times shall be deployed with Use Case 4 in a generation driven scenario. The MV line shall be relieved from additional stress from LV grid levels during times with high generation peak. Therefore, the surplus generation from LV grid during midday shall be stored in local batteries and exported at times, at which it is most beneficial for the MV grid level. If done and coordinated properly, both the peak generation and demand power peaks on the MV line will be reduced and the MV line is relieved. The results in Figure 5 and Figure 6 show that battery charging is most beneficial for the MV grid in the period from 6 a.m. to 7 p.m. The bulk export period (W2) is most beneficial in the period from 8 p.m. to 0 a.m., since the export of generation surplus serves the high demand from other communities on the MV line. Since the functionality of the UC3&4 application should also allow the ALF-C to react on bulk time windows that are demanded external, the bulk time window during the UC case application is therefore not always within the optimal bulk time period.

4.1.2 Bulk energy identification based on residual power forecast ($P_{F,PCC}$)

For the identification of the amount of energy to be imported or exported in form of bulk energy packets, the day-ahead prediction of expected power at PCC plays a crucial role and enables the ALF-C to steer the CBES more efficiently in cases when its flexibility is limited. For example, on days with excess PV electricity generation, the CBES should ideally be active during times of peak generation to reduce load on the grid, i.e., conduct peak-shaving. Thus, the accuracy of the power forecast has an impact on the performance of the ALF-C algorithms. If the forecast becomes too inaccurate, significant potential of the ALF-C is lost or, in the worst case, a miss-steered ALF-C causes additional avoidable stresses on the grid.

The power forecast is computed from two distinct forecasts: a PV generation forecast and an electricity consumption forecast for the community of Abbenhausen. The PV generation forecast is provided by a commercial weather service. Instead of creating a separate forecast for each PV module in Abbenhausen, all PV systems are aggregated into a single system. This is necessary as a German DSO does not have access to all system data required for a forecast, e.g., slope and facing of each PV system. Instead, it was assumed that the general orientation of all modules is 180 degrees south with an average facing angle is 40 degrees. A manual check confirmed these assumptions. The PV forecast comprises 96 15-minute interval values for instant and average power generation. Figure 7 illustrates an example of the forecast of PV feed-in for the 13th of March 2023, that has been determines on the previous day (12th of March 2023).

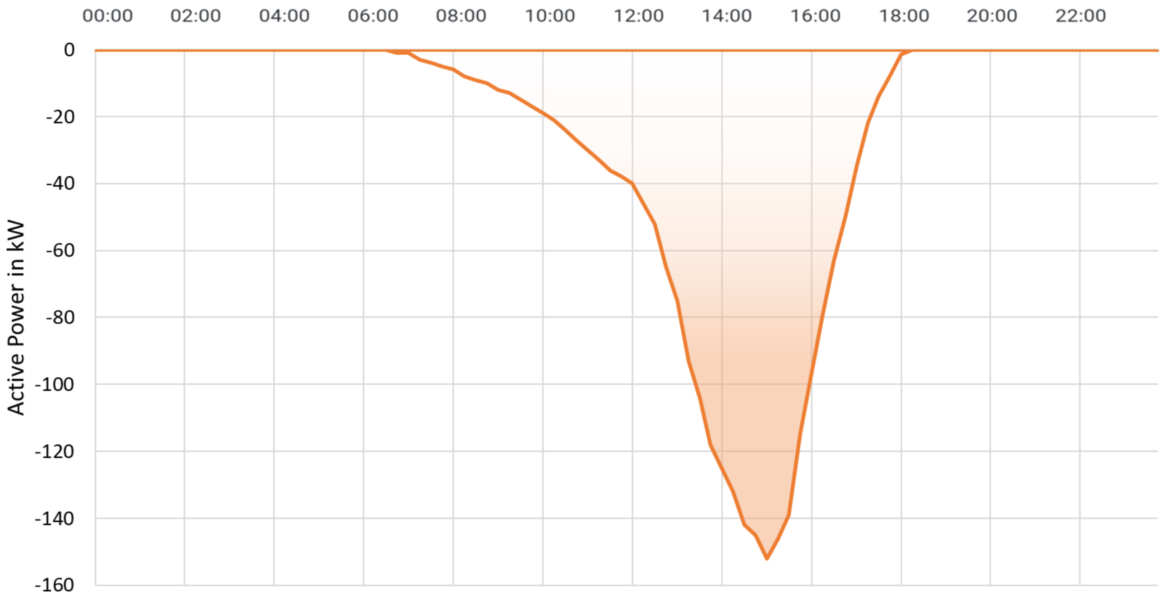

Figure 7: PV Generation Forecast for March, 13th 2023

Standard load profiles (SLP) for electricity consumption are available publicly, see [7]. As Abbenhausen mostly comprises single-family detached homes, the household profile H0 was used and scaled to the assumed yearly electrical energy consumption of the community. The H0-SPL consists of nine individual profiles as cartesian products of the day of the week (workday, Saturday, Sunday) and the season (summer, winter, intermediate). Additionally, a dynamic factor is applied to smooth the load profiles throughout the year. Like the PV generation forecast, the SLP comprise 96 15-minute interval values for average power consumption, see example in Figure 8. Subsequently, the power forecast at the PCC of Abbenhausen is calculated by adding both forecasts, see example in Figure 9.

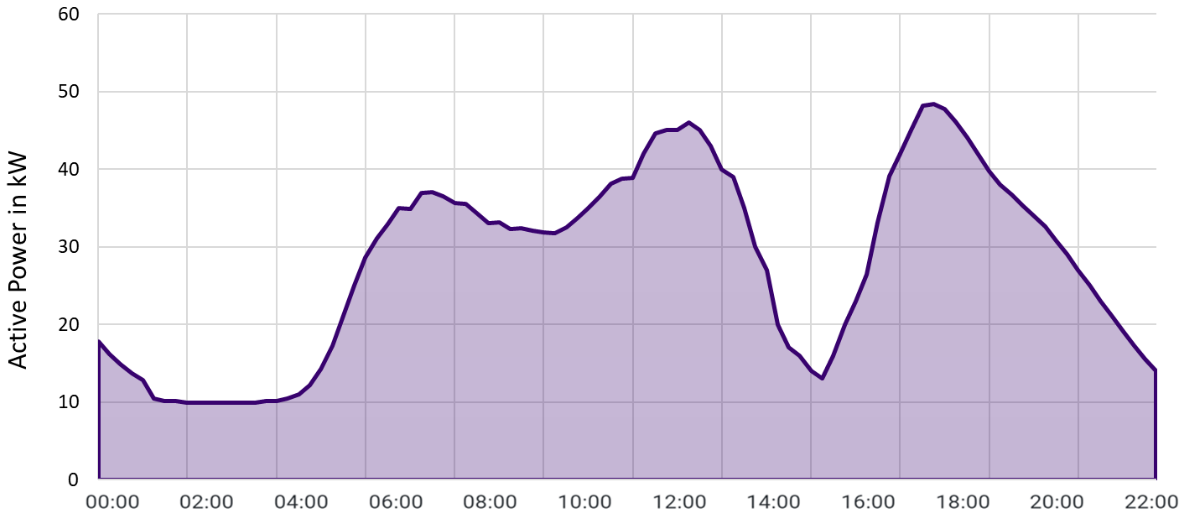

Figure 8: Load Demand Forecast for March, 13th 2023

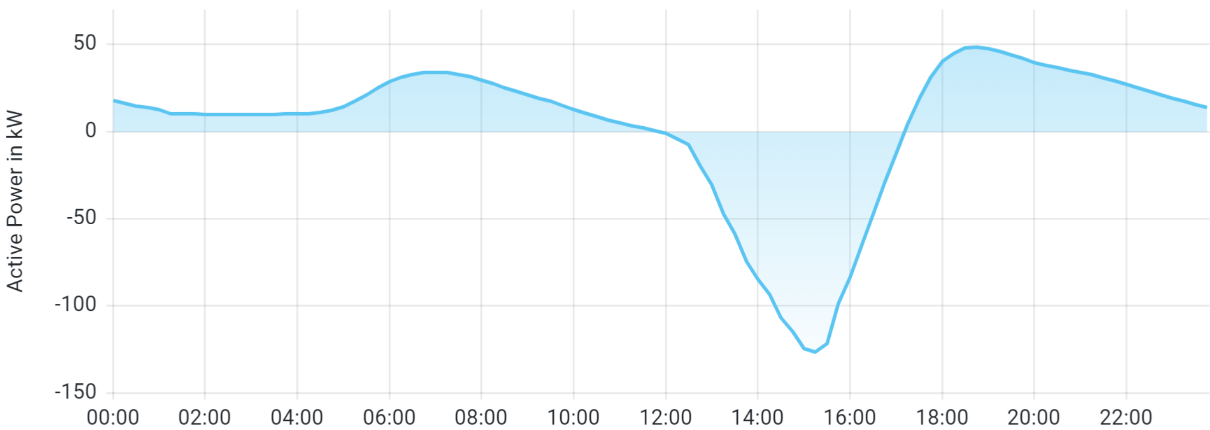

Figure 9: Residual Load Demand Forecast for March, 13th 2023

4.2 UC3/4 control approaches

4.2.1 RBC approach

For the RBC logic, the measurement values of net active power at the PCC are used to steer the CBES during the uncoupling period, i.e. W1 and W3. During the bulk period, i.e., W2, the discharging/charging of the battery storage unit is conducted in order to meet the requested bulk energy delivery/reception (export/import) denoted as bulk energy. In other words, the bulk energy amount to be imported in UC3 or exported in UC 4 is computed based on a load demand forecast ($P_{F,PCC}$) for the next day. Before and after the bulk window (W1 and W3), the RBC logic is applied to minimize the active power exchange at PCC and energetically uncouple the community from the MV grid. Obviously, the performance of RBC to reduce energy exchange and power peaks at PCC depends on the availability of flexibility at each point of time to balance out total generation and consumption. This stems from the fact that RBC implements the control logic purely based on the measured value of residual active power at PCC, i.e., $P_{M,\ PCC}$ (without the consideration of future forecast values) and the available flexibility in the storage unit. For more information about the RBC approach within W1 and W3, the reader can refer to Annex A.

Example of UC 3 with RBC

RBC can be applied for both use cases of UC 3 and UC4. In this section, the results of applying RBC logic for UC 3 on an exemplary day on 16th of December 2022 are presented with the help of Figure 10 and Figure 11. Figure 10 illustrates a forecast for the residual load demand of the LV community Abbenhausen for a 24-hour period from the 16th of December. Figure 11 illustrates the result of UC 3 application for a 24-hour period from the 16th of December 2022. In the given example, the following steps are followed to apply RBC:

1.) The point of time for window W2 start and end ($BWst$, $BWend$) most suitable for the MV feeder is determined based on historical measurement data collected from the MV grid. The point of time of the bulk window is shifted into time at which the MV grid displays the lowest residual load flow. As shown in picture Figure 4 and Figure 5, the red circles indicate periods, which regularly display a comparable low residual MV line load demand in a 24-hour period at winter and sunny summer days, respectively. The periods with a low load demand are regularly between 0.00 a.m. to 9 a.m. for predicted overcast winter days and 0 a.m. to 4 p.m. for predicted sunny winter days., as described in section 4.1.1 In the given example in Figure 10 and Figure 11 the bulk window is set to 9.50 a.m. to 3 p.m..

2.) The bulk energy deficit to be imported as bulk in W3 (UC 3) or surplus of generation to be exported as bulk in W2 (UC 4) is computed based on $P_{F, PCC}$.

3.) Application of RBC balancing in W1 and W 3 with bulk import or export in W2 during a specific use case time window. The RBC balances the energy exchange of the community based only on measurements of the power at the PCC, $P_{M,PCC}$, and at the CBES, P_{CBES}, every 15 minutes. The latter is required to compute the power value that would have been measured at the PCC had the CBES been inactive, $P_{C,PCC.}$ Based on $P_{C,PCC}$ and the desired power at PPC 0 kW for this field test—a new set value for the CBES, P'_{CBES}, is computed every 15 minutes and send to the CBES. The RBC behaves like a proportional controller. However, it also checks for technical limits of the CBES.

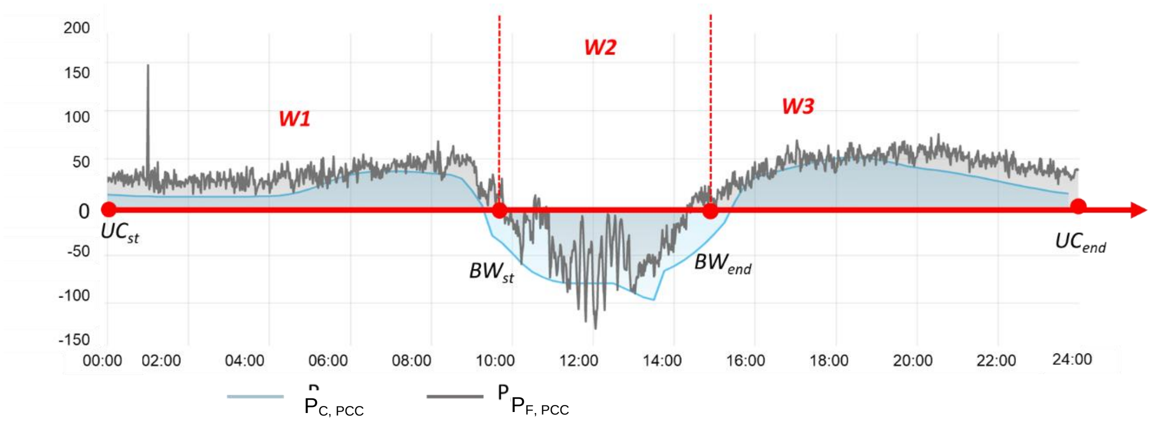

Figure 10: Community residual load forecast ($P_{F, PCC}$) for 16th December 2022

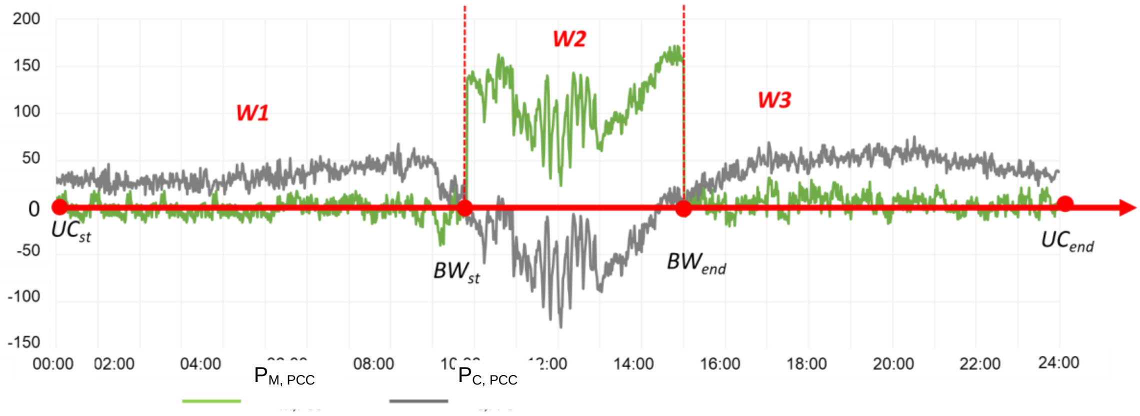

Figure 11: RBC performance applied for UC 3 for an exemplary day on 16th of December 2022

For the exemplary demand-driven scenario and after following the above-mentioned steps, the following findings can be highlighted:

1.) $BWst$ is set 9.00 a.m. and $BWend$ is set to 3 p.m. The bulk window times has been determined based on the logic described in section 4.1.1.
2.) The forecast of the residual load ($P_{F,\ PCC}$) for the 16th of December is indicated in blue line in Figure 10. The grey line $P_{C,\ PCC}$ in this figure indicates the baseline, which describes the load exchange at PCC, that would have been measured, if no UC would have been applied. The blue area between x-axis and positives curve of ($P_{F,\ PCC}$) indicates the predicted energy imported from the MV grid into the LV grid (780 kWh) and the blue area between x-axis and negative curve indicate surplus of energy that will be exported from the LV grid into the MV grid of the community (198,9 kWh). The forecasted residual energy demand in the period from $UCst$ to $UCend$ equals 539 kWh. This amount of energy shall be imported as bulk in windows W2.
3.) The resulting measured active power at PCC after battery control are illustrated in Figure 11. The measured results in this figure are indicated in green ($P_{M,PCC}$) and the computed baseline is indicated in grey ($P_{C,\ PCC}$). The example illustrates that in window W1, the load exchange at PCC ($P_{M,PCC}$) is reduced in comparison to $P_{C,\ PCC}$ due to discharging of the CBES. In W2 the CBES triggered to charge energy, which leads to a high load exchange at PCC of about 150 kW. In this period the computed energy bulk of 539 kWh is imported into the community and stored in CBES to serve the load demand in W3. In W3, the CBES is charged with RBC in times of measured export power flow ($P_{C,PCC}$ with positive values) and discharged in times of measured import power flows (positive $P_{C,PCC}$) at PCC. In result, the measured power exchange ($P_{M,PCC}$) in most of the measurement intervals is closer to a zero compared to $P_{C,PCC}$. However, in some time periods, $P_{M,PCC}$ displays higher magnitudes of P compared to $P_{C,PCC}$, which is the result of volatile PV generation, which leads to multiple changes of the magnitude of the power exchange at PCC, during the 15-minutes control steps.

4.2.2 SBC approach

For the SBC logic, the forecast values of net active power at the PCC are used to steer the CBES during both the uncoupling and bulk periods. During the bulk period, i.e., W2, the discharging/charging of the battery storage unit is conducted in order to meet the requested bulk energy delivery/reception (export/import) denoted as bulk energy. In other words, the SBC logic is applied to minimize the active power exchange at PCC and energetically uncouple the community from the MV grid during the whole use case time window including W1, W2, and W3 but at the same time assuring the delivery/reception of bulk energy during the bulk window. This leads to the optimum set points of the CBES in form of a schedule for the whole use case time window.

Example of UC 4 with SBC

The SBC can be applied for both use cases of UC 3 and UC4. However and as mentioned above, this report focuses mainly on the application of RBC and the intermediate results associated with it (reported in section 4.2.1). However and with respect to the application of SBC, an example is provided in this section for the better explanation of the SBC workflow. Therefore, the results presented in this section are the expected outcome (and not the actual result) of applying SBC for UC4. This expected outcome is described with the illustration of load flows in Figure 12 .The grey curve ($P_{C,\ PCC}$) indicates the residual load demand predicted and the baseline that would have been measured, if no UC control would have been applied. The orange line indicates $P_{M,PCC}$ to be measured. The green curve and area indicate the charging and discharging of CBES. In this example, it is assumed that the forecast $P_{F,\ PCC}$ is 100% accurate. Therefore $P_{M,PCC} = P_{F,\ PCC}$. Furthermore, in the given example, it is assumed that the CBES is fully charged at UC_{st}. In the given example, the following steps are followed to apply SBC:

1.) The point of time for window W2 start and end ($BWst$, $BWend$) most suitable for the MV feeder is determined based on historical data of measurements collected from the MV grid. The bulk window period, most beneficial for MV grid, has been identified for the priod from 8 p.m. to 0 a.m. according to the approach described in section 4.1.1.

2.) The bulk energy deficit to be imported as bulk in W3 (UC 3) or surplus of generation to be exported as bulk in W2 (UC 4) is computed based on $P_{F,\ PCC}$.

3.) The SBC determines the charging/discharging schedule P_{CBES} for the CBES by applying an optimization that aims at minimizing the power exchange at PCC. A detailed description of the SBC with optimization is described in [6] (without the inclusion of bulk window). Intermediate results of the application of this algorithm for UC 1 are described in [4].

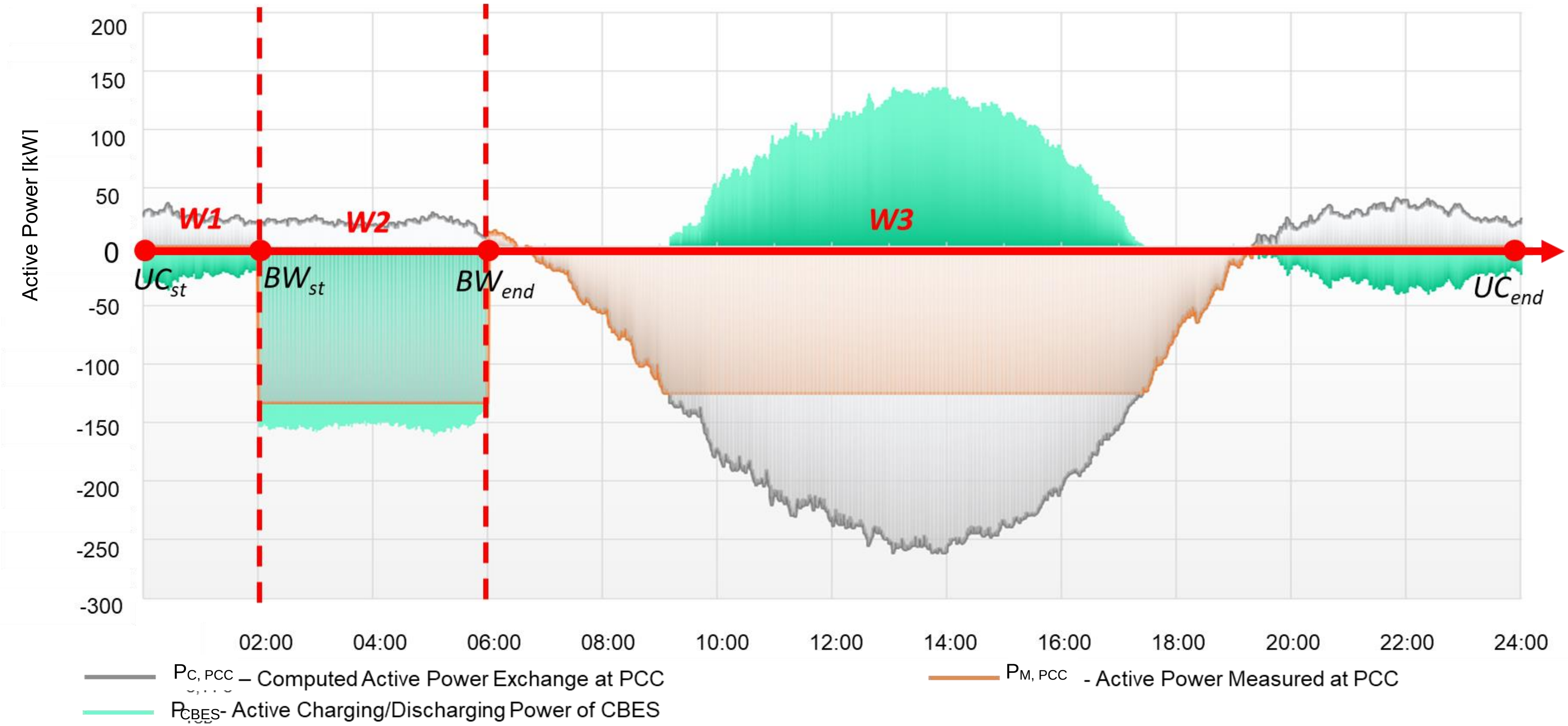

Figure 12: Expected SBC performance applied for UC4 for an exemplary day on *May 30th, 2021*

For the exemplary generation-driven scenario and after following the above-mentioned steps, the following findings can be highlighted:

- In the period W1, the UC algorithm is controlling the battery to discharge with the magnitude of the predicted load demand of the community. As result the load exchange at PCC is reduced to zero. In this period the community is energetically uncoupled from the MV grid.
- In W2 the battery is discharging 532 kWh with a constant power of 133 kW for 4 hours (and only as an exemplary expected outcome). In this period the stored surplus energy from the previous day in the battery, is exported as bulk in order to secure the capacity for storing the forecasted generation of the day. The amount of energy is determined in such a way, that the community self-demand in W1 with 50,9 kWh and times of deficits in W3 (120 kWh) can be served, without violations of capacity limits of the battery. During the bulk export the self-demand of the community is served. As result the absolute value of the measured export power flow at the PCC ($P_{M,PCC}$) with 103 to 115 kW is lower that the discharging power (122 kW).
- In window W3, the energetical uncoupling cannot be reached at any time, since the surplus of generation exported from 6.29 a.m. to 7.19 p.m. cannot be compensated by the battery due to the limited CBES capacity. Therefore, the CBES charging in between 9.11 a.m. and 5.24 p.m. is triggered with a magnitude value that the power exchange at the PCC is reaching a constant value of -125 kW. The battery at 5.24 p.m. reaches the maximum SOC of 100%. From 7.24 p.m. on the CBES is discharging in the magnitude of the load demand of the community.

5 Evaluation of KPIs

In this section, use case 3/4 performance is evaluated according to KPI_DE_07, “Reduction of load peaks in MV grid”, and KPI_DE_08, “Forecast of total Energy Demand”. The goal of UC 3 and UC 4 is to relieve the MV line during times of high peak loads. KPI_DE_07 “Reduction of load peaks in MV grid” evaluates the decrease of load peaks on the MV line during the period at which UC 3 and UC 4 is active compared to an uncontrolled power exchange. The KPI_DE_08, “Forecast of total Energy Demand”, evaluates the accuracy of the predicted residual energy exchange of the community at the PCC. A good forecast is essential for UC 3 and UC 4 to uncouple the LV community from the MV grid and decrease peak loads on HV/MV feeder and MV lines outside of the bulk window (BW_{st}, BW_{end}).

5.1 Evaluation of Forecast Accuracy

This primary analysis of the forecast accuracy focuses on the energy exchange, E, i.e., how much energy flows from the low-voltage grid via the PCC to the medium-voltage grid and vice versa. Given the sign convention, energy import and export, $E_{\mathrm{PCC,im}}$ and $E_{\mathrm{PCC,ex}}$, can be computed separately. The energy exported for each day, $E_{\mathrm{PCC,ex}}$, is computed by averaging the n measurements of power, P, within each 15-minute interval, multiplying it with $0.25h$, and adding up for the whole day:

$$E_{\mathrm{PCC,ex}} = \sum_{1}^{96} 0.25 \cdot \frac{1}{n} \sum_{1}^{n} P_{n,\mathrm{PCC,ex}}.$$

This computation is done for the energy export forecast, $E_{\mathrm{F,PCC,ex}}$ and the occurred export at the PCC had no UC test been conducted, $E_{\mathrm{C,PCC,ex}}$. The same computation so done for $E_{\mathrm{PCC,im}}$.

In the D1.4, the initial formulation of KPI_DE_08 for evaluating forecast accuracy was defined as the ratio between the forecasted energy export to the occurred energy export [8]:

$$E_{\mathrm{PCC,ex,GA}} = \frac{E_{\mathrm{PCC,ex}}}{E_{\mathrm{F,PCC,ex}}}.$$

However, this definition leads to very large values of the KPI in case of $E_{\mathrm{F,PCC,ex}}$ being very close to zero even though from the DSO perspective this inaccuracy is not relevant. Thus, an alternative formulation is proposed that provides better insight into the forecast accuracy—by computing the difference of $E_{\mathrm{F,PCC,ex}}$ and $E_{\mathrm{PCC,ex}}$, the KPI ΔE_{ex}, is defined as:

$$\Delta E_{\mathrm{ex}} = E_{\mathrm{F,PCC,ex}} - EPCC, \mathrm{ex}.$$

KPI_DE_08 is computed identically for energy import, i.e., ΔE_{im}. Because balancing energy generation from PV systems is one of the main topics of this project and its prediction essential for multiple UCs, the KPI analysis starts with ΔE_{ex}.

In the Platone project, power and energy at times of export are denoted with negative values. Thus, if the forecasted energy export is larger than the occurred energy export, ΔE_{ex} becomes negative. On the other hand, if the energy export forecast has a lower value compared to real vlaue, ΔE_{ex} becomes positive. The difference between forecast and occurred energy export (real value) for the year 2022, sorted in ascending order, is shown in Figure 13.

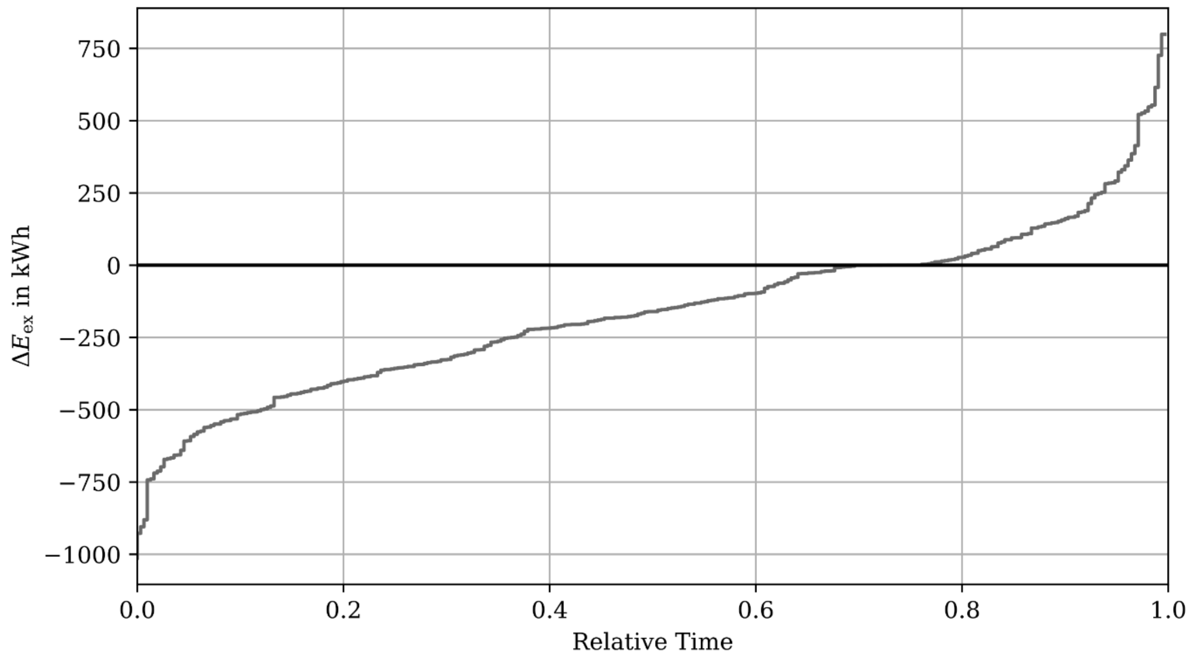

Figure 13: KPI_DE_08 - Difference in Energy Export between Forecast and Occurrence

Figure 13 shows that on about 75% of days in 2022, the forecast overpredicts the energy export, i.e., the forecasted energy export exceeds the occurred energy export. With absolute upper and lower limits of around $750\ kWh$, the forecast error for energy export can be of the same order of magnitude as the CBES capacity with $770\ kWh$. Three representative examples—underprediction, overprediction, and accurate prediction of energy export—will provide further insights into forecast accuracy. Figure 14 shows the power forecasted and occurred at the PCC on a day, where the forecast underpredicted the energy export. The x axis in this figure shows the 96 time intervals of the day corresponding to the 15-min resolution for forecast values of the day.

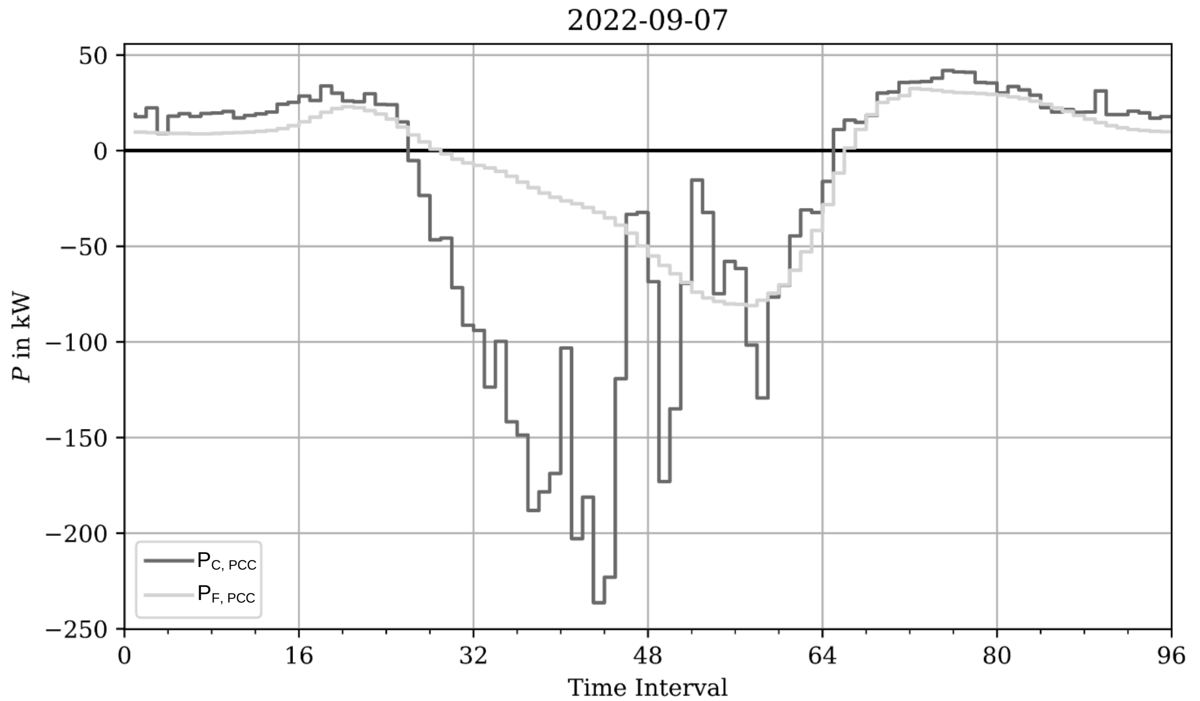

Figure 14: Example of Day with Underprediction of Energy Export

The example provided in Figure 14 shows that for this specific day the forecast was able to predict the power accurately when there was no large generation of PV energy. But especially from morning to noon when very little export of energy was forecasted, significant PV generation occurred. It seems likely that the weather forecast expected a cloud-covered sky which instead was almost clear. If a forecast-based UC had been active, the CBES would not have been active during times of large energy export.

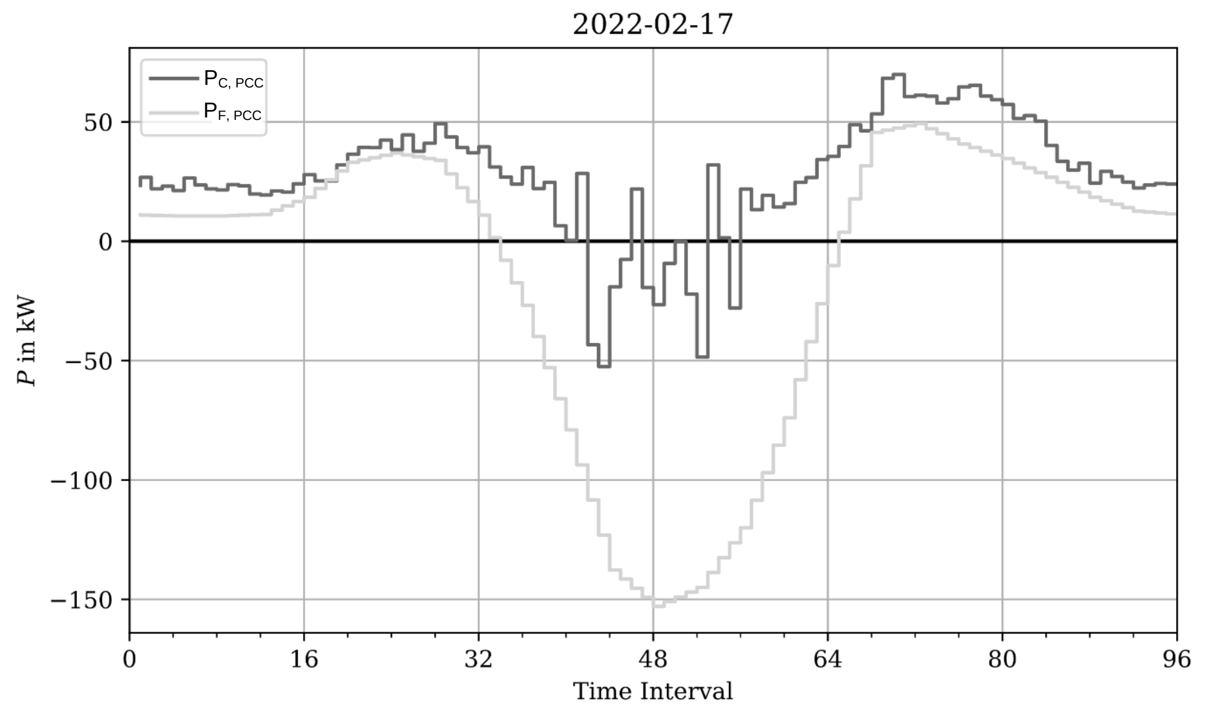

Figure 15: Example of Day with Overprediction of Energy Export

In contrast, Figure 15 shows a day where the energy export was overpredicted. This is likely the reverse of what happened in the underprediction example: instead of a clear day the sky was covered by clouds, thus less excess PV generation. Like in the underproduction example, the forecast is quite accurate predicting the power at times with less PV generation. Had a forecast-based UC been active, the CBES would have tried to engage in peak-shaving by storing excess energy. However, as the PV generation was quite low in comparison to the forecast, the CBES, without feedback loops, would have received its charging energy from the medium-voltage grid instead, increasing energy import unnecessarily.

The last example in Figure 16 shows that the power forecast can be very accurate. A forecast-based algorithm would have been very successful in shaving the power peak, reduce energy exchange at the PCC and improve local self-consumption of energy if a use case had been applied that day.

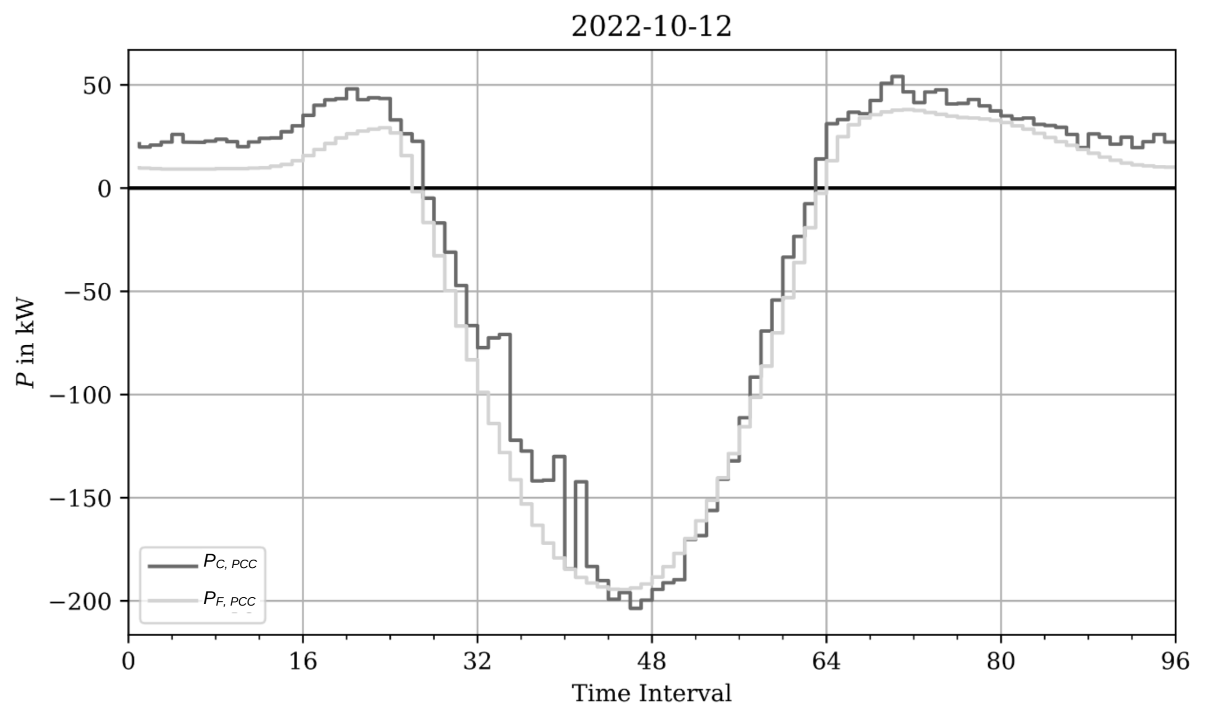

Figure 16 Example of Day with accurate Prediction of Energy Export

Both the over- and underprediction examples hint at the PV generation forecast as the source of the inaccuracy of the power forecast—and by extension the energy export forecast. Figure 17 shows a scatter plot of ΔE_{ex} and ΔE_{im}, the difference in energy import and export, for each day. Note that import power and energy are denoted with a positive quantity. Thus, a negative value of ΔE_{im} means that more energy was imported than was forecasted. Additionally, the plot of the linear interpolation is plotted.

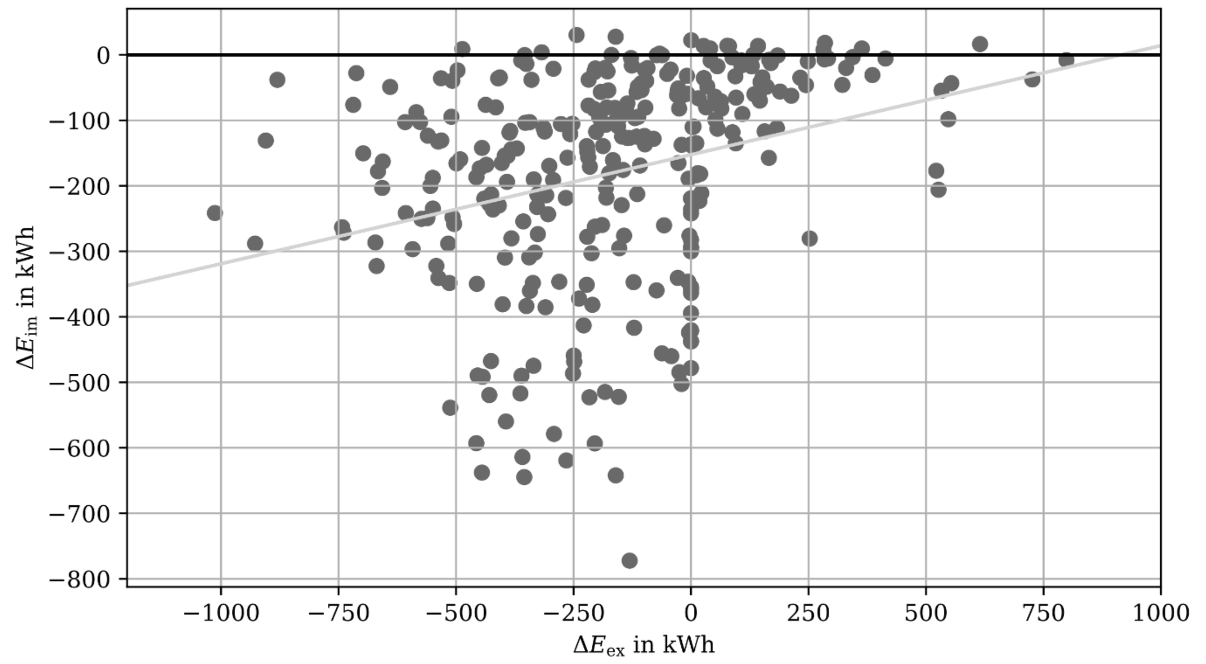

Figure 17 KPI_DE_08 - Differences in Energy Import and Export between Forecast and Realisation for each day available in 2022

In Figure 17, ΔE_{ex} and ΔE_{im} are plotted respectively on the abscissa and ordinate. As seen in the previous examples, the difference in energy exports can be positive (underprediction of export) or negative (overprediction of export), the latter much more common than the former. In contrast, ΔE_{im} is almost exclusively negative (underprediction of import). What becomes apparent is that for negative ΔE_{ex} the spread of $\Delta E\mathrm{im}$ is larger than for positive values of ΔE_{ex}. That indicates that that negative values of ΔE_{ex} can correlate with negative values of ΔE_{im}, i.e., overprediction of energy exports is more likely to results in significant underprediction of import, albeit with a large spread. In contrast, an underprediction of energy export does not correlate with a difference in import energy. Thus, not only is overprediction of PV generation more common, but it is also more likely that instead of an excess of PV generation energy import is required from the medium-voltage grid, changing the direction of the power flow.

A more detailed analysis into the causes of forecast inaccuracies would benefit from a disaggregation of power generation and consumption. One option available in this field test is PV generation measurement data provided by customers. One customer PV system is facing south without any shadowing, making it the ideal reference for evaluating the PV generation forecast. Thus, in addition to the community forecast, a PV generation forecast for this customer PV system is provided by the weather service. To allow a basic comparison between the customer PV forecast and the community forecast, they are both normalised with their respective average export energy $E_{\mathrm{ave,ex}}$:

$$\Delta E_{\mathrm{r,ex}} = \frac{\Delta E_{\mathrm{ex}}}{E_{\mathrm{ave,ex}}}$$

Figure 18 shows the relative difference in energy export for the year 2022 at the PCC and at the customer PV system. As the sample size of both plots is different, the ordinate was normalised to a relative time range between 0 and 1. Note that the forecast error for energy export can be of the same order of magnitude as the average energy export.

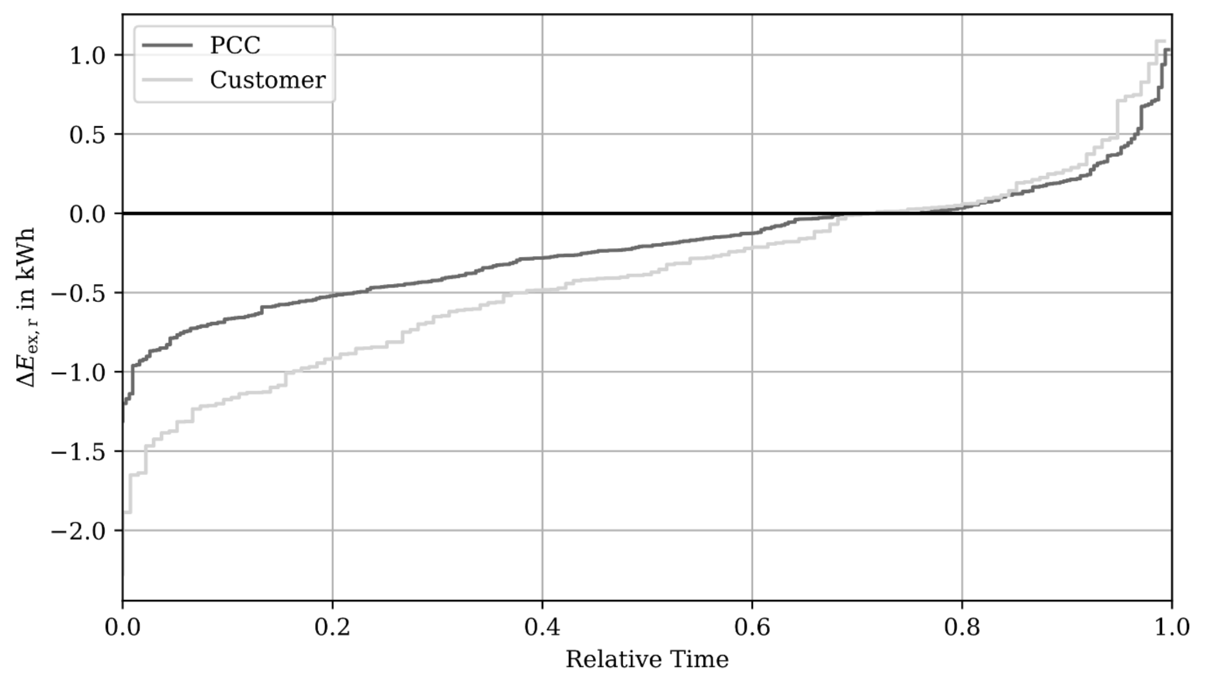

Figure 18 Relative Energy Export Difference at PPC and Customer System

The characteristics of $E_{\mathrm{r,ex}}$ are very similar for both curves. In both cases, $E_{\mathrm{r,ex}}$ is underpredicted in about 25% of days and the relative difference in energy export is very similar. In case of an overprediction of $E_{\mathrm{r,ex}}$, the customer system forecast error is significantly larger. One explanation for this divergence could be the effect of the energy consumption included in the PCC curve, as added energy consumption reduces energy export, i.e., shifting the curve upwards.

Another influence that affects the relative difference in energy export could be that the respective average export energies, $E_{\mathrm{ave,ex}}$ used to normalise each curve are not comparable. Indeed, the PV generation forecast for the customer PV system started in October 2022, i.e., ran only during winter so far. Thus, $E_{\mathrm{ave,ex}}$ is biased towards smaller values, thus increasing $E_{\mathrm{r,ex}}$ in absolute values. As data from spring and summer is accumulated, this could result in a shift of the curve.

In summary, the power forecast at the PCC can deviate significantly from the realised power measured—and thus the energy exchange. When energy export is overpredicted, it can further cause a significant increase in import energy, as there is not enough power generation to balance local demand. Underprediction does not result in significant changes in import energy from the forecast. That implies that the differences between power forecast and occurrence are mostly caused by inaccuracies in the PV generation forecast. This is substantiated by comparing the energy export differences of the community at the PCC with the PV forecast differences of a customer PV system within the community. Both show the same characteristics and difference can be attributed to the added energy consumption in the PCC forecast and the bias towards winter days in the customer PV dataset. The latter will be re-evaluated later this year.

This analysis focused on the energy export on a full day. However, additional insights could be gained by analysing the timeseries of each day with more sophisticated methods, e.g., dynamic time warping combined with clustering.

5.2 Evaluation of Reduction of Absolute Medium-Voltage Peak Power

The value for a DSO in reducing energy exchange at the PCC and increase local self-consumption is that this should result in reduced loads on the medium-voltage (MV) lines. This alleviation would increase its hosting capacity, e.g., for wind turbines directly connected to the MV-grid, enabling more customer connections. The KPI_DE_07 to evaluate the impact of ALF-C uses cases on the MV-line is defined as the reduction in absolute peak power on the MV line, ΔP_{peak}, with and without UC, P_{peak} and $P_{\text{peak,c}}$, respectively:

$$\Delta P_{\text{peak}} = |P_{\text{peak}}| - |P_{\text{peak,c}}|$$

Figure 19 shows the impact of applying UC3/4 logics on the absolute peak power of the MV-line.

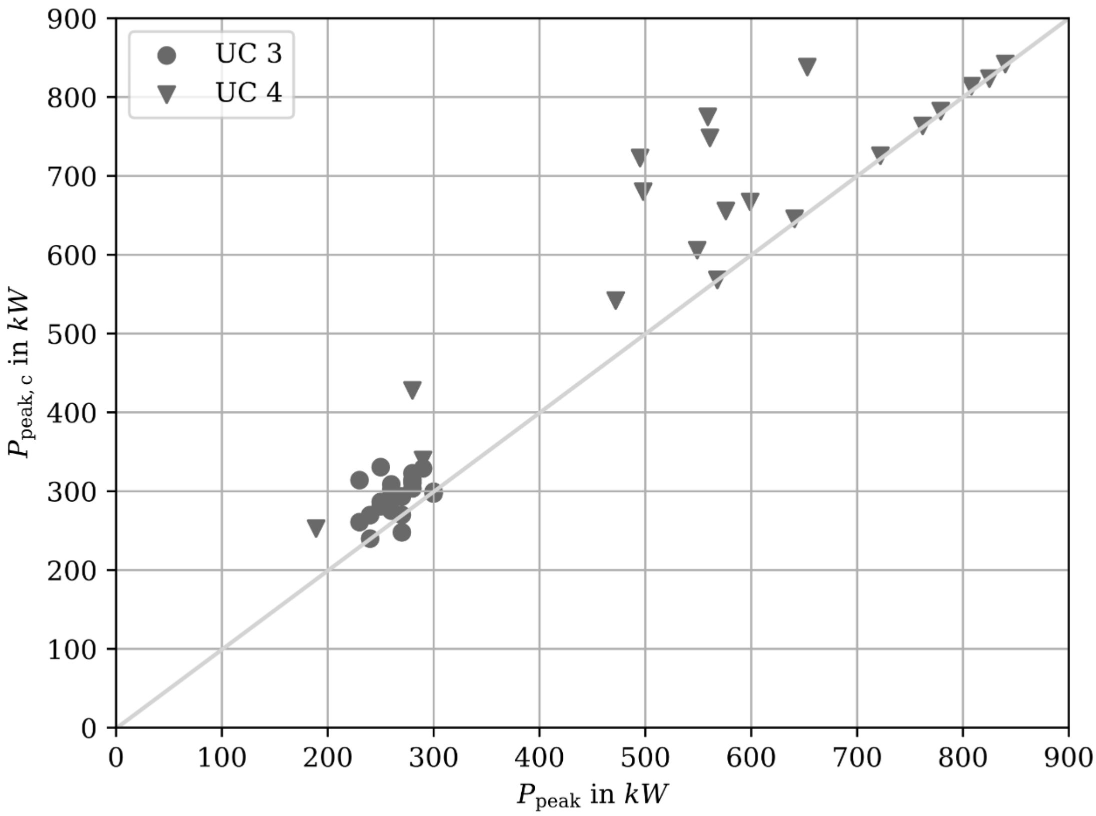

Figure 19 Absolute Peak Power on MV Line with and without UC 3 and UC 4

The ordinate shows the absolute peak power measured on the MV-line for each 24h day the UC 3 and UC 4 were applied between September and December 2022. On the abscissa is the corresponding peak power that would have occurred without UC application is logged. The line $y = x$ demarks where both values are identical. Thus, if the marker is above the line, it means that for this day of UC application there was a reduction in peak power on the MV-line.

It becomes clear that UC 3, i.e., charging the CBES for balancing energy consumption, has only very little effect on MV-line. Additionally, the spread of P_{peak} is much smaller. This results from UC 3 being applied from mid-November to mid-December 2022 where PV generation is low and the power at the PCC is dominated by consumption. As the community of Abbenhausen has no large install base of heat pumps or EV charging stations, there are no large peaks of import power to be compensated. Contrast this with UC 4 with an average reduction of absolute peak power on the MV-line of $77\ \text{kW}$.

Figure 20 shows the power at the PCC and the residual power on the MV-line with and without application of UC 4 for the day with the greatest reduction of peak power, $227\ \text{kW}$. At the PCC, the bulk discharge of the CBES from 0:15 a.m. to 2:45 a.m. is visible. This also results in a lower residual power on the MV-line. During the early afternoon, there is an excess of PV generation that is exported from the community. Outside the bulk window UC 4 operates with a rule-based control and balances the PV generation by charging the CBES. This decreases the residual peak load on MV-line.

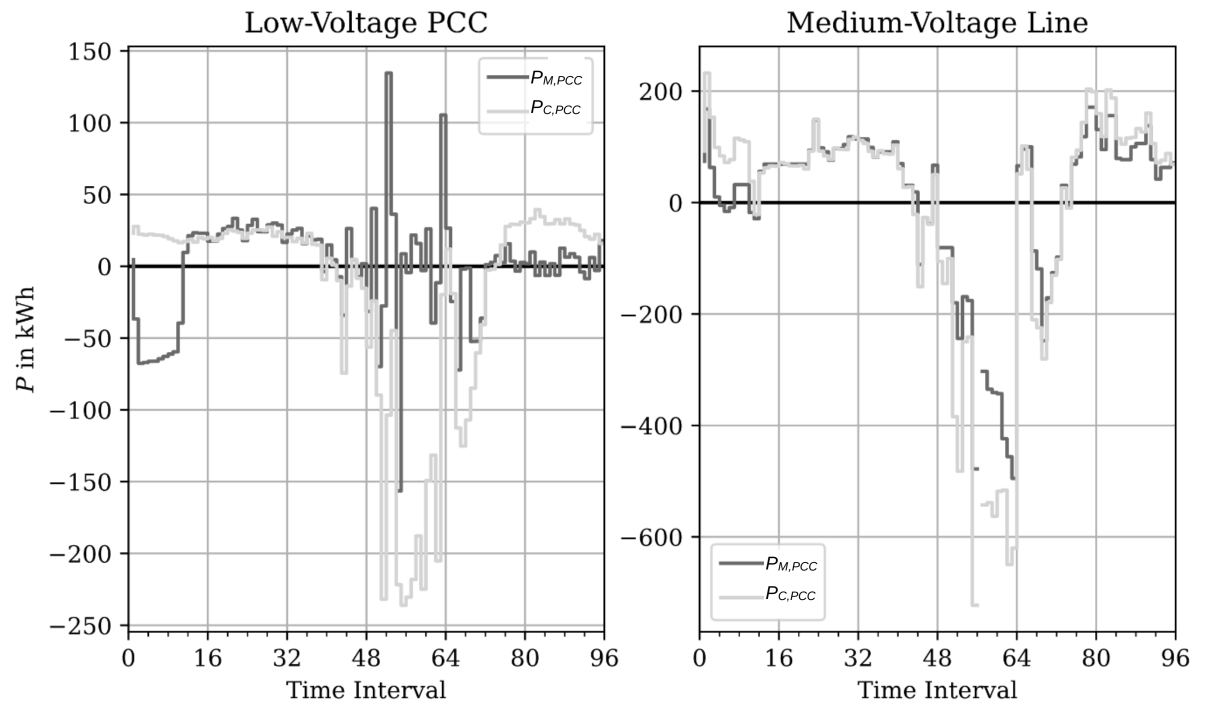

Figure 20: Day with highest Reduction in Peak Power for UC 4

A comparison between UC 4 and UC 1.0—RBC without bulk window—will allow to evaluate the impact of the energy exchange during the bulk window. Figure 21 shows the absolute peak power value on the MV line for days where UC 1.0 was active as well as the absolute peak power value had UC 1.0 not been active on this day.

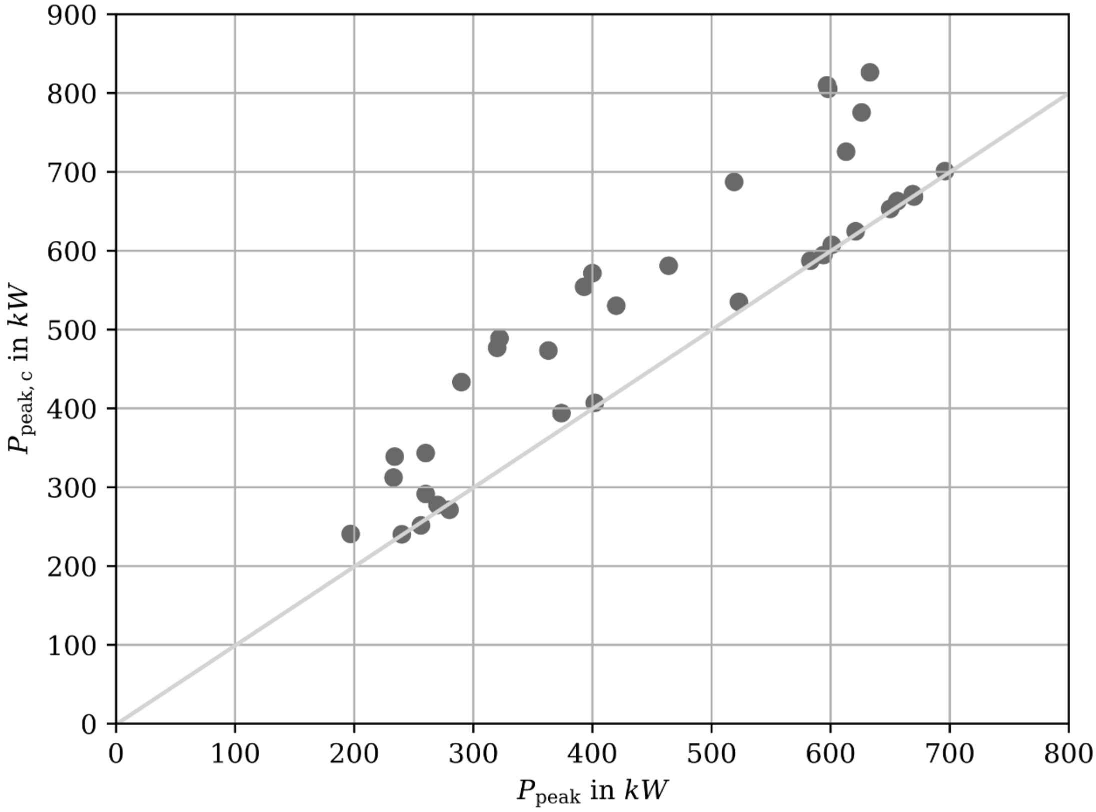

Figure 21 Peak Power on MV Line with and without UC 1.0

For UC 1.0 a peak power reduction on the MV line of up to 212 kW was observed. The maximum increase was only 8 kW. Generally, UC 1.0 can decrease peak load on the MV line and, on the observed days, does not increase peak load. On average, the reduction is 74 kW.

To illustrate the effect of UC 1.0, the day with the best KPI is presented in Figure 22.

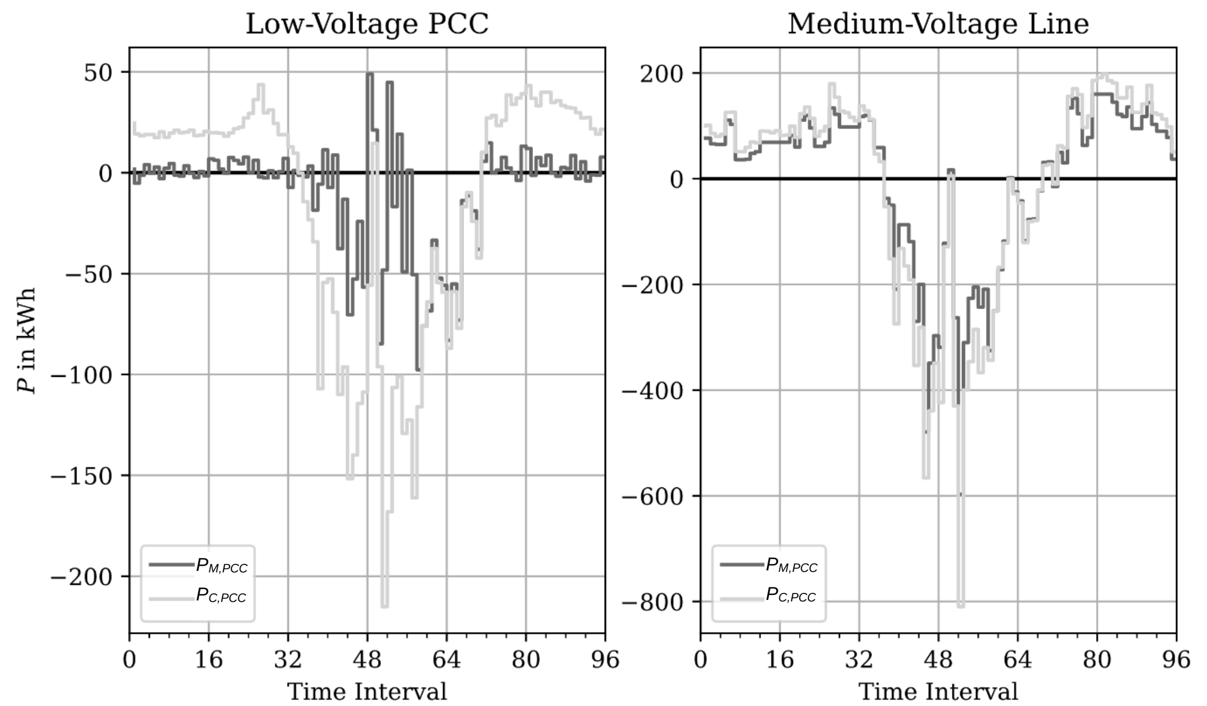

Figure 22 Day with highest Reduction in Peak Power

The left panel shows the measurement at the PCC, $P_{\mathrm{M,\,PCC}}$, and the power that would have occurred if UC 1.0 would not have been active, P_{C}. The latter graph shows that during that day, local PV generation exceeded demand in the community and electricity was exported into the MV-grid. This export was subsequently reduced by the application of UC 1.0 and especially the peak export power was reduced significantly. The effect on the MV line is visible in the right panel. It shows the residual power on the line, i.e., the power drawn or generated from all secondary substations between the primary substations on both ends of the MV line.

In summary, it becomes clear that the power flow at the PCC in Abbenhausen is a significant contribution to the residual load on the MV line. Thus, as shown, the ALF-C is capable to reduce the load on the MV-line, especially when the power peak is driven by PV generation. Comparing the effects of UC 1 as well as UC 3 and 4 on the residual load on the MV line, there is no significant difference between these use cases. However, comparability is limited because the larger number of days with UC 1.0 applications cover more seasons and weather conditions. Additionally, UC 3 and UC 4 test days include days where the bulk energy was provided by the user and not computed from the forecast. Thus, the bulk energy amount was more likely to be insufficient for significant effects. Thus, more test days with UC 3 and UC 4 including automated bulk energy computation are required.

6 Conclusion

This section summarizes the key lessons learned about the Platone WP 5 UC 3 and 4 applications and summarizes implications on forthcoming applications.

6.1 Lessons Learned

Residual Load Demand Characteristics of communities MV level

The evaluations of the residual load demand of the MV line, feeding the field trial community, point out that all 10 communities in summary display a relatively high surplus of generation, which leads to power exports. The field test community Abbenhausen displays the highest share of load demand and power export magnitutes compared to the other communities. The high surplus of generation leading to high peak loads and amounts of energy export at PCC is not a single phenomenon to be observed at the given field test community, but also at other communities in the region.

Bulk Window Identification

As result of the load demand evaluations of communities on the MV Line, the best time for bulk-based energy delivery in a generation driven Scenario (UC 4) the bulk export period (W2) is most beneficial in the period from 8 p.m. to 0 a.m. more detailed information can be found in section 4.1.1. In case of demand driven scenario (UC 3) the most beneficial period for bulk exchange (W2) is in the period from 0.00 a.m. to 4 p.m. on sunny days. However, in case of overcasted days with less PV generation, the period from 0.00 a.m. to 9 a.m. is most beneficial for the MV grid (feeder and line) for bulk energy import.

Load and Energy Demand Forecast

The evaluation of load and energy forecaster pointed out, that the residual load demand forecast can be very accurate on sunny days. On overcast days the forecast still is accurate at night-time (no PV generation). However, on daytime the forecast can be very unprecise 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 over casted unsteady days.

Bulk-Based Energy Supply and Export (UC 3 and 4)

The results of UC 3 and 4 with RBC 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 RBC 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 overcasted 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-overcasted days and overcasted days.

6.2 Future work

Bulk Energy Supply/Export with SBC

As an alternative approach to improve peak load reduction on MV line and uncoupling the LV community in UC 3 and 4, the SBC with optimization will be tested in the field, as described in section 4.2.2. The results will be compared with the RBC in forthcoming deliverables Furthermore, to avoid additional peak load at PPC as result of high charging power during bulk delivery times, the bulk charging (import) period will be longer and part of the optimization period in SBC.

MV Residual Load Demand

The scheduling of bulk window (W2) requires further analysis of the load demand characteristics of the communities on the MV line. The bulk window identification approach described in this deliverable, focuses on the historical measured data of the residual load of the MV line. However, at daytime, the load demand on the MV line is characterized by PV generation, which fluctuates according to the cloud coverage with high sensitivity. A forecast (e.g., day-ahead) could improve the residual load demand predictions on the MV line and could be used to identify periods of low stress for additional bulk exchanges, which improves the degree of freedom for bulk window scheduling.

Furthermore, the bulk window allocation just focuses on the residual load demand of the communities on the MV line. However, since MV grids are operated as mashed grids, the utilization of the considered MV line (power flow, voltage) is also affected by the load demand of assets located outside the considered field test region. For example, high feed in from wind parks and large PV parks can lead power flows on the considered MV line as transit power flows. The power flow transits can lead to higher magnitudes of power on the MV line than the local communities considered in this analysis. A possible way to put respect to transitory power flows for bulk window scheduling could be to make an analysis of the MV line utilization based on historical measured data and not computed residual data. However, this approach requires an evaluation whether the power transits display regular and repetitive characteristics in order to make reliable predictions. Otherwise, a forecast for the MV load demand is required, e.g., in case the transits are driven by wind turbine feed-in.

7 List of Tables

8 List of Figures

9 List of References

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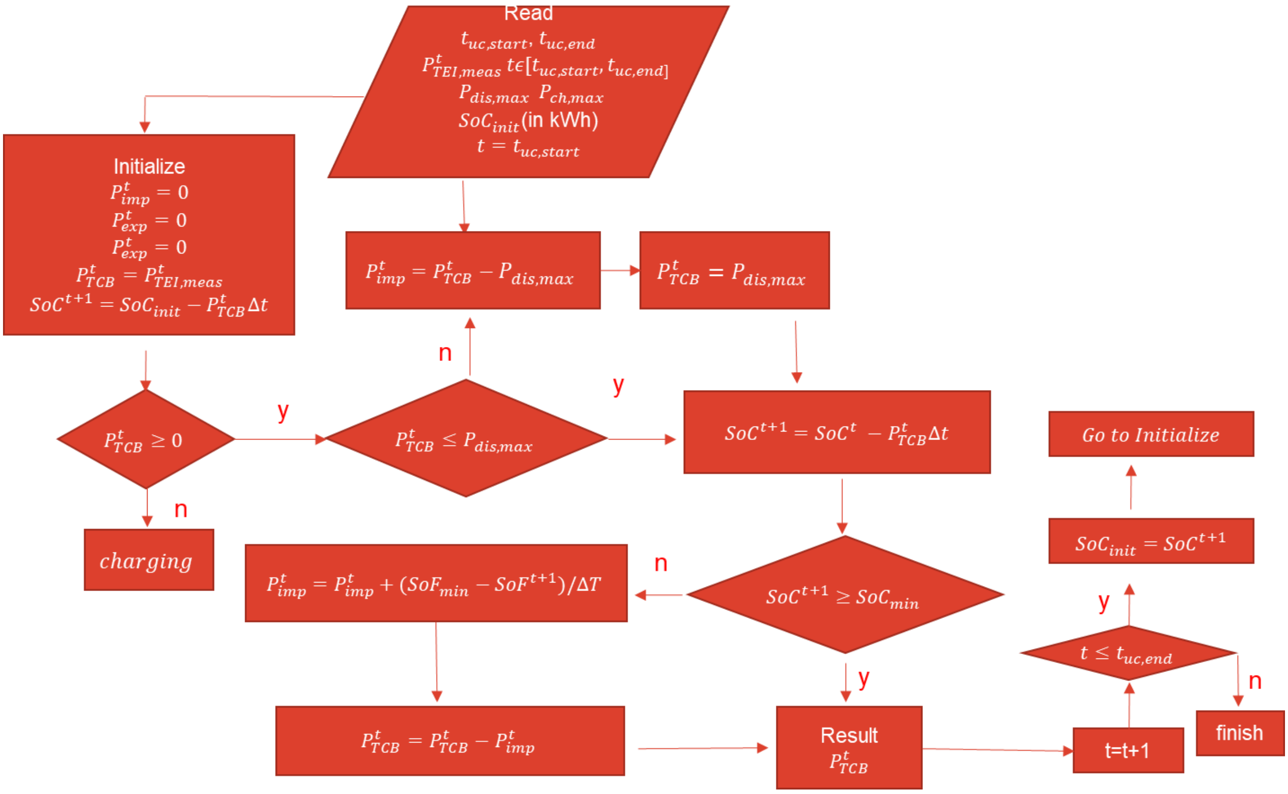
10 List of Abbreviations

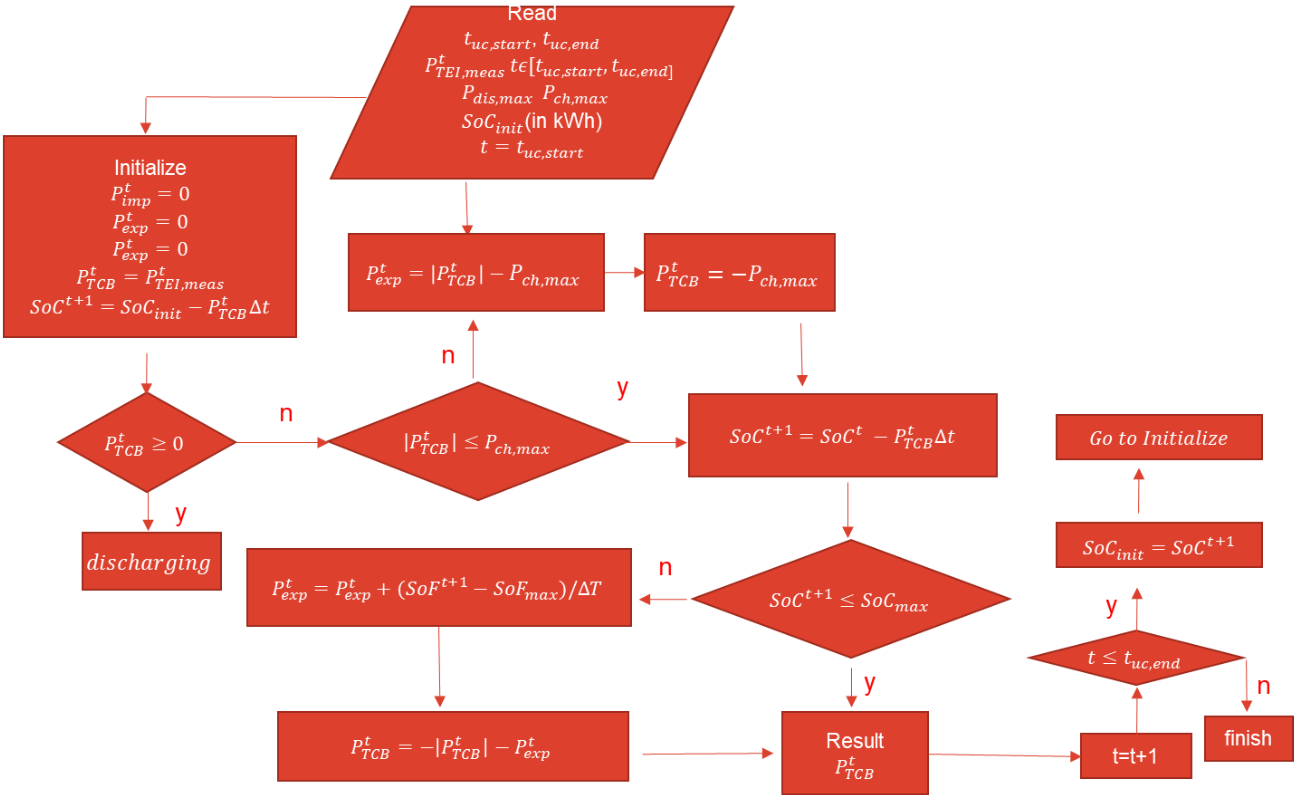
Abbreviation	Term
ALF-C	Avacon Local Flex Controller
CEC	Citizen Energy Community
CBES	Community Energy Storage System
D	Deliverable
DER	Distributed Energy Resources
DSO	Distribution System Operator
EMS	Energy Management System
EnWG	Energiewirtschaftsgesetz
FP	Flexibility Provider
GUI	Graphical User Interface
CBES	Local Battery Energy Storage
HV	High Voltage
LV	Low Voltage
MV	Medium Voltage
KPI	Key Performance Indicator
P	Active Power
PCC	Point of Common Coupling
PV	Photovoltaic
RBC	Rule-Based Control
REC	Renewable Energy Community
RES	Renewable Energy Sources
SBC	Scedule-Based Control
SCADA	Supervisory Control and Data Aquisition
SO	System Operator
SOC	State of Charge
SOE	State of Energy
T	Task
TSO	Transmission System Operator
UC	Use Case
WP	Work Package

Annex A Rule-Based Control

Rule-Based Logic – Discharging Flowchart



Rule-Based Logic – Charging Flowchart



Nomenclature used for the Flowcharts

t: time instant for measurement/forecast values

$P_{TEI,meas}^{t}$: measurement of net active power exchange at the point of common coupling

P_{FTEI}^{t}: forecast of net active power exchange at the point of common coupling

UC_{st}: starting time of UC case

UC_{st}: end time of UC case

BW_{st}: starting time of the bulk window

BW_{end}: end time of the bulk window

$P_{ch,max}$: Maximum allowablw charging power of the storage unit

$P_{dis,max}$: Maximum allowable discharging power of the storage unit

SoC_{init}: initial state of charge of the storage unit

SoC_{end}: final state of charge of the storage unit

$SoC_{init}^{w1\ or\ w2\ or\ w3}$: initial state of charge of the storage unit in W1 or W2 or W3

$SoC_{end}^{w1\ or\ w2\ or\ w3}$: final state of charge of the storage unit in W1 or W2 or W3

P_{exp}^{t}: active power export

P_{imp}^{t}: active power import

P_{dis}^{t}: discharging power of the storage unit

P_{ch}^{t}: charging power of the storage unit

$P_{TCB}^{t} = P_{dis}^{t} - P_{ch}^{t}$: storage setpoint