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D2.9 – "Guidelines for smart controller deployment at the demos"

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ABBREVIATIONS

Abbreviation	Description
ARIMA	Autoregressive Integrated Moving Average
BAT	Storage Plant in La Plana
CHP	Cogeneration Hybrid Power
DHN	District Heat Network
DSM	Demand Site Management
DSO	Distribution System Operators
FMEA	Failure Mode and Effects Analysis
HCA	Hybrid Control Algorithm
IGBT	Insulated Gate Bipolar Transistor
LCoE	Levelized Cost of Energy
LCoH	Levelized Cost of Heat
P	Active power
PCC	Point of Common Coupling
PLC	Programmable Logic Controller
PV	Photovoltaic Plant
Q	Reactive Power
RCM	Reliability Centered Maintenance
SETS	Smart Electric Thermal Storage
TES	Thermal Energy Storage
TRL	Technology Readiness Levels
TSC	Test Site Controller
TSO	Transmission System Operators
VPP	Virtual Power Plants
WTG	Wind Turbine Generator

1 Introduction

The present report constitutes D2.9 “Guidelines for smart controller deployment at the demos”, developed within WP2 of MUSE GRIDS related to the Smart control. This document has two objectives to achieve. One is to define the Smart Control (optimal + predictive) strategy and the other is to focus on the relation between low-level and high-level control. Both objectives will be applied for each demo.
In addition, this document gathers all the information included in already submitted confidential deliverables (D2.2, D2.3, D2.4, D2.5, D4.2, D5.2 and D2.8) to help having a global view of the control architecture and the particularities that apply to each demo.
In the first section, this document will define the general features and modules of the control architecture of the MUSE GRIDS Cloud which could be replicated to any other energy system where the optimization wants to be applied. The following sections focus on the specifics of each MUSE GRIDS demo (La Plana, Osimo and Oud-Heverlee), analyzing the following points for each of them:

- The optimization problem: the system to be controlled and the objectives to be maximized or minimized
- Data management: how and which data will be monitored and shared among the services
- Models and demand prediction modules: how these modules will be deployed in the specific application.
- Demand side management: how some devices can be used for shifting the demand.
- Grid codes: how the electricity exchange with the main grid will be managed.
- Hardware configuration: requirements of the services to be deployed.
- Smart Control Deployment: how the control will be connected and deployed.

In the case of La Plana Hybrid facility, this document will include some results regarding the first tests carried out using the MUSE GRIDS Smart Control and the MUSE GRIDS Cloud at the facility.

2 Smart Controller architecture overview

The software architecture of the Smart Controller has been detailed in the confidential deliverable D2.8. In this section a summary of the global architecture and its components is presented.
The main objectives of the Multi-Objective Smart Controller are aligned with the ones defined in the project:

- Maximize primary energy saving and reduce LCOH/LCOE as optimization targets.
- Increase the self-consumption of the local energy community.
- Increase energy efficiency and performance of each grid (electrical, thermal, water etc…).
- Increase local energy district reliability: guarantee of supply reducing external contribution, increasing lifetime and reducing maintenance.

In Figure 1, together with the Smart Controller – named as MUSE GRIDS Cloud – other elements have been included to understand the whole architecture of the control going from the definition of the strategies to the field devices operation.
The complete architecture covers a control strategy including three different time horizons:

- Day-ahead horizon, based in demand and generation predictions, essential for an optimal management of storage resources and load shifting (or demand side management).
- Quarterly hour horizon, where the operation conditions of the different assets have to be set according to the day-ahead strategy and the actual demand and generation.
- Real-time horizon, understood as the capacity of controlling some of the assets in the range of milliseconds or seconds to guarantee the stability conditions of the grid or attend emergency situations.

A predictive control will be applied along the day-ahead horizon which makes it possible to plan the demand profile (e.g. shifting loads) or the required storage levels (e.g. charging/discharging batteries operation) according to expected users' needs, predicted generated power and services/constraints required by the grid. In this sense, grid connection codes have to been understood not only as real-time restrictions but also as the energy exchange according to the day-ahead market planning.
The predictive control is the core of the Smart Controller, but many other software modules are needed for its operation. Sections 2.1 to 2.6 explain the functionalities of all the components/modules included in the Smart Controller. The low level controls and the cloud software owned by the assets suppliers are described in the confidential deliverables D2.2, D2.3, D2.4 and D2.5. This second control level will include part of the metering instruments, communication gateways and low level controllers that will be in charge of proprietary control modes of some technology providers (e.g.: Glen Dimplex space heaters) or that will aggregate the management of a group of assets/devices.

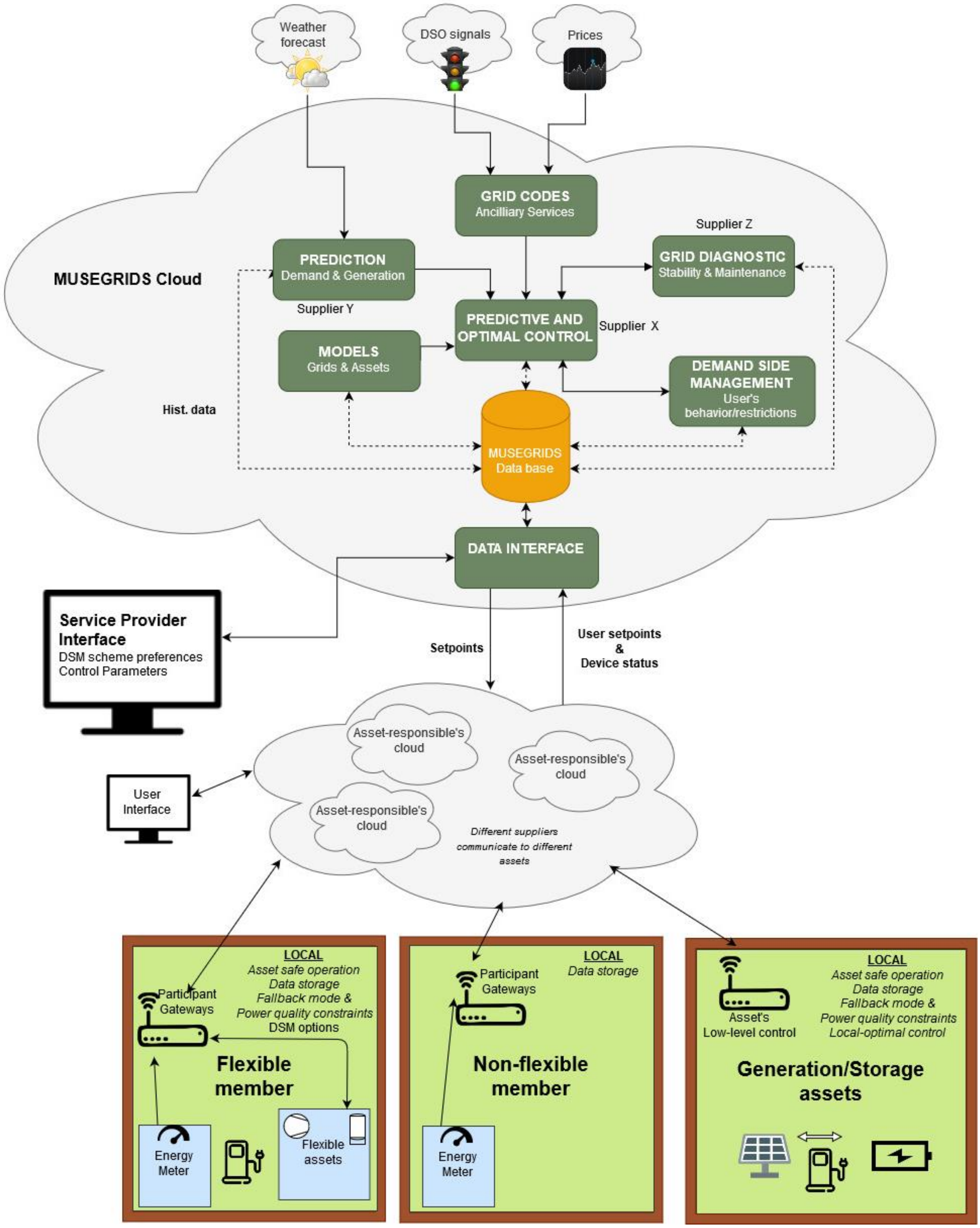

Figure 1. MUSE GRIDS Software architecture.

2.1 Data management and data bases

Data management and databases are managed by MUSE GRIDS Cloud, which is a software developed in Python. It is in charge of the communication with all assets of the facilities and to store all information in a database accessible also by the Smart Controller.
MUSE GRIDS Cloud will access to the data of all assets by using different communication protocols. The assets communication protocols will be different depending on the controlled facility.

2.1.1 MUSE GRIDS database definition

Communication between the Smart Controller and the MUSE GRIDS Cloud inside de MUSE GRIDS server is done by a SQL database, as can be noticed in the below figure. Databases will be different depending on the demo case because those are heterogeneous facilities with different assets and configurations.

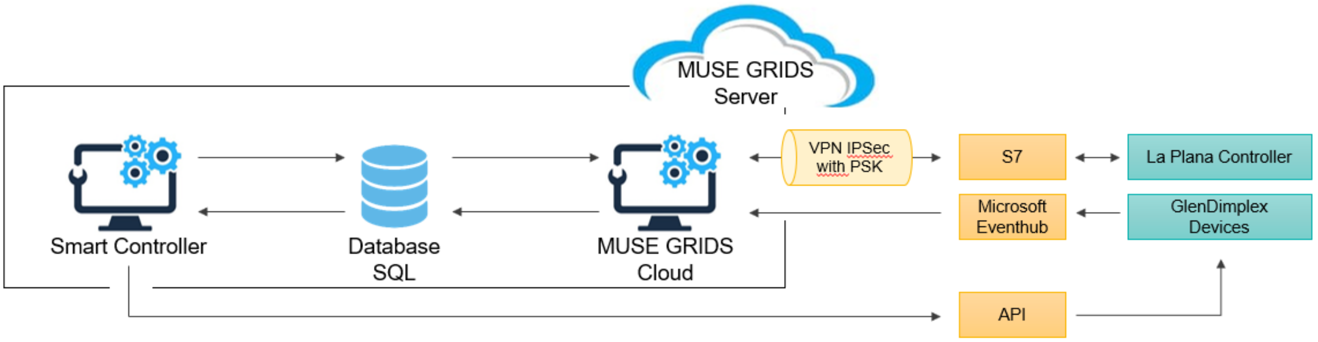

Figure 2. Communication diagram (La Plana demo case).

In the MUSE GRIDS Server there will always be a SQL database with different tables stored inside: it will contain one table for each asset, some tables for meteorological forecast and energy predictions and some tables for the control setpoints and some general tables for the configuration of the facilities. These tables will be used by the Smart Controller to store all calculated information about the facility, to know the current status of the facility and to send the setpoints and commands.

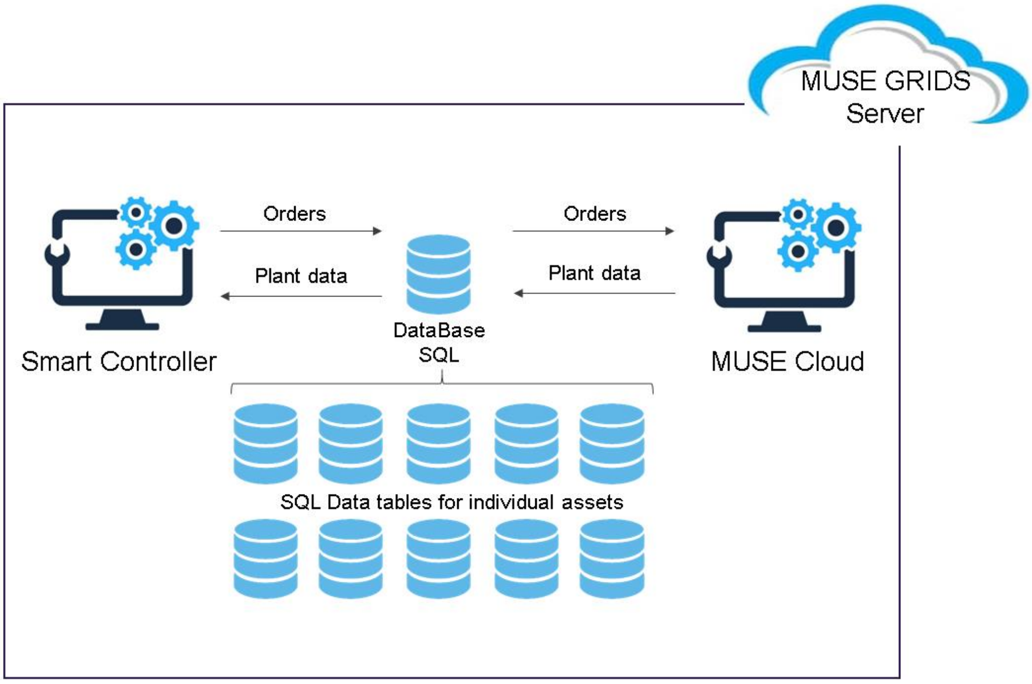

Figure 3. MUSE GRIDS Cloud Database architecture.

Database data is inserted every time the MUSE GRIDS Cloud receives telemetry or data from any asset. This data acquisition rate depend on the assets and the control requirements and vary from the 15 minutes period in Osimo metering, 2 minutes period in the SETS or the 5 seconds in the power plants of La Plana. For the homogenization of the measures and disk space saving, all the measurement tables of the assets are duplicated, and in the second table the 10minutal average values of that data stored. To avoid a fast database saturation 10-minutal tables are stored for long periods, but short-term tables are erased regularly.

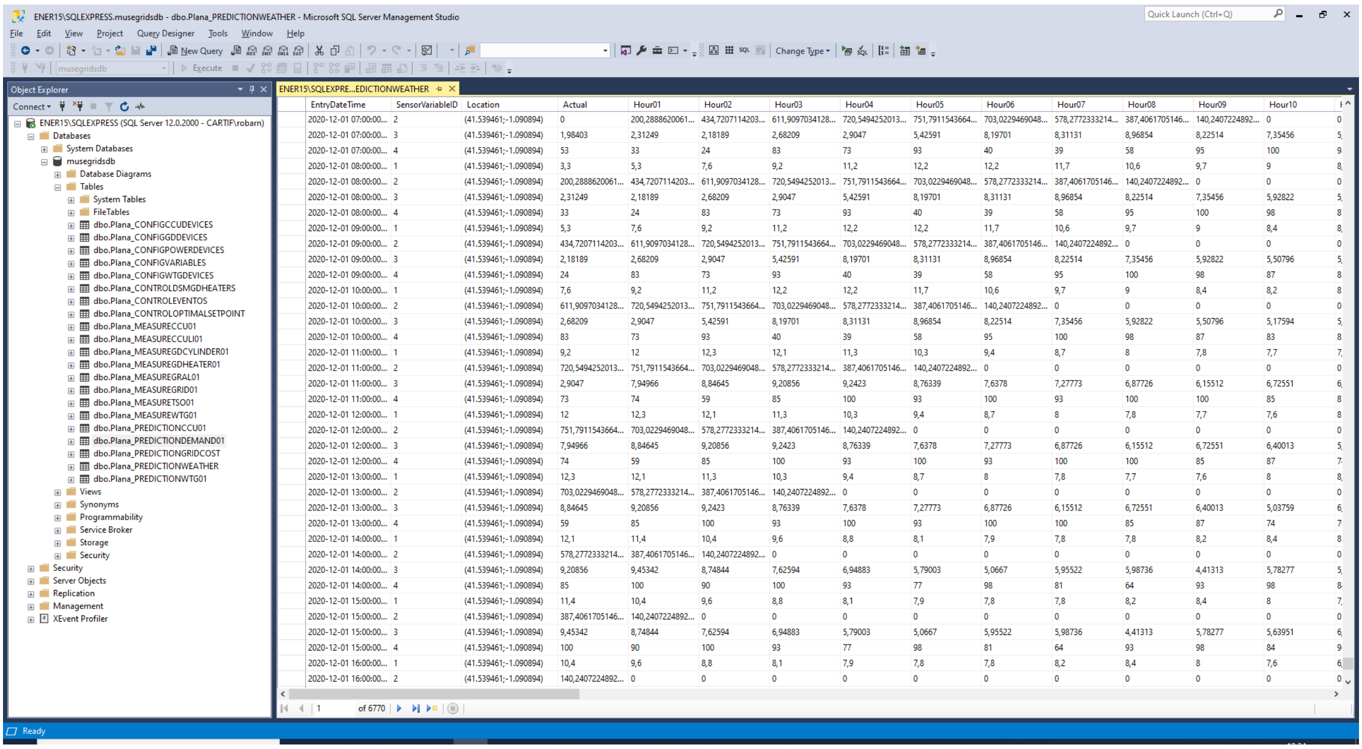

Figure 4. Weather forecast table in MUSE GRIDS database (La Plana demo site).

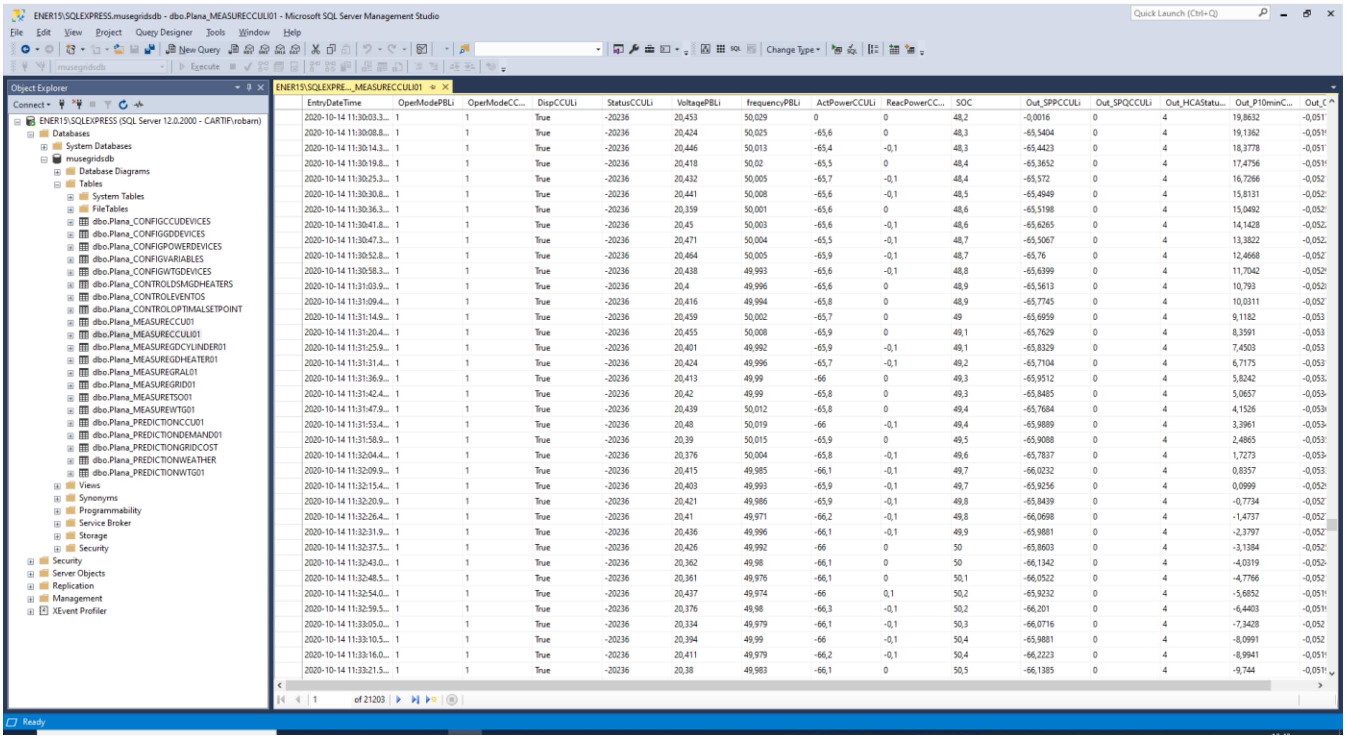

Figure 5. Storage system monitoring table in MUSE GRIDS database (La Plana demo site).

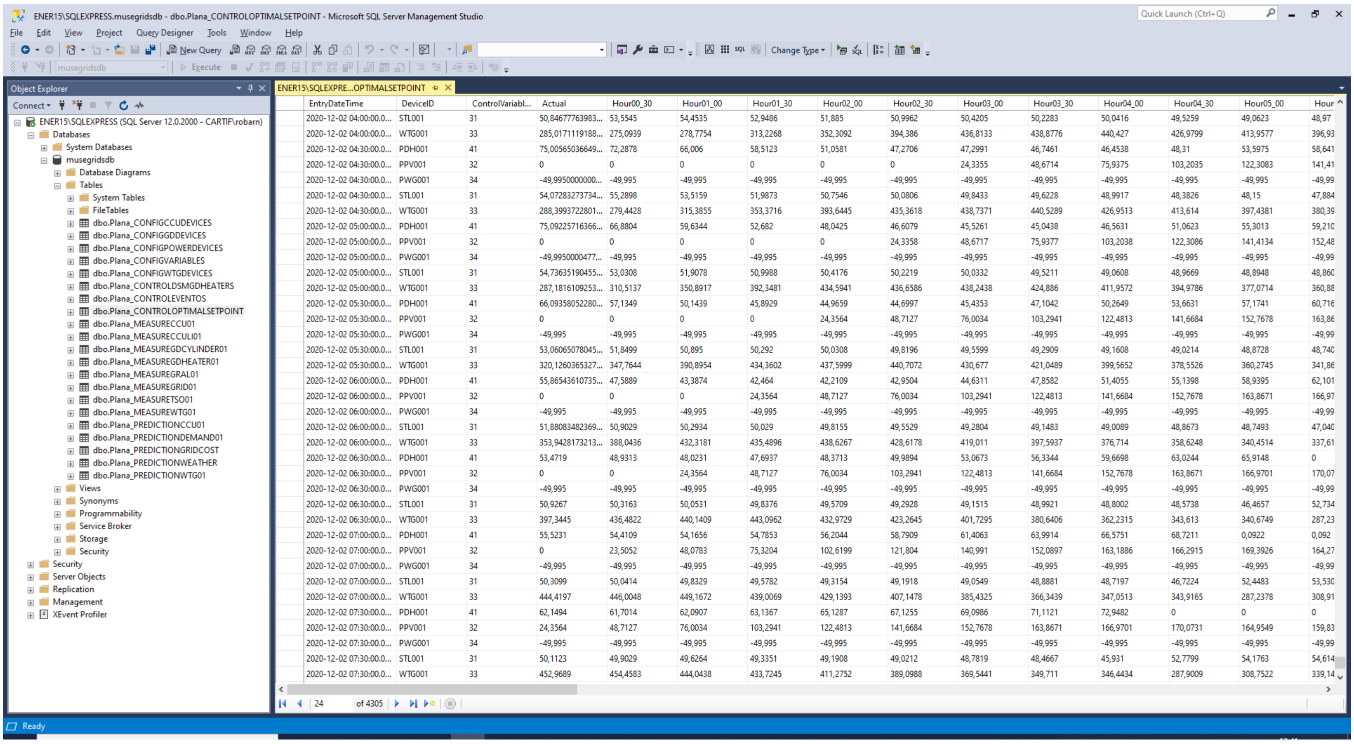

Figure 6. Control setpoints in MUSE GRIDS database (La Plana demo site).

2.1.2 Data interface module

Data Interface module (MUSE GRIDS Cloud) is in charge of managing the communications with all the low-level controllers and every device that needs to be monitored or controlled. Inside the control architecture, this module will be different for each demo, due to in each demo different assets are involved, and MUSE GRIDS Cloud must serve all information to the Smart controller and all orders to the assets.

A first version of the Data Interface module has been programmed in Python 3.8 for the validation tests in La Plana and communicates not only with La Plana local controller but also with two Glen Dimplex devices (cylinder and heater) located at Glen Dimplex laboratory in Ireland (for validation purposes).

The Data Interface will use the Azure Eventhub library for Python to connect and receive Glen Dimplex telemetry data from the devices located in the laboratory. At first MUSE GRIDS Cloud connects to an Azure Eventhub Endpoint in a thread, working as a demon, and the reading of telemetry will be done each time the Data Interface process receives an event.

In MUSE GRIDS the communication through API has been used because of its flexibility and openness. In addition, the SIEMENS S7 over TCP protocol has been used due to the architecture of the facility of La Plana and the local control devices involved. Thanks to the use of different communication protocols and different monitoring frequencies the MUSE GRIDS cloud is able to cover all communication possibilities of MUSE GRIDS project.

2.1.3 Glen Dimplex devices integration

In all MUSE GRIDS demo facilities Glen Dimplex devices are an important pillar, so the Smart controller must always know the status of all Glen Dimplex devices, which can be heaters and cylinders. There are two communication aspects in Glen Dimplex devices, the telemetry, which contains all relevant data of the devices periodically, and the control commands that can be sent to the devices.

MUSE GRIDS cloud is in charge of read the telemetry of all Glen Dimplex devices and store it into the database to make it accessible for the Smart controller.

One example of the telemetry of a heater is in the below table.

Table 1. Glen Dimplex heater telemetry data

Variable	Data type
AppDet_GdId	STRING
AppDet_Status1_IsElementOneActive	BOOL
AppDet_Status1_IsElementTwoActive	BOOL
AppDet_Status1_IsFirstStatusReportSinceApplianceReset	BOOL
AppDet_Status1_IsOpenWindowActive	BOOL
AppDet_Status1_IsComfortStatusOn	BOOL
AppDet_Status1_IsCommunicationStatusActive	BOOL
AppDet_Status1_FanStatus	BOOL
AppDet_Status1_OffPeakStatus	BOOL
AppDet_AppMode_IsNormalModeActive	BOOL
AppDet_AppMode_IsBoostModeActive	BOOL
AppDet_AppMode_IsAwayModeActive	BOOL
AppDet_AppMode_IsHolidayModeActive	BOOL
AppDet_AppMode_IsAdvanceModeActive	BOOL
AppDet_AppMode_IsFrostProtectModeActive	BOOL
AppDet_AppMode_IsSlaveModeActive	BOOL
AppDet_AppMode_IsSetbackModeActive	BOOL
AppDet_CriticalRuntime	INT
AppDet_DynamicRuntime	INT

AppDet_IncrementalRuntime	INT
AppDet_DailyRuntime	INT
AppDet_EnergyStoredNow	INT
AppDet_RoomSetpoint	INT
AppDet_CoreSetpoint	INT
AppDet_RoomTemperature	INT
AppDet_CoreTemperature	INT
AppDet_ElementCount1	FLOAT
AppDet_ElementCount2	FLOAT
AppDet_StoredEnergy	FLOAT
AppDet_ActualPower	FLOAT
AppDet_MaxCapacity	FLOAT
AppDet_SpecifiedCapacity	INT
AppDet_RemainingCapacity	FLOAT
AppDet_ActualRoomTemperature	FLOAT
AppDet_CurrentEnergyOutputInKwh	FLOAT
AppDet_Tariff1Usage	INT
AppDet_Tariff2Usage	INT
AppDet_SingleTariffUsage	INT
AppDet_LifeTimeConsumption	FLOAT
AppDet_TodaysEnergyUsage	FLOAT

Periodically, MUSE GRIDS Cloud is receiving telemetry data in packets referred to a device. Each Glen Dimplex device has its own identifier and gateway, so all data packets are easily assignable to the proper Glen Dimplex asset.

All telemetries are stored in the database of the MUSE GRIDS Cloud so the Smart Controller can use last data to command the facility.

The Smart controller will send the optimal operation strategies to Glen Dimplex devices from the Demand Site Management (DSM) module. It will use the DSM API provided by Glen Dimplex to send the commands that define the charging periods of the devices.

2.2 Demand prediction module

The Demand Prediction module is in charge of providing the optimal control module with the day-ahead demand profile of the connected loads. The demand calculation will be mainly based on historical consumption data and weather forecast. It will be also related to the day of the week, time of year (season) and official holidays.
The underlying algorithms in this module will be specific for every demand in the demo. Equivalent load (e.g. users electricity demand) can share the same approach for the prediction strategy but will always need specific training and validation.
Most common models for demand prediction make use of Random Forest and ARIMA algorithms that are the ones used in MUSE GRIDS demos.
Demand prediction module does not include adaptive or automatic training schemes. When the prediction error is high a new model will be trained and validated off-line and new parameters will be provided to the algorithms.

2.3 Models module

In the architecture definition, this module can have a double role:

- To calculate the day-ahead predicted power generation profiles based on the weather forecast and using models of the energy power system.
- To model the complete system to be controlled and provide the optimal control module with the outputs of the different subsystems when the desired control actions are set.

In MUSE GRIDS Smart Controller only the first one will be deployed as the selected optimal control approach includes the model of the system in its own algorithm definition. In D4.2 the second approach has been used in simulation for evaluating DSM strategies in the CHP plant.
System modelling is a complex issue that covers from first principles modelling to black box or data driven models.
In MUSE GRIDS both statistical and equation based models have been used in the different demos as explained below.

2.4 Demand Side Management module

The Demand Side Management module will manage and communicate with industrial/public users whose demand can be shifted in time according to some restrictions and using storage/reserve systems (user's flexibility). This module will have the double role of providing the optimal control with the energy requirements of the loads and distribute the output demand profile (that leads to the optimal balance of generation and demand) among the deferrable load devices.
MUSE GRIDS has considered for demonstration purposes two types of shifting loads: electric vehicles and smart electric thermal storage (SETS) devices. In both cases there exists flexibility in the demand requirements in terms of a total amount of energy that should be provided before a time limit. Local control is in charge of the calculation of these energy needs, while DSM module will perform the synchronization of the optimal calculated profiles for the whole system with the individual devices.
Other DSM strategies have been also deployed making use of batteries, thermal storage or thermal inertia but their control is not responsibility of this module as cannot be considered as loads. Those equipment/strategies are used for balancing generation and demand but do not have any restriction in their use a part of their operation limits and system boundary conditions.

2.5 Grid diagnostic module

This module will run the fault prediction methods to anticipate failures and faults in the grid or the power energy devices. The detected faults will enable different fault tolerant control modes in the control algorithm. These modes can affect the boundary conditions of the optimization problem or to the objective function.
The algorithms included in this module are specific of each deployment of the Smart Controller. They are based on the state of the art of the diagnosis and predictive maintenance methods. In MUSE GRIDS deployment a detailed Failure Mode and Effects Analysis (FMEA) has been performed for every demo as part of a Reliability Centered Maintenance (RCM) strategy. This help to define the diagnosis algorithms that will be included in this module. Deliverable D2.7 detail the complete process for the maintenance strategies at the demos.

2.6 Grid codes module

This module is responsible of the definition of the grid connection codes and the management of the provided services to the grid. In simple words it defines the requirements and restriction for the electricity energy exchange with the main grid. This is critical in weak grids or energy islands (as the ones studied in MUSE GRIDS project) but also have a great impact in any other situations.
The operation modes will be communicated to the high-level control module as restrictions, generation availability or energy demand in order to accomplish with the grid codes. This will be basically a configuration module to select the different connection modes.
This module has its counterpart at local level where the low-level control must guarantee that the defined grid codes are fulfil in real-time. Several local active and reactive control modes have been developed in the MUSE GRIDS project. These control modes have been designed by analysing DSO requirements in different countries.
Each mode of operation can be activated in a predefined way by the controller through internal parameters or can be activated / deactivated by the operator through the SCADA.

2.6.1 Active power control modes

The local control algorithm will involve several local modes of control. They may operate autonomously or simultaneously according to the philosophy of operation of the plant. In this way, more than one control mode must work at the same time, so the controller will manage all compatibilities between them.
All active power control modes will have more priority than the reactive control modes and the lowest set point will be the highest priority.

2.6.1.1 Balance Control

This control mode will enable manual active power setpoint operations of the energy exchanged with the main grid. The balance control will allow the operator to set active power values to be delivered to the power grid using all the available power sources.
The controller operating in balance control mode will allow the following:

- Each subsystem can be used independently in "manual" mode, in which case they will participate in the controller algorithm with a constant active power value.
- In addition to the choice of active power value, the maximum values of the active power ascent and descent ramps may also be limited.

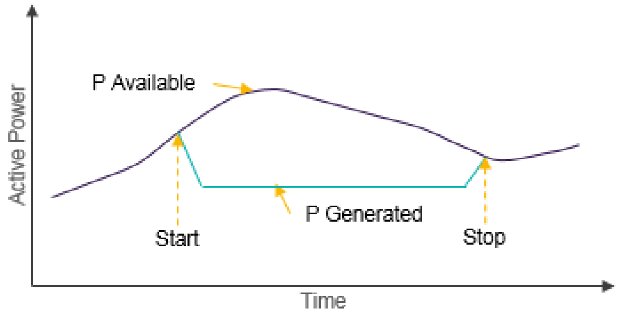

Figure 7: Active Power Control Mode: Balance Control.

2.6.1.2 Power Available

In this automatic control mode, the controller must work on an open-loop mode. Therefore, the controller delivers to the electrical power grid all the renewable active power available in the primary subsystems.
Among the most important features of this control mode are highlighted the following:

- Each subsystem will have the possibility to be used independently in "manual mode", in which case they will be considered by the controller as constant power sources.
- The controller will allow the use of a restriction of storage systems depending on the price of the energy. This function and this parameter can be configured by the operator in the low level controller. When connected to the MUSE GRIDS cloud it will be the Predictive and Optimal Control module the one in charge of defining the storage use.

2.6.1.3 Smoothing Control

This control mode will allow to compensate for possible variations in primary energy resources (e.g. wind fluctuations, shadow effect…) which might otherwise cause power oscillations in the electrical power grid. This control mode is defined for the low-level controller.
The controller will calculate primary power fluctuations in real time and compensates for those variations with the use of the storage system. Fluctuations will be calculated based on power measurements in a user-configurable time window. In short, the smoothing control will act as an adjustable oscillation filter.
Among the most important features of this control mode of are highlighted the following:

- Each subsystem can be used independently in "manual mode", in which case they will be considered by the controller as constant power sources.
- Independent filtering for solar and wind can be configured.
- The control mode has a sequential data buffer of up to 10 minutes to do filtering.

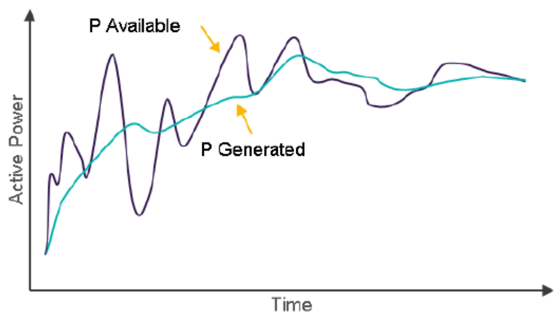

Figure 8: Active Power Control Mode: Smoothing Control.

2.6.1.4 P(f) Control

This control mode will allow the energy system to operate in frequency droop mode. This mode is mainly defined for the case of the operation of one power plant and only for the low-level controller. In this case the controller will automatically increase or decrease the production of active power depending on the frequency of the network at the point of connection of the plant. In this way the plant will contribute with its spinning reserve to stabilize the frequency and to cover the initial frequency transient.
The following figure shows the values involved in frequency control. Thresholds, ramps, and frequency dead band can be configured according to current mode of operation and network code.
In the event of a phenomenon that produces frequency transients with frequency fluctuations outside the death band, the controller will maintain its limit values for a certain amount of time. After the end of the event, it cannot be re-operated for a while. These times will also be adjustable by the plant operator.

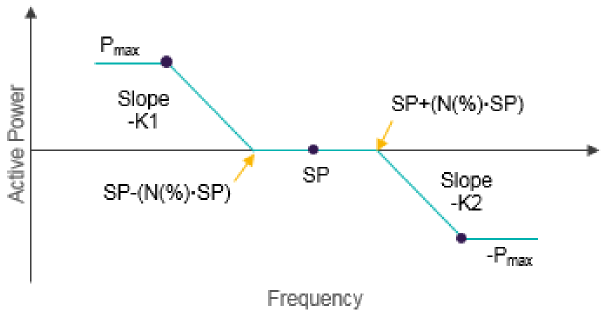

Figure 9: Active Power Control Mode: P/F Control.

2.6.1.5 Peak Shaving

This control mode will be used in cases where the energy system feeds a common demand with another plant or the electric power grid. The second feeder will provide the base power for demand, while the controlled system will provide power at peak demand. When demand grows above a configurable value (base active power) the controller will generate the active power needed to supply peak demand. In this way the controller ensures the power that demand requires at all times.

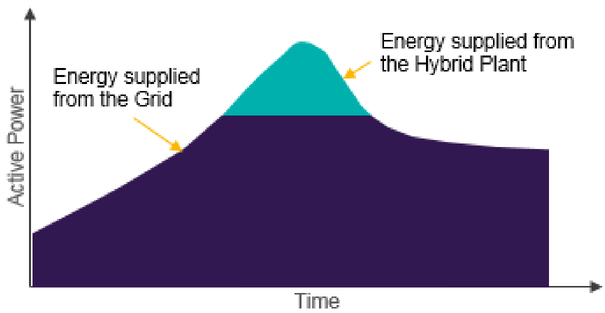

Figure 10: Active Power Control Mode: Peak Shaving.

2.6.1.6 Ramp Rate Limit

Any control mode should be limited by maximum power ramp values (in kW/s). This will allow rapid fluctuations of primary power sources not to be transmitted as power oscillations to the electrical power grid, in order to ensure compliance with typical requirements of network codes for generation plants.
Maximum ramp values include increased and decreased power. They will be configured by the plant operator of the Local controller.

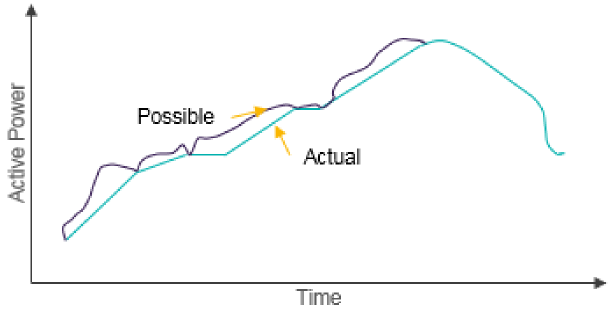

Figure 11: Active Power Control Mode: Ramp Rate Limit.

2.6.1.7 Delta control

It should also be possible to include an active power offset (delta) between the power production and the available power. In this case the active power production of the hybrid plant will be limited to a delta value of the active power corresponding to the dominant control mode.
Independent delta values will have the possibility to be parameterized for each renewable energy source, in order to separately limit solar and wind energy resources.
It will also be possible to set minimum values for active power; in which case the active power cannot decrease below these values. This will ensure the operation of subsystems above their technical minimums.

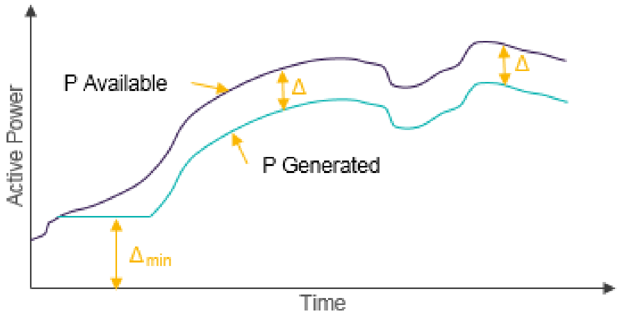

Figure 12: Active Power Control Mode: Delta Control.

2.6.1.8 Power Limited

In this control mode the active power production of a dominant control mode will be limited to a specific value, which will never be exceeded. The Power Limited will then be a priority mode, which can be useful for both the plant operator and the grid operator.
The function shall select which subsystem or power source to limit in function of the operating costs presented by each subsystem.
The control mode will allow adding a restriction to the use of the storage system. In this way the use of the batteries is conditioned to the cost of energy coefficient that will be set by the local controller operator by a value sent from the SCADA.

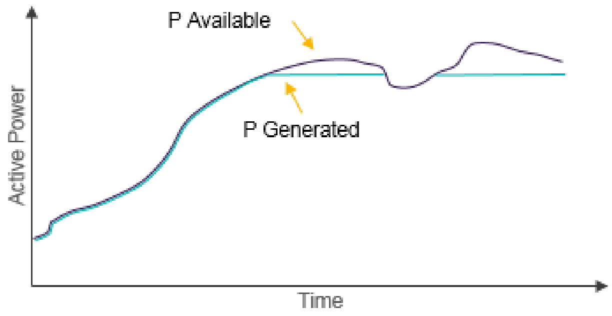

Figure 13: Active Power Control Mode: Power Limit.

2.6.1.9 Base Load

In this control mode the controller will guarantee an active power amount to the power electrical grid that was configured by the local controller operator. To supply the grid with this minimum power, the control mode will use all available power sources.
To supply this minimum power, energy from renewable sources will be used first. In the case of a storage system, the battery will charge when the available renewable power is greater than the set point and will discharge when the available renewable power is less than the set point in order to supply the minimum power.

2.6.2 Reactive power control modes

The controller will be able to work with different control modes to meet the appropriated grid codes. They may also operate autonomously or simultaneously according to the philosophy of operation of the energy system.
All active power control modes have more priority than the reactive control modes and the lowest set point will be the highest priority.

2.6.2.1 Power Factor (PF) Control

This control mode will work as closed-loop type control mode. In this case it uses as an input power factor information of the hybrid plant connection point with the electrical power grid. This value is compared to a power factor setpoint value that can be set by the plant operator. The controller will use the reactive power resources available in the subsystems to reach the required value.
The controller in PF control mode will use only reactive power for grid power factor regulation. To do this, use the sub-systems that are currently in automatic mode to reach the setpoint value. Manual devices will be treated as negative loads.
The value of the setpoint power factor may have a value of between -1 and 1.
Power factor regulation will be performed in two different modes in relation to input variables. On the one hand, the power factor can be measured in real time. On the other hand, a value that results from the average of several measurements in a time window can also be used.

2.6.2.2 Reactive Power Control

In this control mode the operator will set a reactive power setpoint value for the generation venue. The controller will inject the requested reactive power into the electrical power grid, using all available generation sources.
All subsystems shall be adjusted around their capability curves to achieve the reactive power setpoint.

2.6.2.3 Voltage Control

This control mode will work similarly to P(f) Control for the active power. In this case the variable to be controlled is the voltage at the point of connection of the hybrid plant to the electrical power grid. The operator will fix a voltage set point that works in a closed-loop voltage control system.

2.6.2.4 Q/V Control

This control mode will allow to one power plant to operate in voltage droop mode. In this case the controller will automatically increase or decrease the production of reactive power depending on the voltage of the grid at the point of connection of the hybrid plant. In this way the plant will contribute in order to stabilize the voltage of the system and to cover the initial voltage transient.

In the event of a phenomenon that produces voltage transients that operate fluctuations outside the death band, the controller will maintain its limit values for a certain amount of time. After the end of the event, it cannot be re-operated for a while. These times will also be adjustable by the plant operator.

The following figure shows the values involved in voltage control. Thresholds, ramps, and voltage dead band can be set according to current mode of operation and network code.

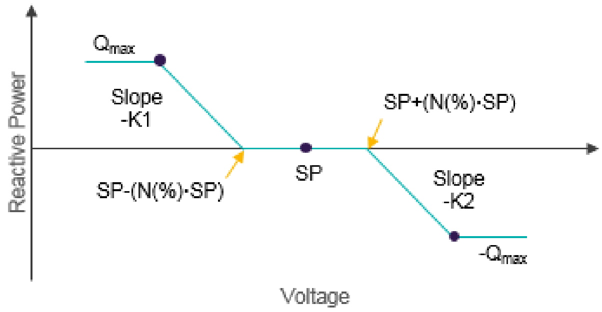

Figure 14: Reactive Power Control Mode: Q/V Control.

2.6.2.5 Reactive Power with no Active Power

In this control mode the controller will permit to inject an amount of reactive power into the power grid without simultaneously generating active power. The controller uses the technology of subsystems that have the ability to generate reactive power without active power generation and compensates for those that cannot generate reactive power without delivering a portion of active power.

2.6.2.6 PF/P Control

In this control mode, the control will operate under the same operating conditions that PF control, but in this case the power factor setpoint is a dynamic value that depends on the active power generated by the hybrid plant. Through this, the plant will work over-excited with low active powers, and sub-excited with high active powers.

The relationship between PF and active power is as follows. The operator will be able to set all the values in the figure (e.g. PFmax, PFmin, Slope, P1, P2).

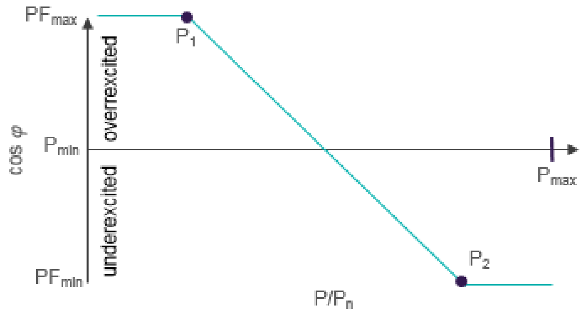

Figure 15: Reactive Power Control Mode: PF/P Control

2.6.2.7 Apparent Power Limited

In this control mode the apparent power production (S) of a dominant control mode will be limited to a specific value, which will never be exceeded. The S limited will then be a priority limit for the algorithm, which can be useful for both the plant operator and the grid operator.
The function will select which subsystem or power supply to limit based on the criteria of prioritizing active power over reactive power.

2.6.2.8 Reactive power Standby

In this control mode the controller will stop any control mode that is attempted to modify the reactive power setpoint. At the same time, it will reset all reactive power setpoints in the control modes that are operational.

2.6.3 Compatibilities between active and reactive control modes

Some rules must be defined to make all the mentioned control modes work together.

- Active power is always prioritized to reactive power.
- If there are several type of active power control modes:
  - Lowest priority: **P Available**.
  - Control modes that cannot work by themselves and without priority level because they have the highest priority: **Ramp Rate Limit** (compatible with Balance Control), **P Limited** (able to modify any control mode by limiting the maximum output).
  - Modes that only use storage for energy arbitrage (depending on the grid energy cost): **Delta Control, P Available.**

  The rest of the control modes will have a parameter to define the priority level.

  In case that several modes with the same priority level are activated at the same time, the one with the lowest set point is prioritized.
- If there are several types of reactive power control modes:
  - Control modes that will modify others with no priority level: **Q with P = 0** (that will permit Q Control and Q/V Control generate reactive power without active power).
  - Active power set point following, no compatible each other: **PF Control**, **PF/P Control**, **S Limited**.

The rest of the control modes will have a parameter to define the priority level.
In case that several modes with the same priority level are activated at the same time, the one with the lowest set point is prioritized.

3 La Plana demosite deployment

La Plana is a hybrid power plant located in La Muela, Zaragoza (Spain). The facility was commissioned in December 2015. Until 2019 the hybrid plant was an Offgrid system, but since then it is able to operate both connected and disconnected from local grid to perform a great test variety. It is composed by the following assets:

- **Diesel Power Plant** formed by 3 genset groups of 222 kW.
- **Photovoltaic Plant** formed by 816 panels (48 strings) with peak power of 245 kWp. The panels are connected to a Gamesa Electric 500 kW inverter.
- **Wind Farm** formed by a G52 wind turbine generator with a nominal power of 850 kW.
- **Storage System** formed by:
  - Ion-Lithium Battery of 429 kW/143 kWh. The BMS is connected to a Gamesa Electric 1.25 MW PCS. In the Offgrid mode, this plant has the capability of work in ZDO mode (Zero Diesel Operation), if the stability of the hybrid plant allows it.
  - Vanadium Flow Battery of 120 kW / 400 kWh. The BMS is connected to a Gamesa Electric 200 kW PCS.
- The **Load** to be able to perform any demand simulation:
  - A variable resistance bank of up to 1.1 MW.
  - A variable reactance of up to 750 kVAr.
- The **Substation** manages the connection to the grid with a voltage of 20 kV.
- **Weather station** to measure data on temperature, irradiance, wind speed, wind direction, humidity, dew point and rain.

This facility offers a whole hybrid scenario to validate any type of generation or storage technology as well as to validate any plant controller, which is always ready to carry out any test. These features have made this facility the best option to test and develop the Smart Controller.

Figure 16. La Plana hybrid facility.

The plant is managed through the TSC (Test Site Controller). It is a real-time controller whose main objective is to reduce the cost of generation in hybrid plants (LCoE) by targeting to achieve the maximum integration of renewable energy in optimal conditions.

Figure 17. Test Site Controller.

In order to meet the requirements of the MUSE GRIDS project and to be able to validate the Smart Controller, several tasks were carried out on the plant itself and on the TSC:

- Requesting grid connection permits to inject the energy produced into the grid. Due to the fact that the plant is connected to the grid of a wind farm there is a generation limit on the Point of Common Coupling (PCC) of 850 kW.
- Install a synchronization switch between the grid and the facility. This switch is a protection that checks that the phase, frequency and voltage are the same in the plant and in the grid of the wind farm. If they are different, it will not allow to connect the plant to the grid.

Figure 18. Synchronization switch.

- Development of the TSC (PLC + HCA (Hybrid Control Algorithm) + SCADA) for the ongrid operation modes with active and reactive control modes:
    - The control modules corresponding to the ongrid control modes and the module for connection to an external control (VPP, Virtual Power Plant) have been created in the HCA.

      The control modes developed have been those explained in the section 2.6.

      When this VPP control mode is active the local active and reactive controls are disabled, and the VPP control for active and reactive is managing the power output of the generation venue.
      This control mode will distribute set points received from the cloud into all subsystems of the facility considering the available power of each subsystem.
      The communication between the VPP/Cloud controller and the Local controller will be in 2 seconds interval, for commands, set points and status data (status of the plant, available power, current power measurements…).
      This control mode will be in communication with the MUSE GRIDS Smart Controller.

    - The PLC program, in charge of the field communications, has been updated to receive power meter data from the grid, to meet the new requirements imposed by the new version of HCA and SCADA and to establish communication between the TSC and the Smart Controller.

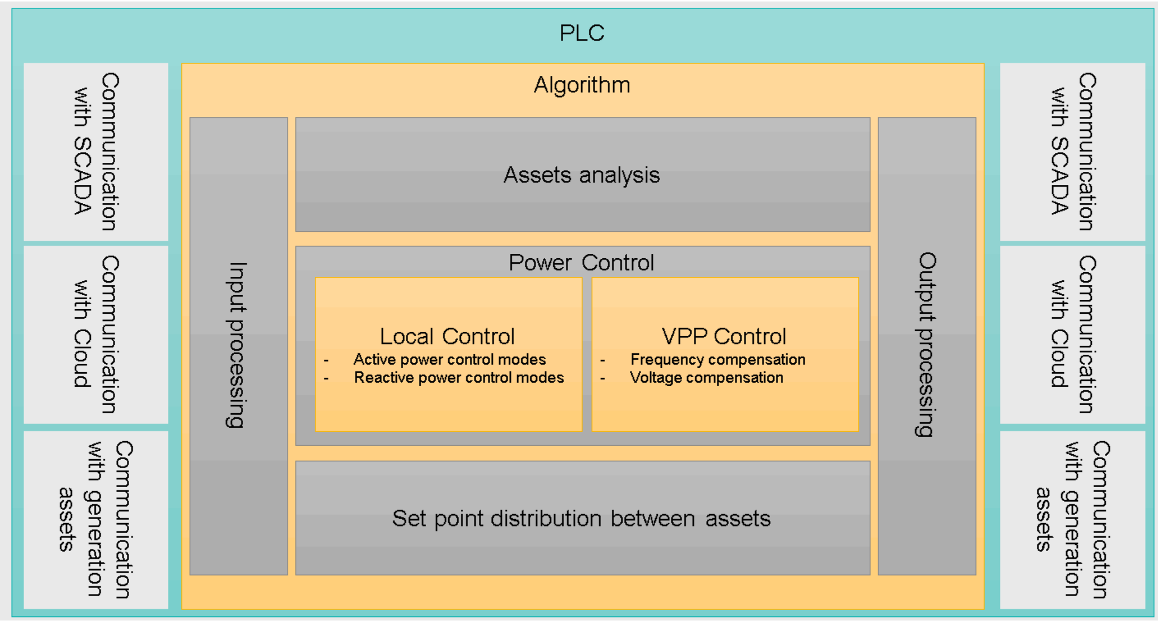

Figure 19. PLC and HCA diagram.

- The plant's SCADA has been updated to incorporate the grid as another control plant where the control modes can be activated and deactivated, the set points corresponding to each mode can be sent, the grid switch can be opened and closed, and the measurement equipment related to the grid can be displayed.

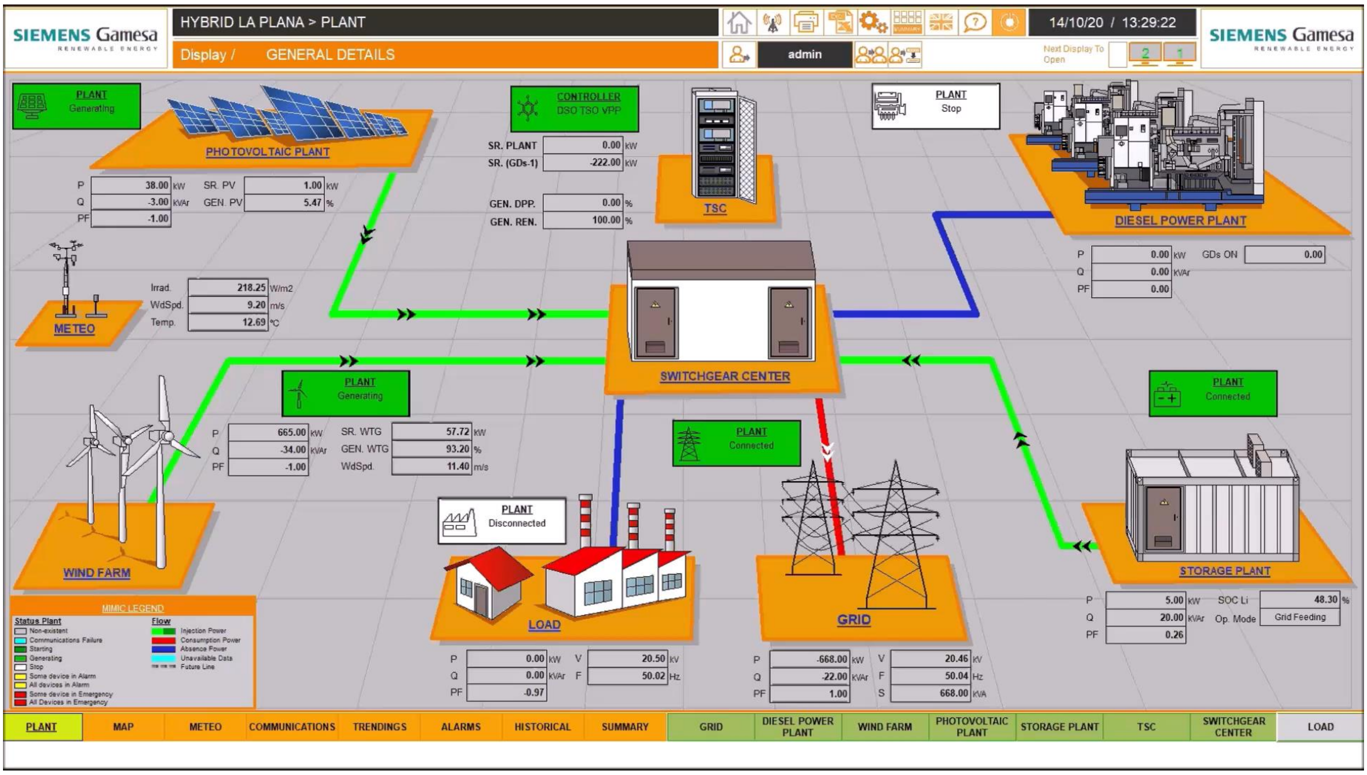

Figure 20. General details.

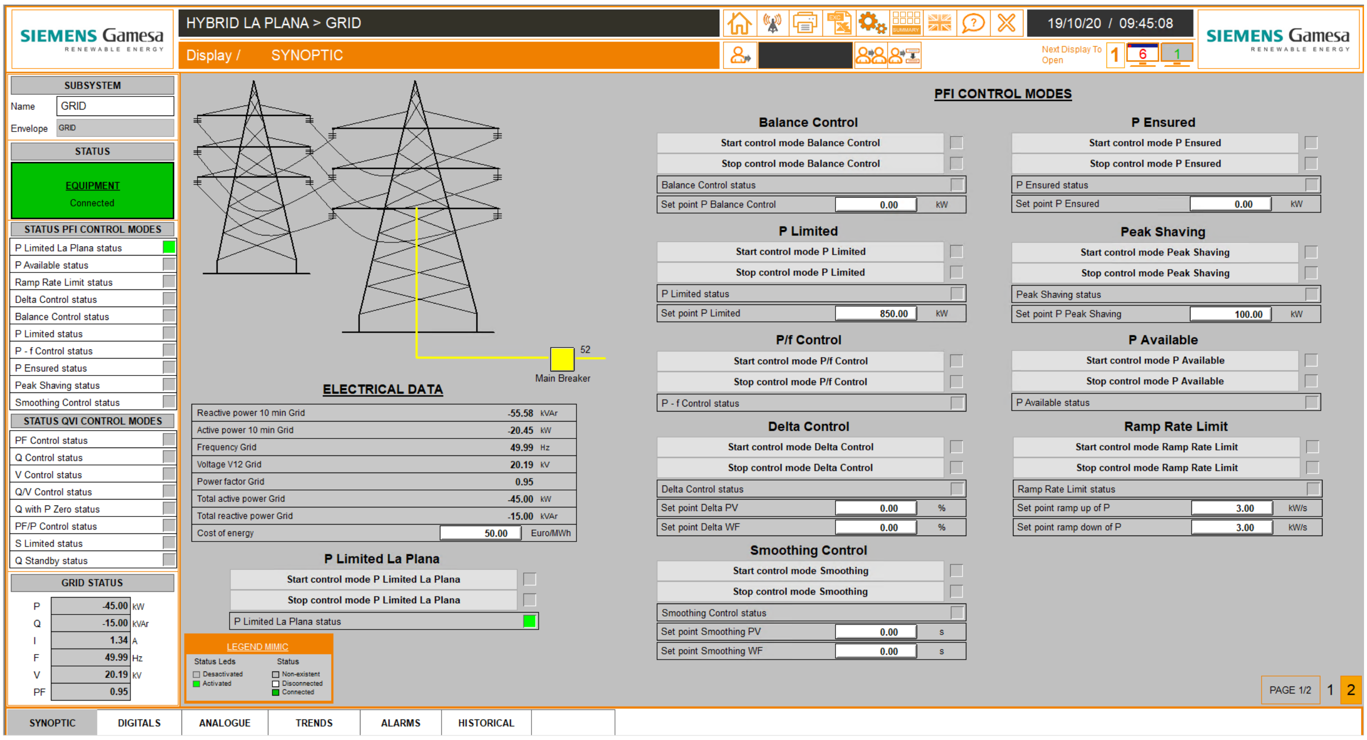

Figure 21. Grid: P control modes.

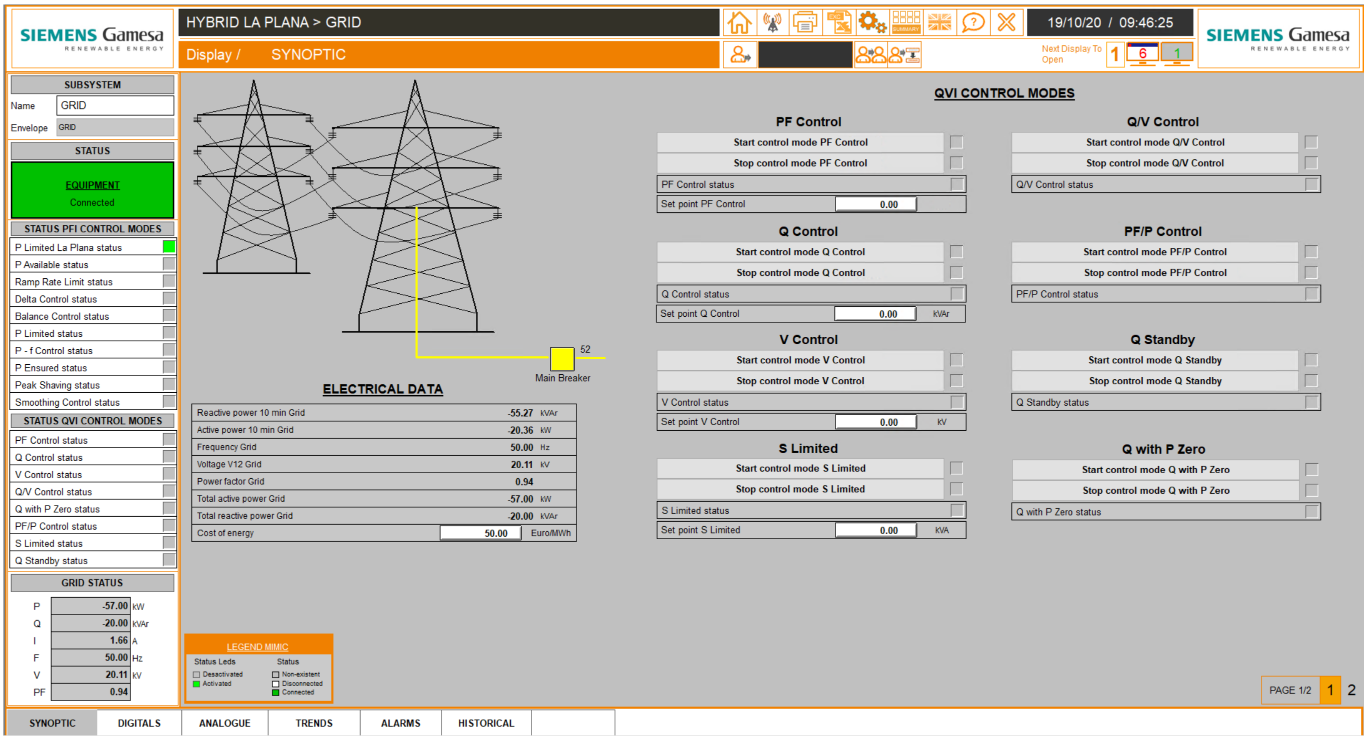

Figure 22. Grid: Q Control Modes

- A TCP S7 communication has been developed to communicate the MUSE GRIDS Cloud and the TSC. The server with the MUSE GRIDS Cloud is located at CARTIF's headquarters and the TSC is in the installation, so to communicate them a VPN IPSec with PSK tunnel has been established.

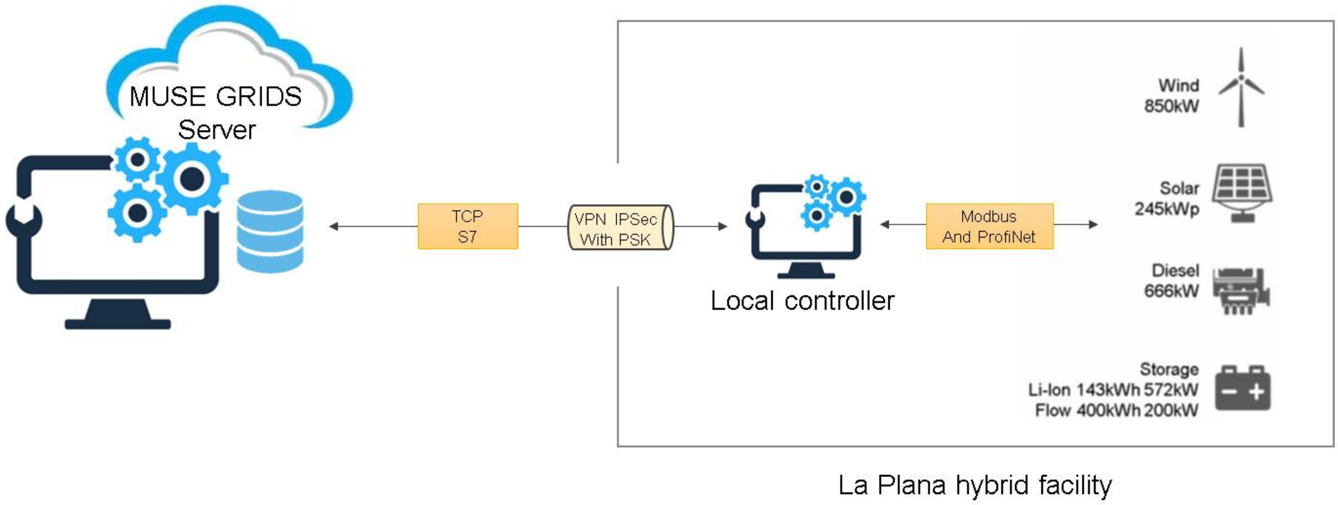

Figure 23. La Plana communication diagram.

The deployment of the optimization problem in La Plana has the main objective of validating and demonstrating the MUSE GRIDS software architecture in a real environment. In La Plana case the MUSE GRIDS Cloud including the Predictive and Optimal Control module has reached a TRL7 for the hybrid power plant connected to the main grid. It has been probed that the defined architecture provides with solid foundations for the replicability to other real deployments. The main difference among the different deployments will be the control problem to solve and how the optimal objectives are defined. In future scenarios and applications, the specific control problems will need to be properly validated off-line and using simulation models and then integrated in the MUSE GRIDS Cloud. The backbone of the Predictive and Optimal Control module based on an open source tool for optimization problems solving facilitates this design, programming and validation process of new control problems. In the same way, other modules (e.g. demand prediction) will need to develop specific algorithms that will be embedded in the tested architecture. As long as these new algorithms are properly validated off-line and their provided outputs and required inputs are adapted to the ones defined in the architecture, it is expected a smooth integration of the new modules and a fast deployment period. Of course, this never will avoid the required validation period in the real system that will be conducted according to a realistic deployment and test plan with the objective of avoiding any operational problems in the system.

3.1 Optimization problem definition

The optimization problem definition (detailed presented in D2.8) has two main parts:

- The objective function: that in the MUSE GRIDS case and according to the global objectives of the Smart Controller should represent the objectives of maximize the primary energy saving, reduce LCOH/LCOE and increase the self-consumption of the local energy community.
- The constraints and boundary conditions: that in the MUSE GRIDS case are related to the model of the system and operation conditions of the devices that should guarantee the rest of the Smart Controller objectives, being these to increase energy efficiency and performance of each grid and increase local energy district reliability.

In relation to the modelling of the energy system in the constraints function it has been defined trying that this first validation held in La Plana can be easily adapted and deployed for the Osimo and Oud-Heverlee demo sites.

With this purpose the optimization problem includes the next systems:

- Electricity main grid: that exchange power with the rest of system both providing and consuming with the only limitation of the maximum power flow allowed by the owner/operator of the main grid.
- Fully controllable energy source: power generation plant whose output can be controlled from zero to its nominal power. A second restriction is applied to the maximum power available to simulate renewable energy sources where the power is limited to the renewable resource such as wind or irradiance. This maximum available power is provided to the problem as a profile for the next 24 hours. It will be used to simulate PV panels present in the three demo sites.
- Region controllable energy source: power generation plant whose output can only be controlled in some segments of the whole range between zero and the nominal power. Restrictions are applied to the minimum and maximum power allowed that are provided to the problem as profiles for the next 24 hours. In relation to the definition of the problem this implies the use of integer variables what make more complex to find the optimal solution. Examples of this plant is the wind generator of La Plana than can only be controlled when its output is over 185 kW but can only operate at the fixed power with low wind speeds. So, it is not possible to be operated between zero and the minimum available power. Also, the CHP plant of Osimo can be considered of this type, as it can be connected only at its nominal power, not allowing a control of its output.
- Electric storage system: that is able to generate or demand electrical power according to its state of charge. The state of charge increases according to the energy supplied to the system and decrease proportionally to the energy supplied from the system to the grid. It is used to simulate the batteries that will be present in the electrical network.
- Shifting demand loads: whose energy demand can be provided with any profile that guarantee that the total required energy is satisfied before a prefixed time limit. This is the case of the Glen Dimplex devices that using their Critical Run Time an Incremental Run Time parameters inform of the amount of required energy in the morning and afternoon slots respectively. Also, the EVs could have a similar operating pattern in case the user allows some flexibility about when the car should be charge (e.g. time desired for at least 50% of charge and time limit for the 100% of charge).
- Non-controllable demand load: this demand simulates the users demand and any other loads that can be randomly connected or disconnected. The demand profile will be predicted and provided to the optimization problem as a demand power that has to be guaranteed.

For the definition of the objective function three complementary options have been programmed and validated:

- Minimization of the LCOE: based on the price of the energy production in the different assets (including operation and maintenance costs), the price of the energy sold or bought from the grid, the benefits of selling energy to the demand loads and other operation costs. The optimization problem minimizes the operation cost in the 24 hour time horizon according to the terms included in this objective function.
- Maximization of the self-consumption: based on the energy exchange with the main grid in the PCC can be configured to focus on the global balance in the 24 hour time horizon or in minimizing the amount of energy consumed from the grid in that 24 hour.
- Following of a grid power balance set-point: based on the minimization of the following error and programmed to fulfil the grid codes requirements. Depending on the operation mode of the control, these grid codes will be defined in the boundary conditions of the problem.

The optimization problem is solved using the CasADi open-source tool for nonlinear optimization (Andersson, Gillis, & Horn, 2019). This tool provides full-featured interfaces to Python and Matlab that can be used to model and solve optimization problems including ordinary differential equations in the restrictions. The core of CasADi

consists of a symbolic framework that allows users to construct expressions and use these to define automatically differentiable functions. Once the expressions have been created, they can be used to efficiently obtain new expressions for derivatives using Algorithmic Differentiation or be evaluated efficiently. CasADi provides both powerful solving algorithms and the easiness to represent the problem.
With CasADi tools the problem has been defined using the collocation points approach, which transforms the differential equations into linear restrictions (Barrio, 1999) (Andersson, Gillis, & Horn, 2019). This is done by dividing the total time interval to be controlled into subintervals and approximating the functions involved in the optimization problem by piecewise polynomials of a fixed degree. These polynomials satisfy the differential equation at the subinterval boundaries (called “control points”) as well as at auxiliary points inside each subinterval (called “collocation points”). Then, the optimal solution is obtained solving the transformed problem, whose mathematical form is a Mixed Integer Non Linear Problem (MINLP).
To improve the robustness of the problem both the equations of the model and the objective function has been transformed into a convex one using auxiliary variables. This makes the definition of the problem more difficult to understand and maintain as the variables related with physical variables are replaced with the auxiliary ones. In change it prevents that the algorithm could not find the optimal solution.

3.2 Data management and data base validation

MUSE GRIDS Cloud in La Plana communicates not only with La Plana local controller but also with two Glen Dimplex devices (cylinder and heater) located at Glen Dimplex laboratory in Ireland.
All information in La Plana facility is centralised in the local controller, thus, MUSE GRIDS Cloud communicates with the La Plana hybrid controller through S7 communication protocol (which is a version of the TCP protocol by Siemens) using the library snap7 in Python. Facility measurements are stored in the database accessible for the Smart Controller, which will write all commands and set point in the same database. MUSE GRIDS Cloud will use those commands and set points to send them to the power assets as can be seen in the following figure.

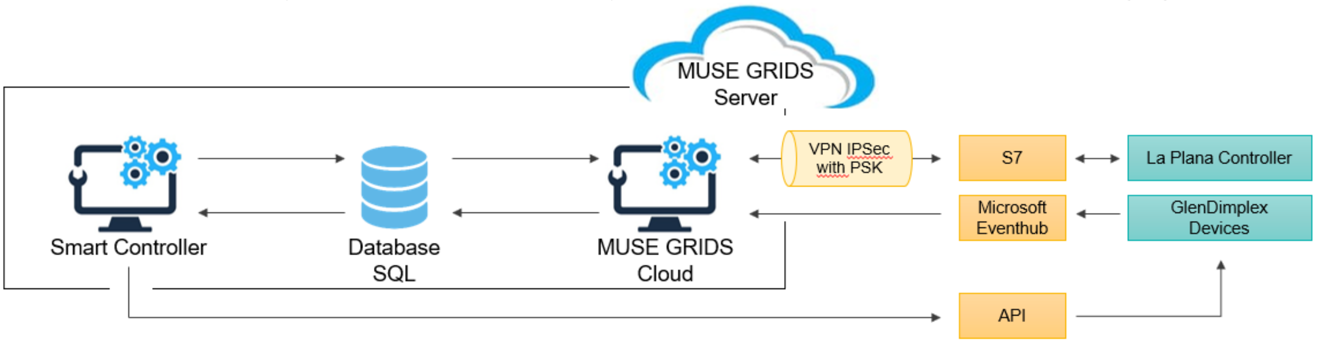

Figure 24. La Plana communication architecture by MUSE GRIDS Cloud

As already mentioned in section 2.1, MUSE GRIDS Cloud will use the Azure Eventhub library for Python to connect and receive Glen Dimplex telemetry data from the devices located in the laboratory. At first MUSE GRIDS Cloud connects to an Azure Eventhub Endpoint in a thread, working as a daemon, executed each time MUSE GRIDS Cloud receives an event.
Periodically, MUSE GRIDS Cloud is receiving telemetry data in packets referred to a device. Each Glen Dimplex device has its own identifier and gateway, so all data packets are easily assignable to the proper Glen Dimplex asset. All telemetries are stored in the database of the MUSE GRIDS Cloud so the Smart Controller can use last data to command the facility.
The setpoint to Glen Dimplex devices are sent using the DSM API provided by the manufacturer. This communication is done in the output interface of the Demand Side Management Module (section 3.4)
All data received from the facility and the Glen Dimplex devices is stored in the database, which contains one isolated table for each asset.

Inside the database, depending on the variable, not only instant values are included but also 10 minutes average values. The distribution of the tables for the La Plana MUSE GRIDS Cloud data base is the following:

- Facility main configuration
- General measurements such as meteorological data and the status of the local controller.
- Photovoltaic inverter data, 24-hour production forecast and a table for the photovoltaic inverter configuration.
- Wind turbine data, 24-hour production forecast and a table for wind turbine configuration.
- Lithium battery data, 24-hour production forecast and a table for the lithium battery configuration.
- Glen Dimplex cylinder data and a table for the Glen Dimplex cylinder configuration.
- Glen Dimplex heater data and a table for the Glen Dimplex heater configuration.
- Local grid status and measurements.
- Weather forecasts for the following 24 hours.
- Demand predictions for the following 24 hours.
- Generated power prediction for the following 24 hours
- Energy cost forecasts for the following 24 hours.
- Optimal control set points for the following 24 hours.
- Demand Side Management profiles for the Glen Dimplex devices for the following 24 hours

3.3 Models and demand prediction modules validation

These two modules are in charge of providing the optimal control module with the day-ahead predicted demand and power generation profiles
The demand calculation will be mainly based on historical consumption data and weather forecast. It will be also related to the day of the week, time of year (season), and official holidays. The Demand Prediction algorithm has been programmed in Python 3.8 with the following structure:

- Input interface: that will connect with the data base to collect the weather forecast and the historical data required by the demand prediction algorithms
- Demand Prediction manager: in charge of synchronizing the availability of the demand prediction with the needs of the control algorithm. It has been programmed with a synchronous execution basis and a period of 10 minutes. When the execution is triggered, it is checked if there exist any update in the forecast since the last execution of the algorithm. If there were any update or the last demand prediction calculation was performed more than 1 hour ago, a new prediction is calculated.
- Demand Prediction calculation: for validation purpose the Osimo's electricity demand model has been programmed and validated in La Plana. The calculated predicted demand is scaled according to the nominal power of the power plant. The original algorithm defined in D1.2 (https://www.muse-grids.eu/project-public-report/)was developed using R, and their integration in the Python code of the Demand Prediction algorithm has been done using the rpy2[1] package.

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[1] https://pypi.org/project/rpy2/

- Output interface: that will connect to the data base to upload or update the new demand prediction.

The power generation prediction includes models for the photovoltaic plant and wind generator, the two renewable sources present in La Plana.
The Models algorithm has been programmed in Python 3.8 with the following structure:

- Input interface: that will connect with the data base to collect the weather forecast and the parameters of the power plants required by the algorithms.
- Models algorithm manager: in charge of synchronizing the availability of the generation prediction with the needs of the control algorithm. It has been programmed with a synchronous execution basis and a period of 10 minutes. When the execution is triggered, it is checked if there exist any update in the forecast since the last execution of the algorithm. If there were any update or the last generation prediction calculation was performed more than 1 hour ago, a new prediction is calculated.
- Generation Prediction calculation: different functions have been programmed according to the type of power plant to be modelled. The main algorithm decides which one is used according to the stored configuration in the database. At this moment two main groups of plants have been programmed: PV plants and wind generators. The models are embedded in the Python code using their mathematical equations (PV plants) or data based models (wind generator).
- Output interface: that will connect to the data base to upload or update the new generation prediction.

3.4 Demand side management (DSM) validation

The DSM module is in charge of providing the optimal control module with the day-ahead load requirements of the shifting load and once the optimal demand profile is calculated is in charge of distributing that load among all the controlled devices.
In La Plana demo site the DSM algorithm has been developed for the Glen Dimplex Smart Energy Thermal Storage (SETS) devices. The DSM module takes the role of an aggregator for the heaters, collecting individual requirements of every installed device and distributing the available power among them according to those requirements. The available power will be in this case the one calculated by the predictive controller. This scheme will be the one used in in Osimo in the case of the electricity system problem and in Oud-Heverlee for the neighbourhood energy management.
The DSM algorithm has been programmed in Python 3.8 with the following structure:

- Input interface: that will connect with the data base to collect the load requirements of the devices in the next 24 hours. In this case these requirements are defined by the Critical Runtime (CRT) and Incremental Runtime (IRT) values read from the Glen Dimplex devices. These parameters are calculated by the device at midnight and noon and indicate the time that it needs to be charging before 12 pm and 0 am respectively to supply the required energy according to the users setpoints. More details about these parameters and how they are calculated are included in D2.3.

  The input interface also connects to the database to collect the demand profile for the shifting loads that the control algorithm calculates as solution of the optimization problem.
- DSM algorithm manager: in charge of synchronizing the availability of the shifting loads requirement prediction with the needs of the control algorithm. It has been programmed with a synchronous execution basis and a period of 15 minutes. When the execution is triggered, it is checked if there exist any update in the CRT and IRT values since the last execution of the algorithm or a new calculated optimal demand profile. If there were any update or the last demand distribution calculation was performed more than 1 hour ago, a new distribution is calculated.

- DSM calculation: an optimization problem has been defined and programmed for the optimal distribution of the global shifting load among all the controlled devices (in this case Glen Dimplex heaters). The profile for the global demand is provided as one of the output variables of the control algorithm, and the optimal distribution of this demand is based on the priorities assigned to every device. This priority can be related to the price of the electricity in every location (if different) of to any other criteria imposed by the owner of the devices. The DSM algorithm fulfils both the global demand desired by the control algorithm and the storage requirements of every independent device. To find the optimal solution, the DSM algorithm solves an Integer Linear Programming problem using a Branch-and-Bound and Gomory Cut approach (Makhorin, 2000) (Sandia National Laboratories, 2013). Figure 25 and Figure 26 shows an example of the results of this DSM algorithm for the simulated case of 28 heaters and the global demand obtained in a simulated control case. Every time slot (bar in the graph) correspond to 30 minutes operation and every coloured box represent the energy that one of the devices should demand during that time slot. This energy is the result of demand the 3.3 kW rated power of the heater during the time determined by the DSM optimal algorithm. Due to the operation conditions recommended by the manufacturer, this time is restricted to be at least 15 minutes and when the device is switched off it needs at least another 15 minutes in that mode.
- Output interface: that will connect to the data base to upload or update the distribution of the demand and also will convert this distribution in time slots to send them to the device according to the Glen Dimplex DSM API definition as explained in D2.3.

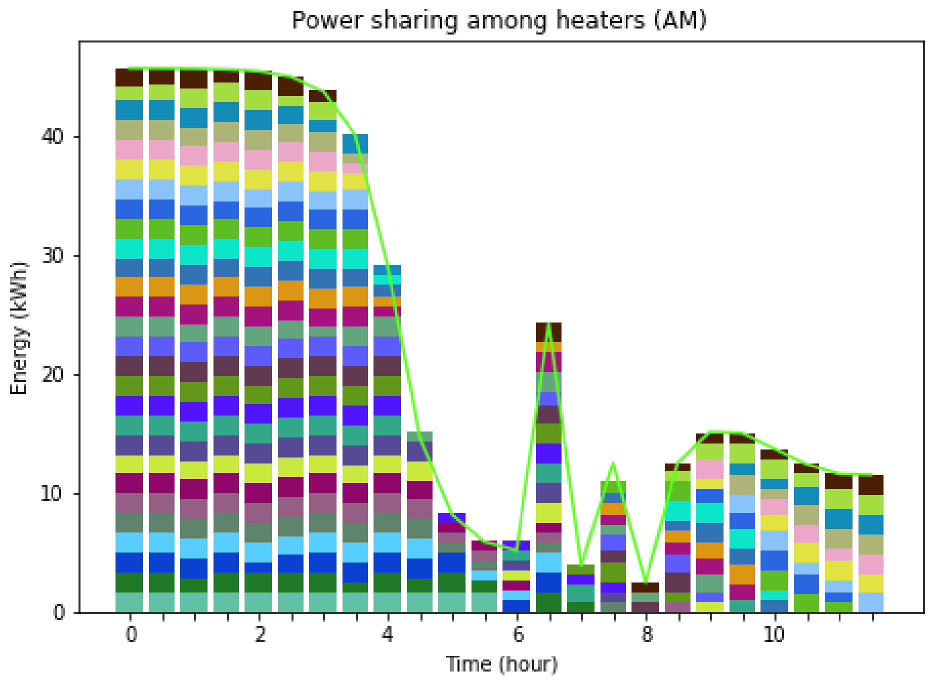

Figure 25. Distribution of morning energy demand among a group of heaters.

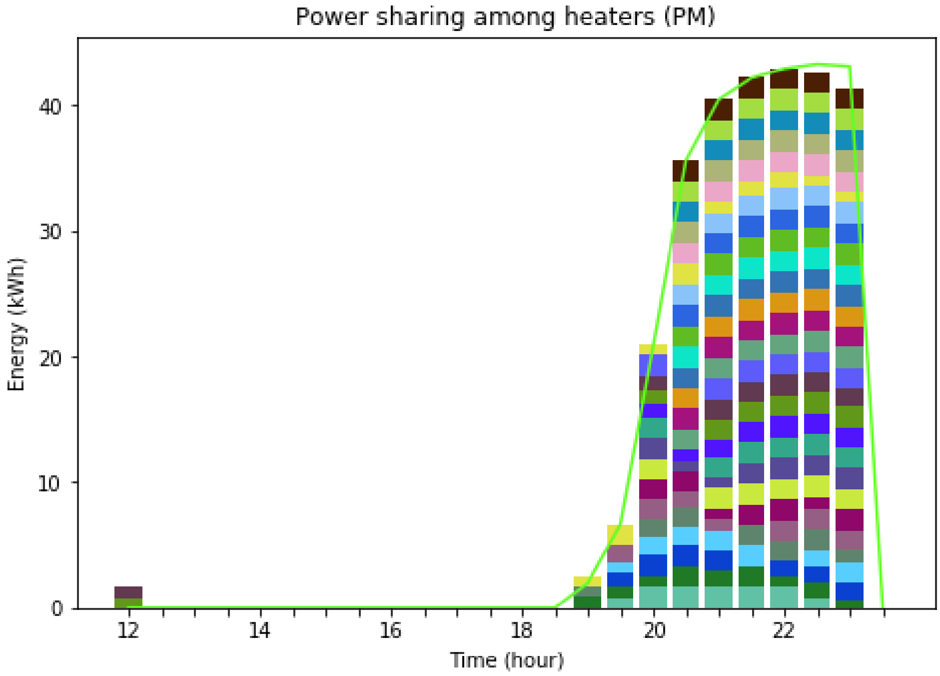

Figure 26. Distribution of afternoon energy demand among a group of heaters.

3.5 Grid codes validation

The control modes defined in section 2.6 and programmed in the TSC have been tested and validated in La Plana. To carry out the tests, each device can be configured independently, with the following possibilities:

- In automatic mode, where it will be the controller who will send the set points depending on the control mode.
- In manual mode; the operator will set up the SOC, active and/or reactive power setpoint through the SCADA.
- Enabled or disabled so that the control does not take them into account.

The following image shows the different configurations and set points that can be sent to each device:

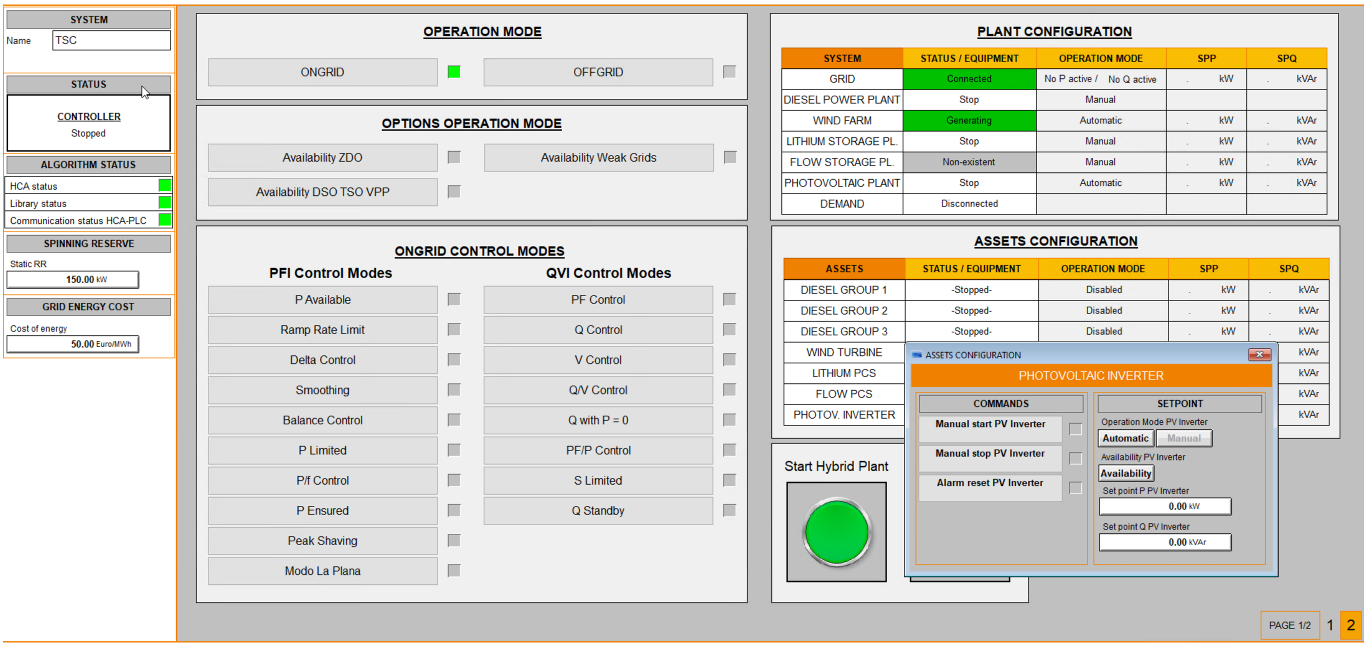

Figure 27. Device configuration in the SCADA.

Below there are some of the tests that have been carried out with the following control modes active:

- Base Load
- P Available + P Limited

3.5.1 Base load

In this test the plant will be able to provide at least active power level that determines the P_base_load setpoint. This test will be divided into 4 subtests in which a different P_base_load setpoint will be set to check how the power system behaves when:

- There is excess renewable energy and the battery can be charged.
- There is not enough renewable energy and the battery has to be discharged.
- The battery charge or discharge according to the variability of the renewable energy.

BASE LOAD CASE 1, P = 400 kW

In this first scenario, the setpoint of P_base_load is adjusted to 400 kW and the battery will supply the difference so that the PCC has 400 kW, either through charging or discharging operation.
As shown in Figure 28, the active power on the PCC (red) is always above 400 kW. In those cases where it is exceeded, the battery is not being able to absorb all the excess P that is being produced by the photovoltaic plant and the wind turbine.

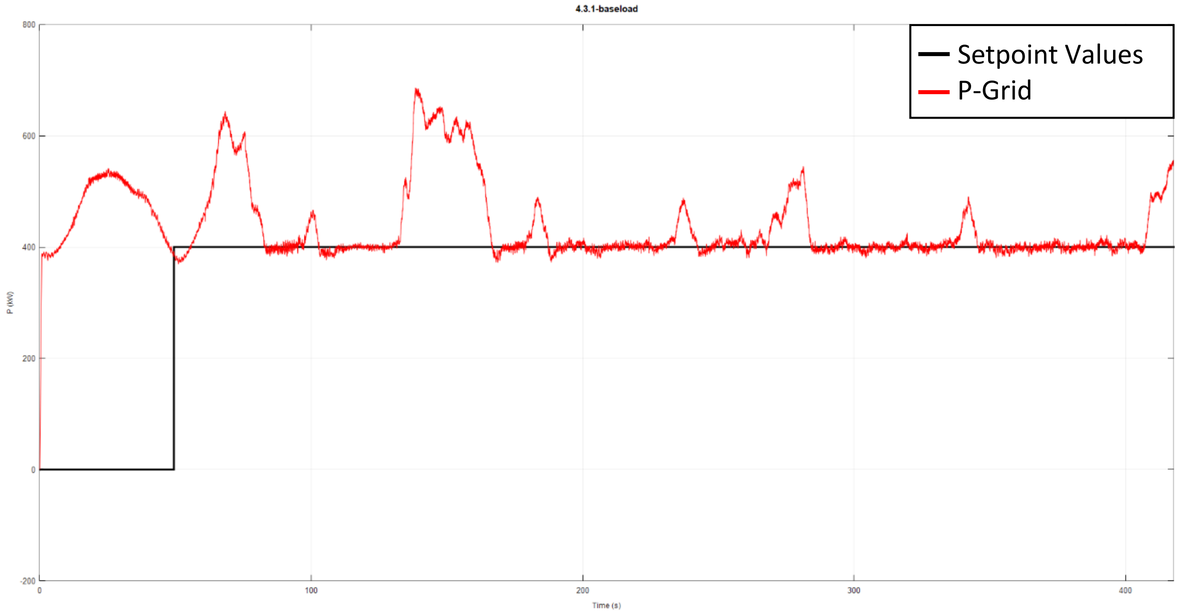

Figure 28. PCC Active Power - Base Load Case 1.

The following picture, Figure 29, shows the sum of the power of the PV plant and the wind turbine (in red) and the power of the battery (green) that will be negative when it is charging. It can be seen how the battery adapts to the generated power in order to try to keep the 400 kW in the PCC, injecting P between the second t=110 s and t=131 s.

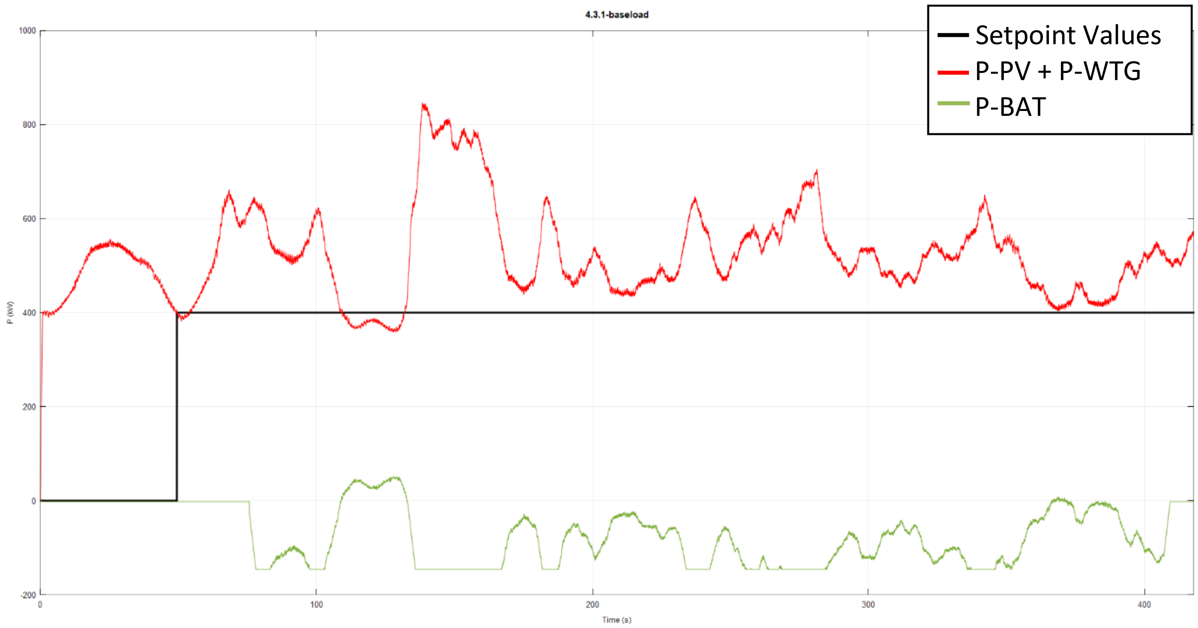

Figure 29. Active power PV, WTG and BAT - Base Load Case 1.

BASE LOAD CASE 2, P = 200 Kw

In the second scenario, the P_base_load setpoint is adjusted to 200 kW and the battery, as before, will supply the difference so that the PCC has 200 kW, either by charging or discharging.
Figure 30 shows how the active power on the PCC (red) always remains above 200 kW. As in the first scenario, in certain situations the battery does not have enough capacity to absorb the excess active power produced by the photovoltaic plant and the wind turbine compared to the 200 kW setpoint.

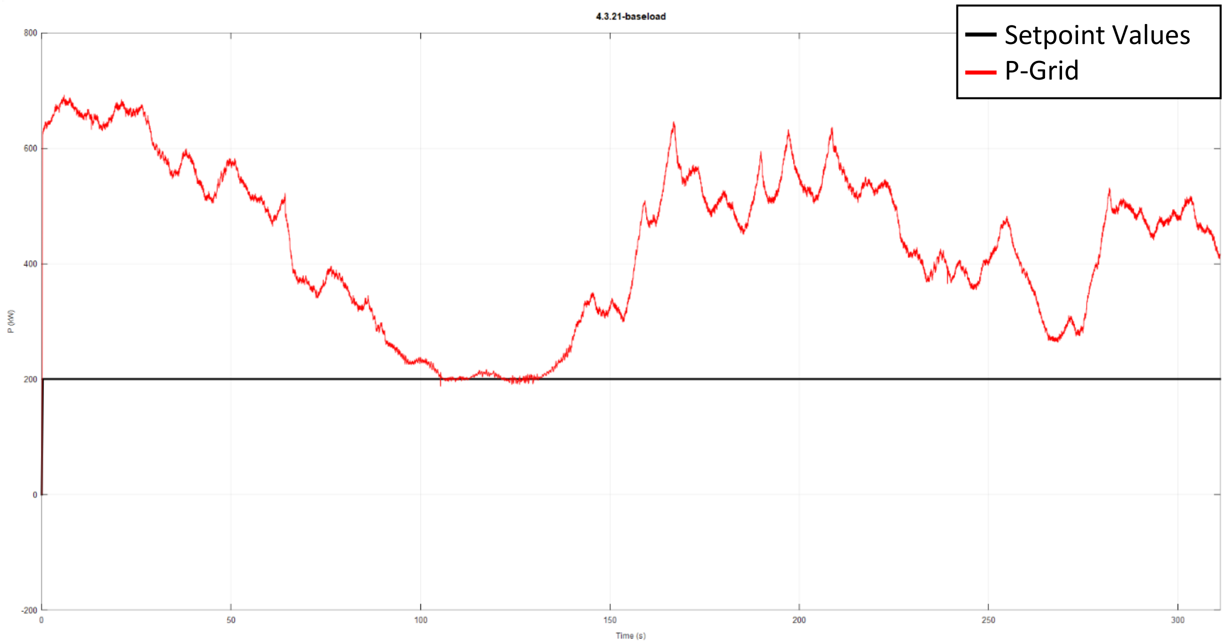

Figure 30. PCC Active Power (PV + WTG + BAT) - Base Load Case 2.

Figure 31 shows the sum of the power of the PV plant and the wind turbine (in red) and the power of the battery (green), that will begin to charge the maximum power available due to the excess of renewable energy with respect to the Base Load set point.

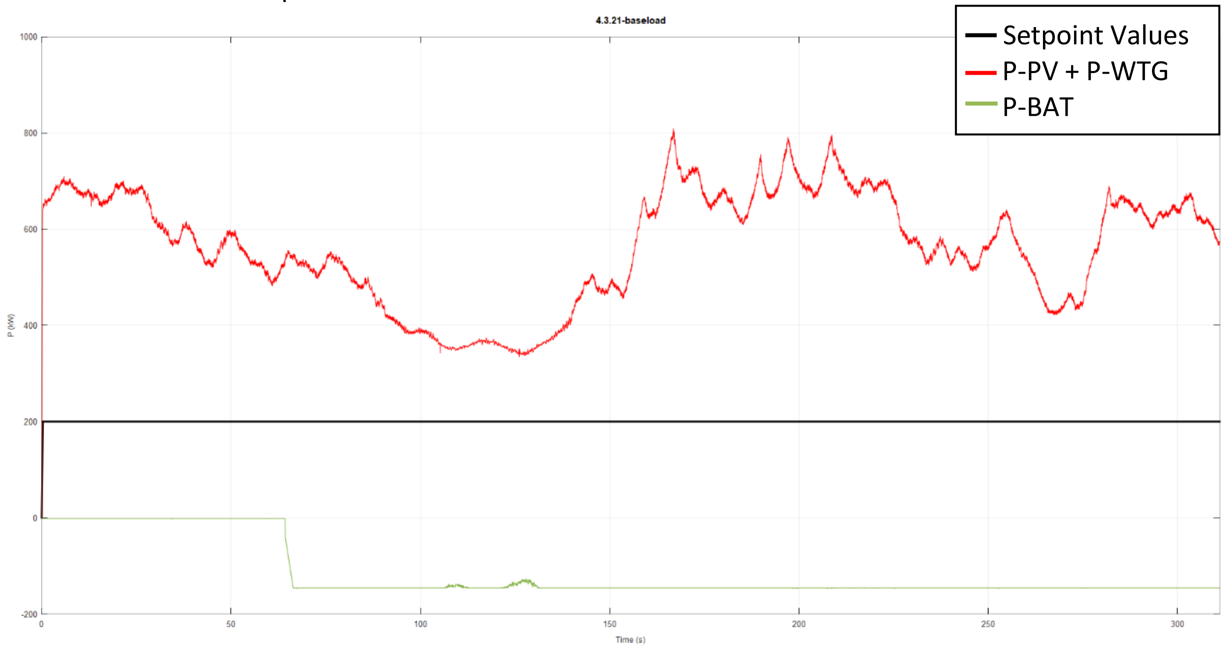

Figure 31. Active power (PV + WTG) and BAT power - Base Load Case 2.

BASE LOAD CASE 3, P = 850 Kw

In this third scenario, the P_base_load setpoint is adjusted to 850 kW. In order to reach this value, as in previous tests, the available resources (PV, wind turbine and battery) will be used. In this case, it will be observed how the battery will inject active power because there is not enough resource. Even though with that injection it is not possible to fulfill the conditions.

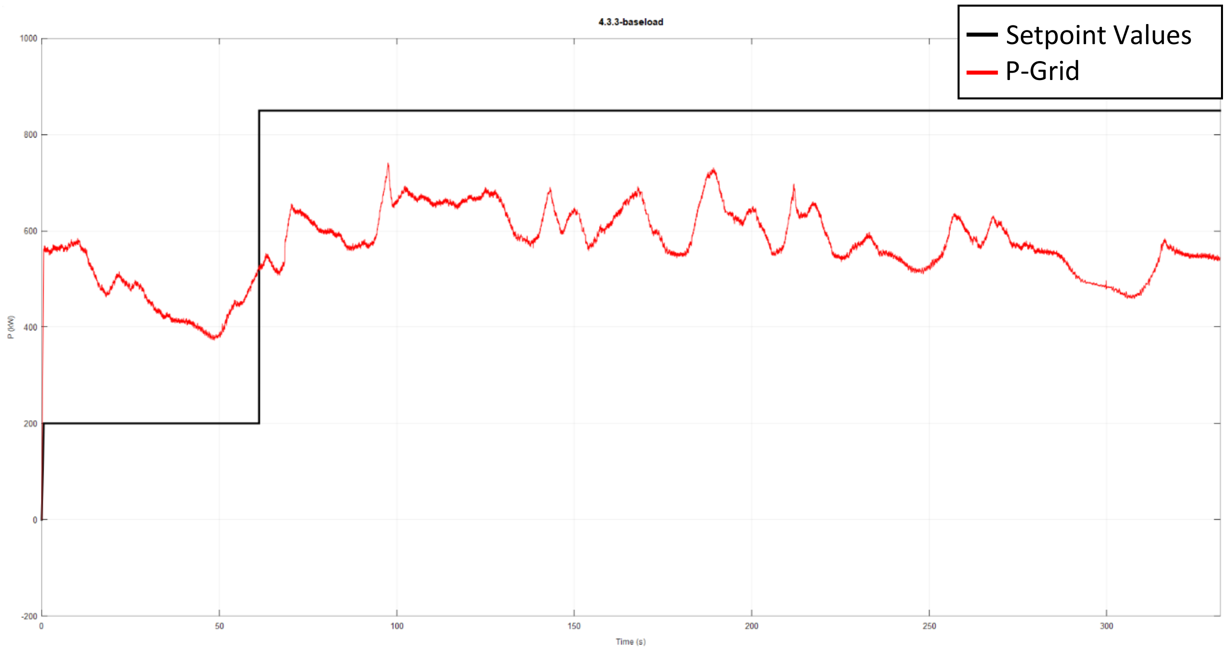

Figure 32. PCC Active Power (PV + WTG + BAT) - Base Load Case 3.

In the following picture, Figure 33, it may be seen how the battery (green) discharge the maximum possible power due to the fact that the sum of the photovoltaic plant and wind turbine power does not reach the minimum power. The active power Base Load mode is activated in the second 60.

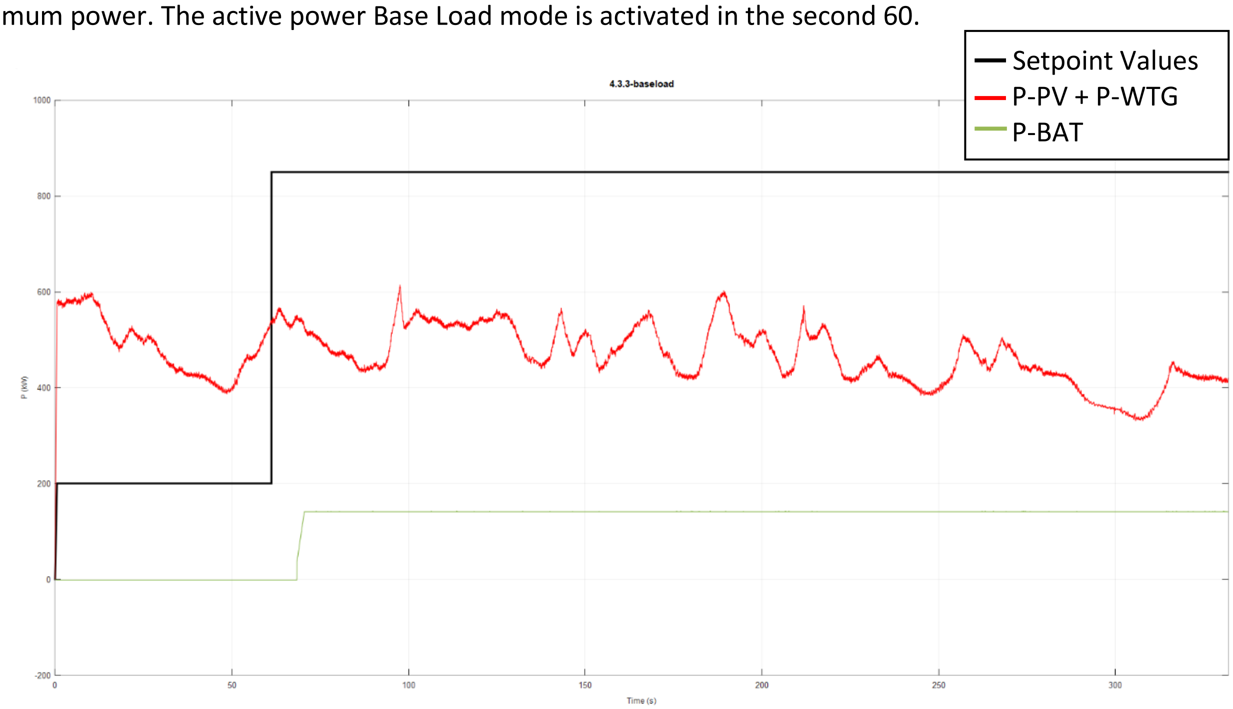

Figure 33. Active power (PV + WTG) and BAT power - Base Load Case 3.

BASE LOAD CASE 4, P = 500 kW

In the last case, the P_base_load setpoint is adjusted to 500 kW. Figure 34 shows how the control manages to keep the active power in the PCC (red) at 500 kW except in a period that goes from t=57 s to t=89 seconds, approximately. Even though the battery injects as much power as possible, it does not reach 500 kW.

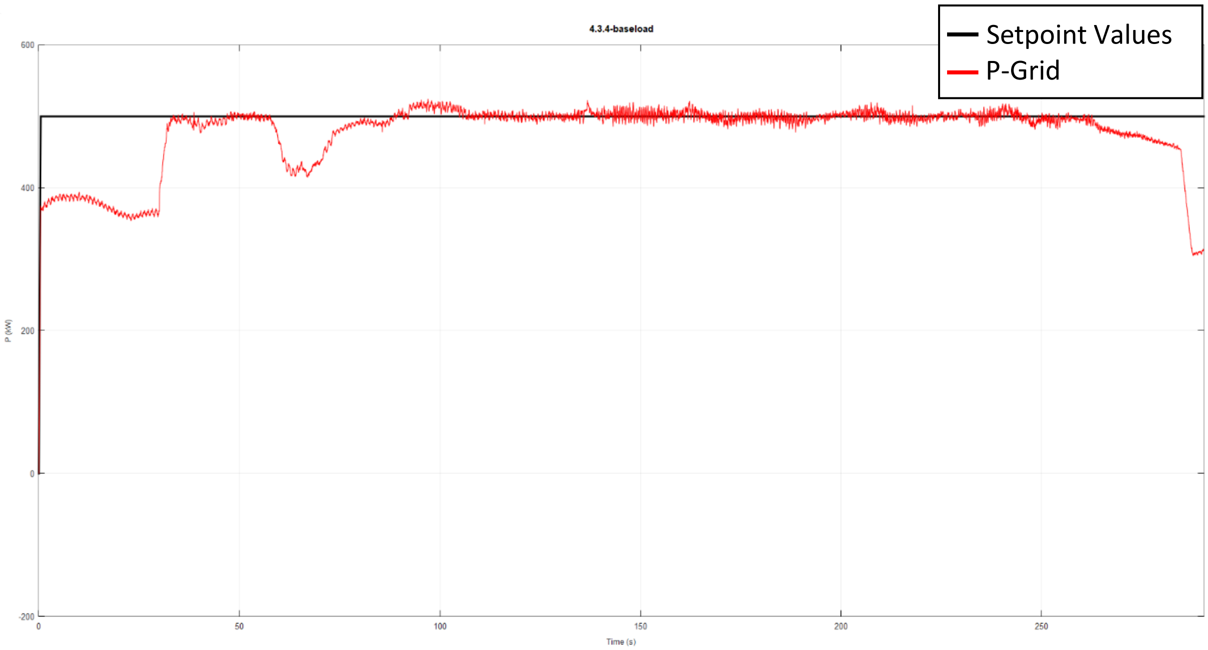

Figure 34. PCC Active power (PV + WTG + BAT) - Base Load Case 4.

Besides, in Figure 35, shows how the battery (green) charges or discharges depending on the energy produced by the photovoltaic plant and the wind turbine. If this active energy is greater than the set point, the battery charges, if not, it discharges. The result has been shown in the previous figure.

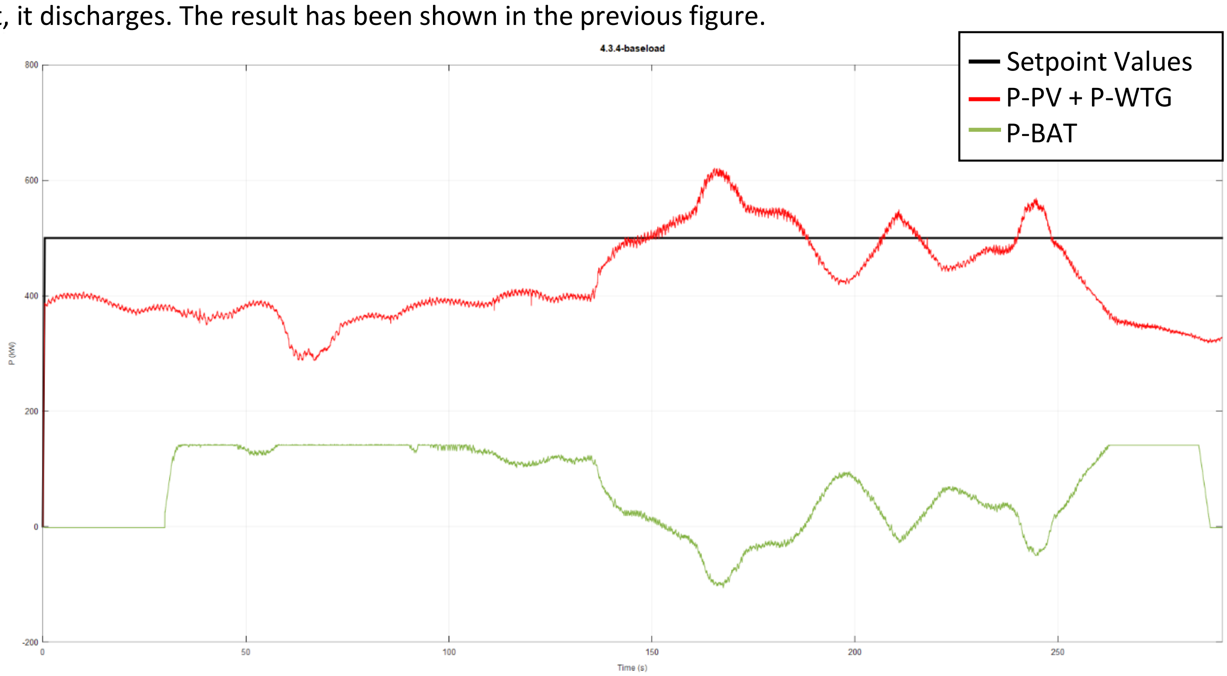

Figure 35. Active power (PV + WTG) and BAT power - Base Load Case 4.

3.5.2 P Available + P Limited

In this test the plant must limit the delivered power to the grid. As explained in section 2.6.1.8 the operating mode P limited shall not operate alone, but shall limit another mode which, in this case, shall be P available.
Within the test, three tests with different P limitation were carried out. These tests will show the priority in power reduction according to generation cost and the capacity of the battery to be charged according to the available power and energy price. These 3 tests are the following:

- P limited to 70%
- P limited to 50%
- P limited to 25%

The set point value for P Limited is calculated in relation to the maximum permitted plant output, 850 kW.

P LIMITED 70 % CASE 1.

The first of the three tests has the active power limited to 70%. Figure 36 shows how the active power limitation occurs in the wind turbine, while the photovoltaic produces the maximum it can at any given time. In fact, if the graph is analyzed in more detail, it can be seen how, when the production of the photovoltaic increases, the controller limits even more the production of the active power from the wind turbine.
Likewise, there are times when 595 kW (70% of 850 kW) is not reached, due to insufficient renewable resources. However, this is a situation that can occur, above all, if the P limited requirement is very demanding and the variability of the resource is high, as is in this situation.
P Limited mode is activated by the operator in t = 170 s and deactivated in t = 800 s.

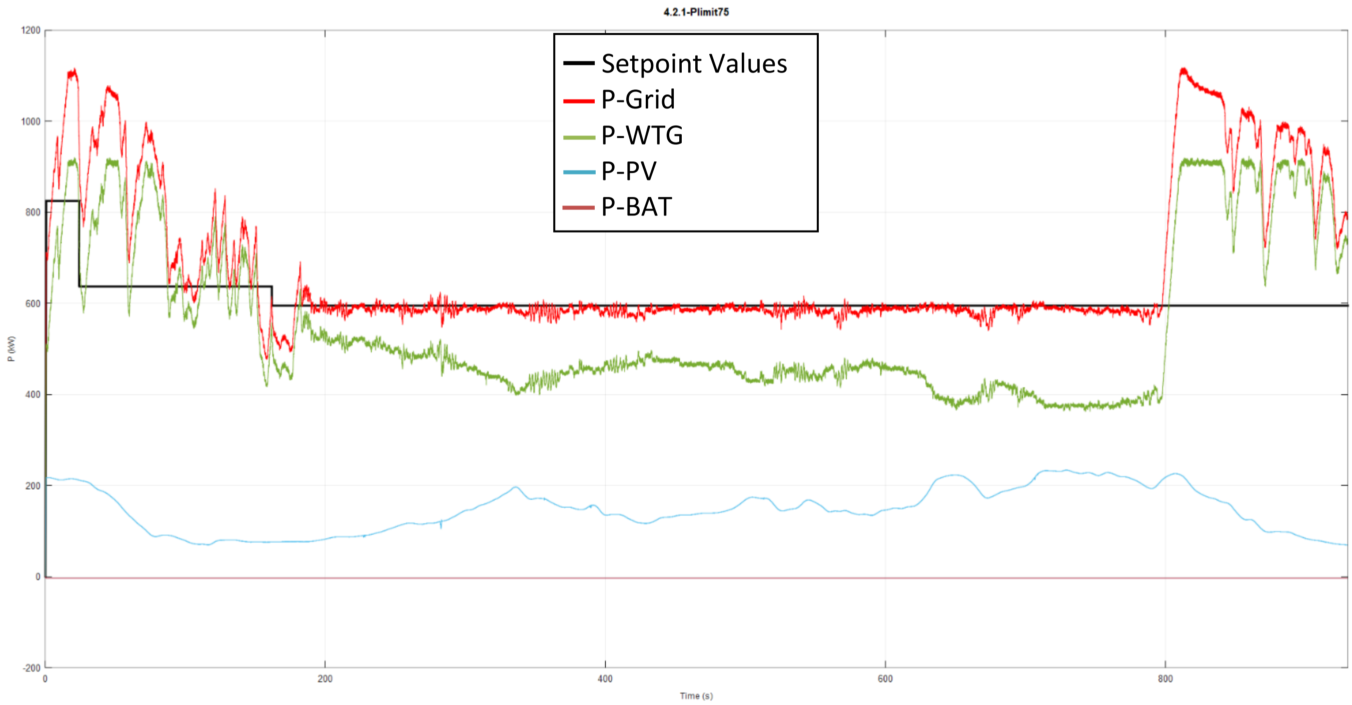

Figure 36. P Limited to 70 % Case 1.

P LIMITED 50% CASE 2

In this case the production of active power will be limited to 50%, which is 425 kW. P Limited mode is activated by the operator after 170 s and deactivated after 800 s.

In Figure 37 it can be seen how, as in the previous case, the limitation of P occurs in the wind turbine, while photovoltaic produces the maximum it can at any given time.

P Limited mode is activated by the operator in t = 170 s and deactivated in t = 800 s.

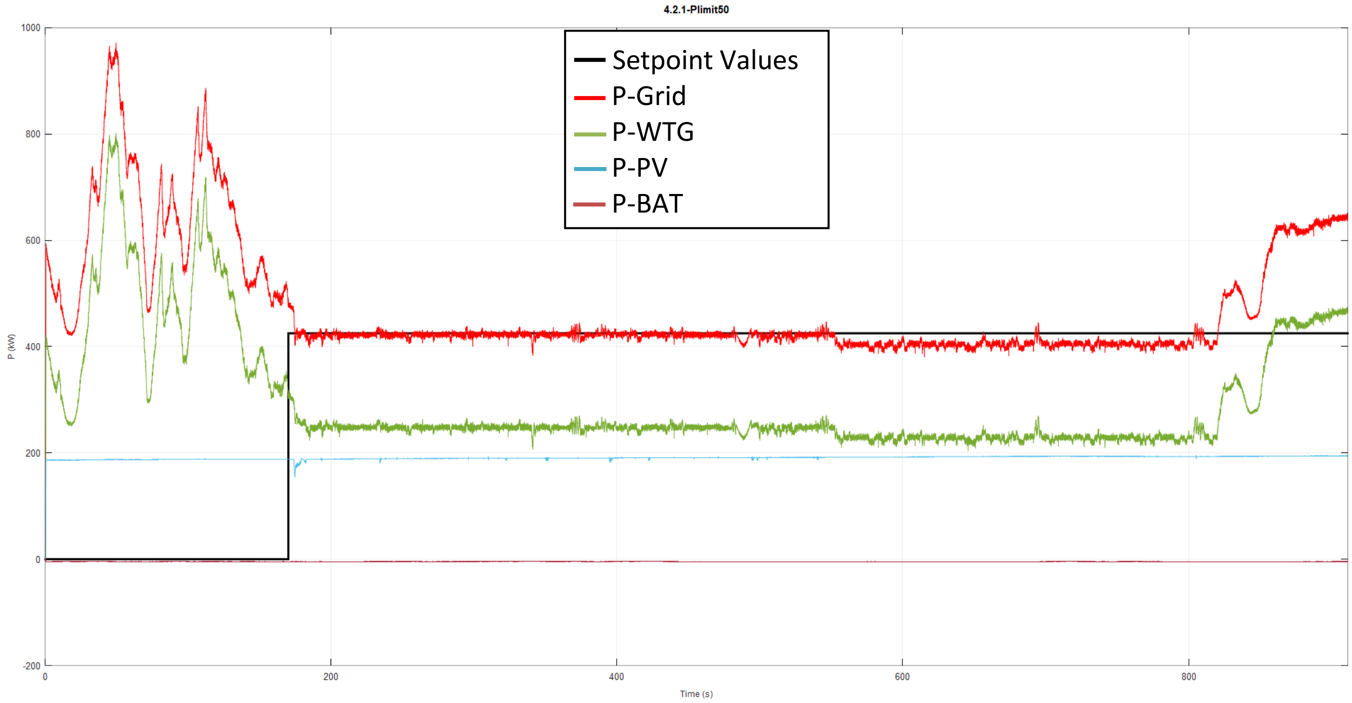

Figure 37. P Limited to 50 % Case 2.

P LIMITED 25 % CASE 3

In this case the active power production limitation is set at 25%, 212.5 kW. P Limited mode is activated by the operator after 80 s and deactivated after 750 s.
What will be observed is that the reduction of the wind turbine will be the maximum possible, but it will not be enough. Therefore, the photovoltaic plant must also limit its power production.
On the other hand, a second variable is added to this test, which is the battery. By modifying the price of energy, it will be observed how the plant reacts to a setpoint of power absorption by the battery.
Figure 38 shows how during the first phase of the test, where the price of energy is at 40 €/MWh, the battery is not activated (t= 0 s to t = 210 s). Therefore, the photovoltaic plant will be forced to reduce the power production. When the energy cost is reduced to 5 €/MWh (t = 210 s to t = 770 s), the battery starts to absorb energy and the PV plant increases its active power generation as much as possible until the total active power production reaches 212.5 kW.

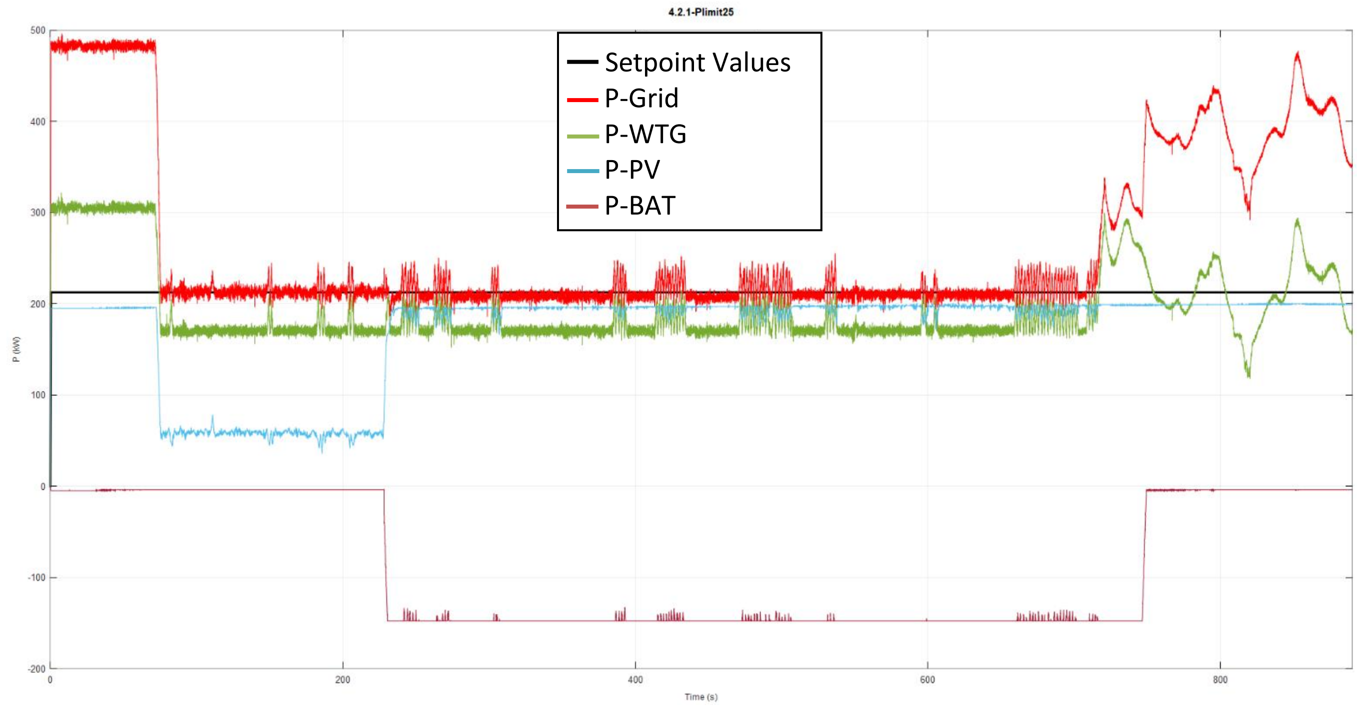

Figure 38. P Limited to 25 % Case 3.

3.6 Hardware configuration

The server used for the deployment is a DELL OptiPlex 7070 Micro Form Factor with the next specifications:

- Processor: Intel Core i7-9700T.
- Memory: 8Gb RAM.
- Storage: 256GB SSD M.2 PCIe NVMe.
- Communications: 2 x 802.11ac Wi-Fi Dual Band.
- Operating system: Windows 10 Pro.

3.7 Smart Control validation

The validation of the Smart Controller was held operating La Plana hybrid facility in real conditions, under a simulated demand and with the high-level and low-level controls cooperating to achieve the objectives of the control.

The experiments related to the validation of the control were done along September and October (some other tests were done to test the communications). There is a limitation for these tests related to the weather conditions, as the significant tests have to include both wind turbine and PV plant.

As explained in the introduction of this section, the TSC program has been modified to make possible the coordinated operation of the Predictive and Optimal Control with the local control. Once the optimal profiles for generated power and SOC are calculated it is necessary that the local controller follow these set-points. As the actual generated power in every plant depends on the weather conditions it is not possible to base the interactions between both controls on the generated power in the plants. So, it will be the desired SOC the only set-point that the power plant has to follow. In this way it is always guaranteed, according to the predictions, that there will always be enough energy available to fulfil the objectives even though when the generated power is low. In the same way when the energy stored is used it is guaranteed that it won't be needed in the short term or is really used to help in the maximization/minimization of the objective. The defined strategy is based on the double requirement of:

- The low level control needs to apply the grid codes in real-time. This means that it needs to control the actual power of the plants to maintain the required power at the PCC even though the weather conditions such as wind gusts or clouds can change the available power in a few seconds. The power of the plants (and in some cases the power exchange with the grid) offer enough degrees of freedom to the low level controller to perform the real time control.
- The long term operation of the plant follows the optimal profiles trends and achieves the programmed objective. In this sense it is important to note that the SOC desired profile is calculated using the predicted average power per hour in the plants. It is expected that the average of the actual power (or the total energy) per hour will be the same of the predicted value. So even though in the real-time operation there are changes in the available power (associated to the changes in the operation conditions) the total energy exchanged among the sources and demands will be the one predicted if the stored of generated by the storage system is the optimal one.

This strategy of connecting high-level control and low-level control is specific of La Plana hybrid facility.

Figure 39 to Figure 41 show the results of the tests performed on October 14th of 2020 between 10:30 and 12:30 CEST. First, Figure 39 shows the 24 hours prediction inputs and outputs of the optimization problem solved at 10:30 CEST. The predicted demand has been defined according to the available predicted power that is based in the real weather forecast. Figure 40 and Figure 41 show the actual power measurements and SOC during the test. In the first hour the storage system discharges and generates power even though the generated power is higher than the demand. The optimization problem makes this decision because the energy can be sold obtaining a benefit and as the prediction shows, the storage system can start the charging from 11:30 to 12:30 to have enough energy to cover the demand excess from that hour. These three figures show how the optimization problem works in real time providing the optimal set-points, and at how the low level control follow the required SOC set-point.

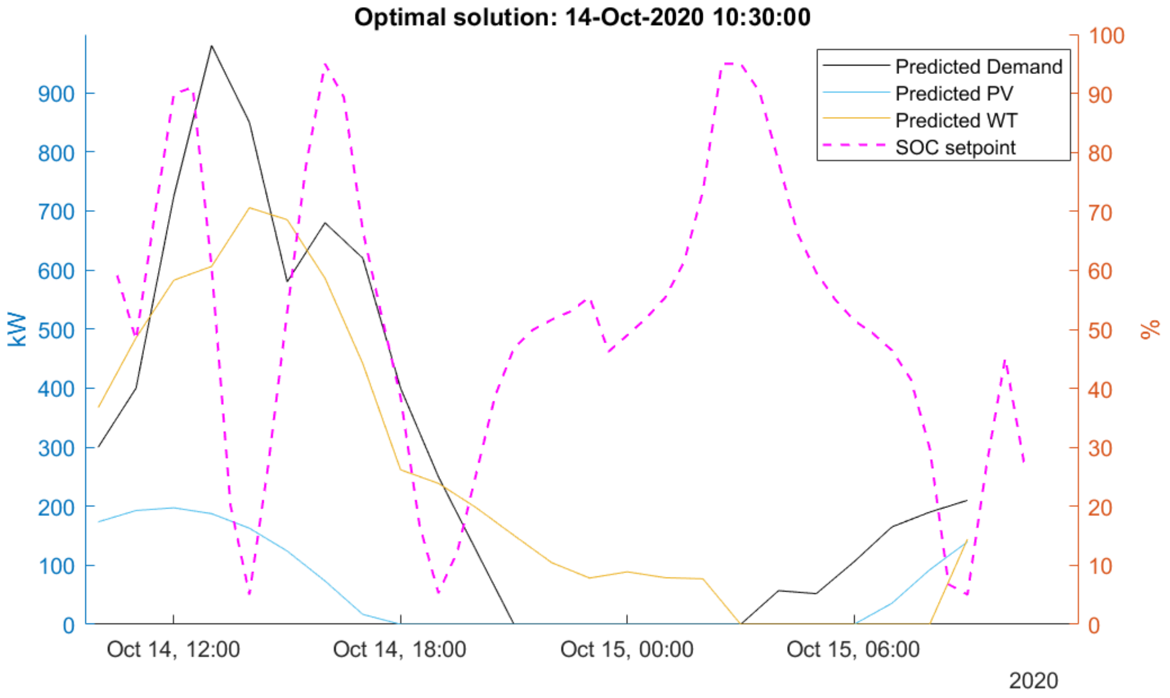

Figure 39. Day-ahead set-points profiles calculated by the predictive and optimal control

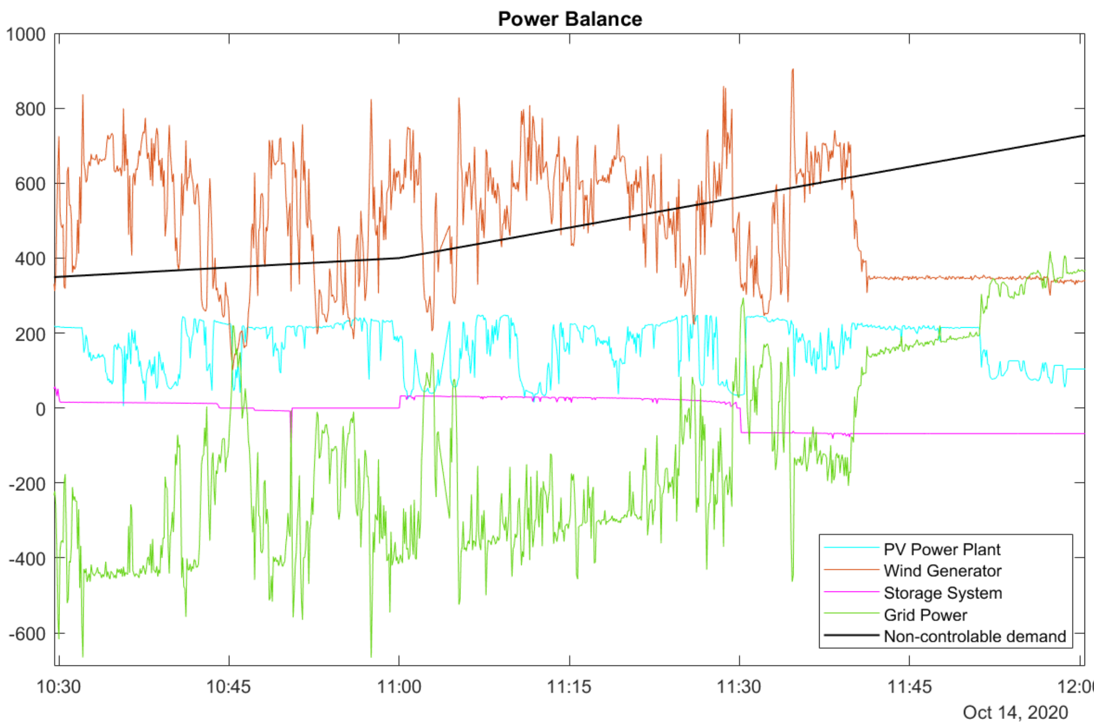

Figure 40. Actual power measurements for the tests on October 14th 2020

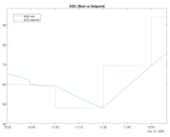

Figure 41. Actual and desired SOC for the tests on October 14th 2020

4 Osimo controller deployment guideline

The Italian demo site of the MUSE GRIDS project is represented by the whole town of Osimo: it arises on the Marche hills, a region located in the Italy center, and it has a population of around 35,000 inhabitants. Three are the peculiarities that distinguish it and make it an ideal research area: the fact of arising on a hill means that the water service uses these differences in level to deliver water to users through gravity and not only therefore with water pumping stations; it has a single connection point with Terna, the national TSO; finally, most of energy networks are managed by the local utility ASTEA and by its subsidiary company (e.g. DEA, The local DSO). These characteristics make Osimo a city rich in data and information useful for this project.
Osimo has furthermore a high share of renewable energy: its electric network in fact, is characterized by several distributed generation technologies:

- CHP: 1200 kW_e coupled with district heating network.
- Biogas: 1 plant, 999 kW_e.
- Biomass: 1 plant, 200 kW.
- Miny-hydo: 2 plants, 100 kW_e and 110 kW_e.
- PV: 973 plants ranging from 1 up to 973 kW_p for a total installed power of 33795 kW_p

The technologies managed by Astea instead, involved in MUSE Grids Project, are:

- the 1.2 MWe CHP plant with a gas engine serving a District Heating (DH) network of roughly 1250 users
- Astea office building: considered a microgrid able to provide limited flexibility to the grid
- two water pumping stations, one of which with 100 kW of mini-hydro.

4.1 Optimization problem definition

The optimization problem in Osimo will focus on the control of the Cogeneration Hybrid Power Plant that connects three different grids: natural gas, district heating and electricity networks. In a second stage one of the pumping stations of the water network of the city will be considered also for optimization with the objective of increasing its self-consumption and taking advantage of possible synergies of electricity and water networks.
For the multigrid system to be controlled, the assets and devices that will be included in the control are:

- Natural gas engine cogeneration system: its main function is to produce thermal energy for the district heating network when required. At the same time, while producing the thermal energy, it will deliver electrical energy to the grid. Even though it is a controlled power generation plant due to legal restrictions it can operate only at nominal power when it is switched on.
- Natural gas boilers: three boilers are used to provide thermal energy to the DHN when the demand exceeds the production of the cogeneration system. The generated power can be controlled.
- Thermal Energy Storage Tank: controllable storage system used in the DHN. The thermal production of the cogeneration system can be total or partially stored in this device. The output of the TES can be delivered direct to the DHN or through the boilers when the demand is high.
- District Heating Network load: is the aggregated and not controlled thermal demand of the users.

- PV panels: is the aggregated solar energy produced in the Osimo grid. It is a non-controllable renewable power energy source as the produced energy is locally managed at home level. The variability in this production and the high number of installed PV panels is the origin of the difference in the power delivered and consumed at the PCC at different moments of the year.
- Electrical loads: the uncontrolled loads present in the Osimo grid.
- Smart Electrical Thermal Storage (SETS) devices: a virtual network of heaters and water tanks used for thermal storage at home level. Five of these devices have been installed in ASTEA building and cogeneration plant offices and they can be used to extrapolate their behaviour at city level. Their electric charging load can be controlled and shifted using the Glen Dimplex DSM API.

A detailed description of these systems, their nominal power and operation modes have been included in deliverables D2.4, D4.1 and D4.2. Also the possible DSM strategies were analysed and are the basis for the definition of the optimization problem.
Two optimization problems will be defined for the multigrid system related to the cogeneration power plant. Both problems will have the common objective of **minimization of the natural gas fuel consumption and maximizing self-consumption in the electricity grid**. These two problems will be:

- Control of the cogeneration system, boilers and TES to provide the required thermal demand of the DHN at the optimal supply temperature. The objective function will balance the minimization of the gas consumption and to avoid the injection of electricity power in the grid. Variable weights can be given to these two objectives to prioritize one over the other when they require opposite decisions about the use of the assets. As analysed in D4.2 there will be situations along the year in which electrical power in the order of 1 MW is injected in the grid, and the disconnection/shifting of the electricity generated in cogeneration system can avoid it. This is possible if the thermal energy balance can be achieved thanks to the use of the boilers, TES or changing the supply temperature.
- Based on the previous problem it will be considered at simulation level the use of a significant number of SETS to reduce the renewable electricity re-injection events

Regarding the pumping station the control problem definition will include the next assets:

- Water tanks: where the water is stored for the delivery to the network. The level in these tanks has to be maintained between the defined limits to guarantee the water supply to the network.
- Water pumps: controlled by inverters what allow controlling the water flow supplied to the tanks.
- Hydraulic turbine: power generation unit that produces electricity locally when the water is conducted from a dam to the pumping station

In this case the optimization problem will focus on the control of the water pumps to **maximize the self-consumption of the pumping station system** and especially avoiding the injection of electricity in the grid.
In all the defined problems, the optimization algorithms and controls will be programmed using CasADi framework and tools as explained in section 3.1 for La Plana controller.

4.2 Data management and data base deployment

All information in Osimo facility except for Glen Dimplex devices is centralised by the ASTEA Cloud Server, thus, MUSE GRIDS Cloud communicates with this interface and with three Glen Dimplex devices (cylinder and two heaters) installed in Osimo. The communication architecture of the demo facility is shown in the following figure.

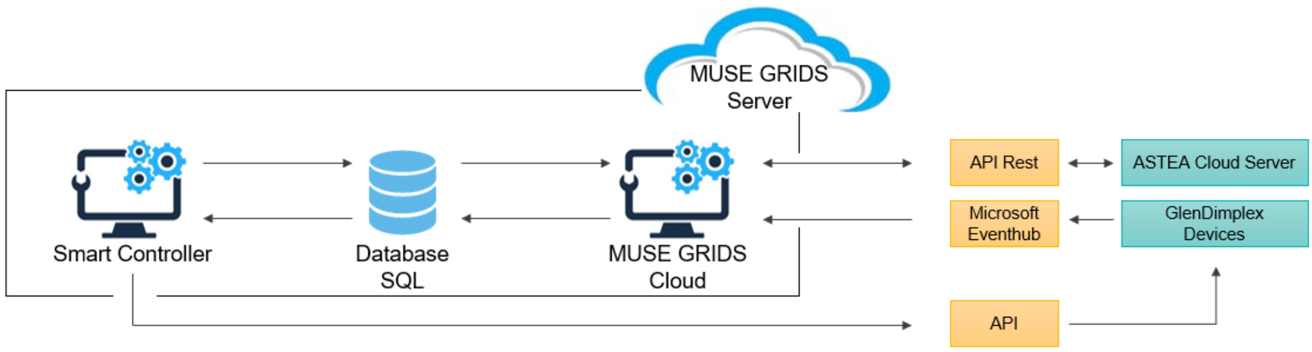

Figure 42. Osimo facility communication architecture

ASTEA Server works in a position between the field devices and the MUSE GRIDS Server to allow the Smart Controller to access all data from the facility in an encrypted way. Therefore, MUSE GRIDS Cloud version for Osimo will have a periodic thread that every 15 seconds will download data from the ASTEA Cloud and will insert it into que MUSE GRIDS SQL database. The server, whose architecture is shown in the following figure, will also collect the data coming from different energy assets of ASTEA such as the energy meters, the DUFERCO platform (PV, EV charging stations, ASTEA building), and electric storages. Further definitions about ASTEA Server can be found in the deliverable D2.4.

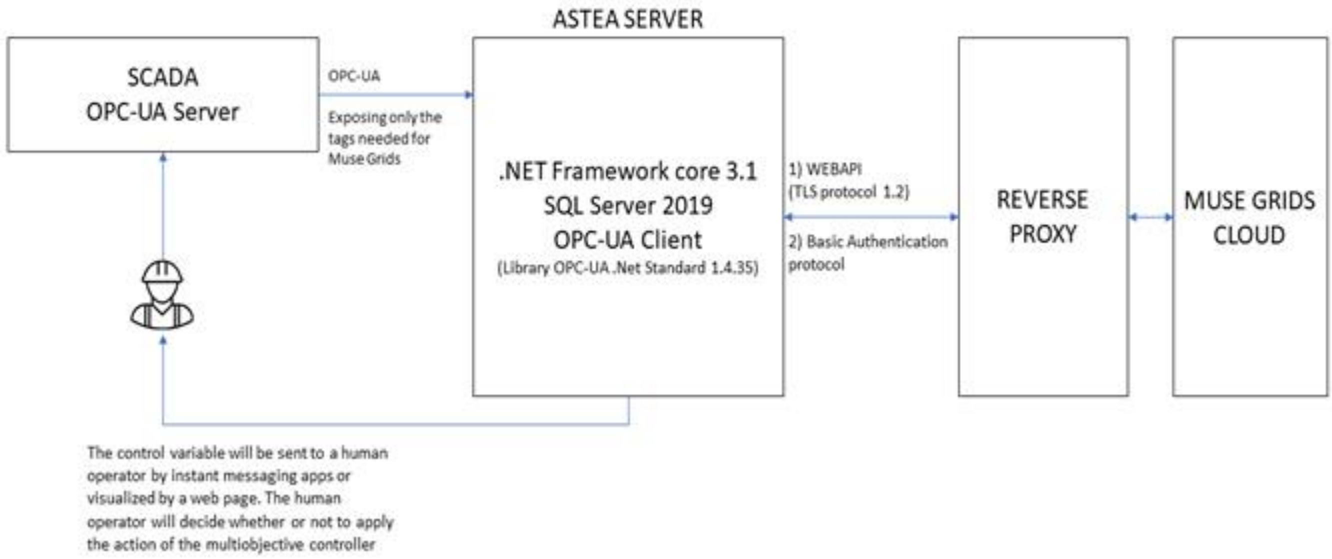

Figure 43. ASTEA Server architecture

ASTEA information is published in a webserver accessible through and API request from the MUSE GRIDS Cloud. The connection is protected by user and password credentials. The API allow to select the start date and end date of the data to be downloaded. That information is stored in the MUSE CLOUD database in a place accessible for the MUSE GRIDS Smart Controller.
Data received from the ASTEA Cloud is shown in the following table:

Table 2. ASTEA data

Variable	Data type
CT_AUX_EE_ActivePower	FLOAT
TLR_ET_Flowrate	FLOAT
TLR_ET_Power	FLOAT

TLR_ET_SupplyTemperature	FLOAT
TLR_ET_ReturnTemperature	FLOAT
ZE003_ET_Flowrate	FLOAT
ZE003_ET_Power	FLOAT
ZE002_ET_Flowrate	FLOAT
ZE002_ET_Power	FLOAT
ZE002_ET_SupplyTemperature	FLOAT
ZE002_ET_ReturnTemperature	FLOAT
TLR_ET_HeatingEnergy	FLOAT
ZE002_ET_HeatingEnergy	FLOAT
ZE004_ET_ReturnTemperature	FLOAT
CT_AUX_EE_ActiveEnergyTotal	FLOAT
CT_SC_ActiveEnergyAbsorbed	FLOAT
PDC_ET_SupplyTemperature	FLOAT
CT_SC_ActivePowerAbsorbed	FLOAT
ZE002_GAS_Qb	FLOAT
ZE003_ET_SupplyTemperature	FLOAT
G1_ET_SupplyTemperature	FLOAT
ZE004_ET_SupplyTemperature	FLOAT
G1_LT_ET_ReturnTemperature	FLOAT
PDC_ET_ReturnTemperature	FLOAT
G1_LT_ET_SupplyTemperature	FLOAT
G1_ET_ReturnTemperature	FLOAT
FV_EE_ActivePower	FLOAT
FV_EE_ActivePowerTotal	FLOAT
TLR_H2O_V	FLOAT
TLR_H2O_Q	FLOAT

As already mentioned in section 2.1 and 3.2, MUSE GRIDS Cloud will use the Azure Eventhub receive Glen Dimplex telemetry data. All data received from the facility and the Glen Dimplex devices is stored in the database, which contains one isolated table for each asset.

The distribution of the tables for the Osimo MUSE GRIDS Cloud data base is the following:

- Facility main configuration
- Glen Dimplex devices configuration
- Glen Dimplex cylinder data.
- Glen Dimplex heater 1 data.
- Glen Dimplex heater 2 data.
- ASTEA building devices measured data
- Cogeneration power plant measured data
- Weather forecasts for the following 24 hours.
- Demand predictions for the following 24 hours.
- Renewable generated power prediction for the following 24 hours
- Optimal control set point for the following 24 hours.

The technical specifications of the monitoring system architectures within the Astea building, such as communication protocols, the list of measurable variables and the on-site metering devices needed for the monitoring of the main loads as well as the PV production will be described.

The monitoring system is made of 4 main components:

- Smart meters: measure all the significant electric units such as: current, voltage, frequency, power, energy, power factor, harmonic distortion.
- Repeaters: connect with the meters through RS485 serial communication and allow transferring the data with a radio signal. Moreover, they create a mesh network with one another in order to overcome more easily physical obstacles that could block the radio signal like walls and metal structures.
- Gateway(s): store the data from all the meters and create the network of smart meter and manages it.
- Router: connects the gateway with the cloud architecture through GSM connection.

The monitoring system embedded at the Astea headquarter collects the most significative energy consumptions (table 1) of the building.

Table 3: variables monitored in Astea headquarters

Description	Unit	Data Manager	Data Acquisition Mode	Time Step (min)
PV Plant 2 Production	kWh	DUFERCO Cloud DB	real-time	5; 15
PV Plant 1 Production	kWh	DUFERCO Cloud DB	real-time	5; 15
Point Of Distribution (POD)	kWh	DUFERCO Cloud DB	real-time	5; 15
CED Air- conditioning system	kWh	DUFERCO Cloud DB	real-time	5; 15
Air Handling Unit	kWh	DUFERCO Cloud DB	real-time	5; 15
Air conditioning system (Directional Officies)	kWh	DUFERCO Cloud DB	real-time	5; 15
Heater 1 (provided by GlenDimplex)	kWh	DUFERCO Cloud DB	real-time	5; 15
Heater 2 (provided by GlenDimplex)	kWh	DUFERCO Cloud DB	real-time	5; 15
Boiler (provided by GlenDimplex)	kWh	DUFERCO Cloud DB	real-time	5; 15
Charging station (phase 1)	kWh	DUFERCO Cloud DB	real-time	5; 15
Charging station (phase 2)	kWh	DUFERCO Cloud DB	real-time	5; 15

The collected data follow a communication flow from the smart meter to the IoT Site of Duferco (figure 1):

- firstly, data are forwarded through serial cable (RS485) from the smart meters to the Remote Terminal Unit (RTU): KET-RMB-211, this device is provided by Kerberos s.r.l., It manages up to 32 Modbus RTU slave devices connected to its RS485 port. It can be programmed to read a series of registers and send them to the Gateway. The integrated repeater function reduces the number of nodes required and increases the reliability of the network. It has an extended radio range that allows you to reach over 1000m in free air;
- secondly, the measured quantities are sent by radio frequency (ZigBee) from the RTU devices to the gateway: KET-GZE-220, this device is provided by Kerberos s.r.l., it is a gateway suitable for installation in switchboards industrial and civil electrical, also in outdoor installations. Using the supplied X-Manager software it is very easy to install even complex sensor networks by setting all the parameters necessary and verifying in real-time all the acquired measurements. In addition to the ability to send data to external platforms (such as X-Platform), it is available an internal SD memory that allows storing data for long periods. The RS485 port works in both Master and Slave RTU mode. In this way, it is possible to connect devices directly to the gateway or to access an external RTU Master registers of connected

devices. Furthermore, the KET-GZE-220 incorporates a Modbus TCP / IP server that allows the connection of the X-Monitor network to SCADA systems, programmable logic (PLC), and human-machine interfaces (HMI systems and displays).

- Finally a router linked to the gateway through an ethernet cable sends the monitored data to the IoT Site of Duferco by means a SIM M2M, the installed devices is a Teltonika RUT 950, provided by Teltonika, it is a professional 4G/LTE Dual SIM router with advanced WiFi, Ethernet and industrial grade networking functionality support.

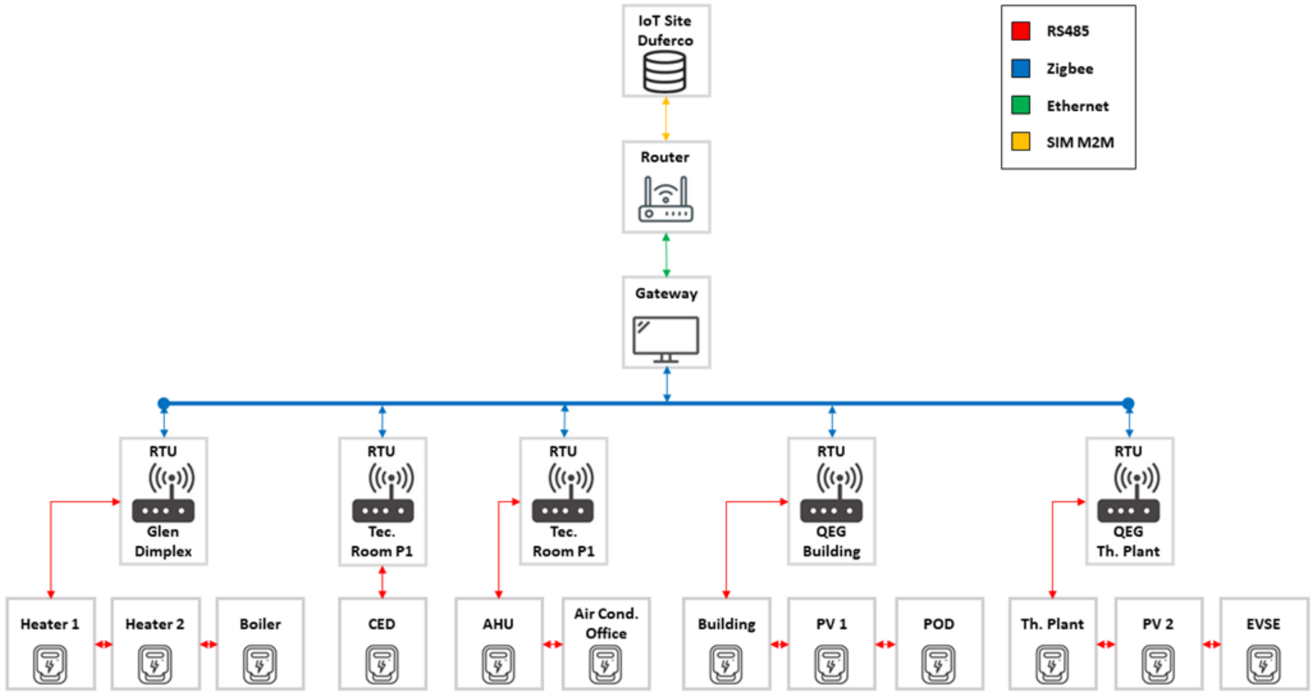

Figure 44. Monitoring system structure.

4.3 Demand Prediction module deployment

The demand prediction module has been programmed with the same structure described in section 3.3 and validated in La Plana demo.
Two prediction algorithms of the ones reported in D1.2 are required in the optimization problem defined for the cogeneration plant:

- Osimo's District Heating Network demand: hourly forecasting using clustering for prediction of the type of day and ARIMA models for the demand profile prediction.
- Osimo's Electricity demand: hourly forecasting using clustering for prediction of the type of day and ARIMA models for the demand profile prediction.

The original prediction algorithms developed in R have been coded in Python and will be integrated in the algorithm of the demand prediction module.

4.4 Models module deployment

The optimization problem defined for the cogeneration plant needs the prediction of the PV panels generated power. This will be the only prediction model included in the module that will be deployed in the same way that it

was described in section 3.3. The PV model used will be the same developed for La Plana but changing the configuration parameters (e.g.: nominal power, panel surface tilt and orientation…). As there are a great number of installed PV panels, the prediction will aggregate the power production in one or more virtual PV panels whose parametrization allow the adequate energy prediction.
For the programming of the control algorithm, also the models of other assets are required: gas boilers, gas engine cogeneration system or thermal storage tank. The models used will be based in the ones developed and described in D4.2. The mathematical models of these assets will be included in the control algorithm to define the so called boundary conditions of the optimization problem as explained in section 3.1. So in the MUSE GRIDS approach for solving the optimization problem based in the CasADi tools, these models won't be part of the models module.

4.5 Demand side management deployment

Demand Side Management strategies in Osimo demo site were analysed in D4.2. This section will focus on the DSM of user's loads at building level. The strategies related with storage in power plants will be included as part of the optimization problem, as explained in section 4.1.
SETS and EVs will be the devices to include in the Demand Side Management module in Osimo. Both will be deployed and tested in ASTEA tertiary building as part of the Energy Management System designed for the local control of the building. The integration in the optimal high-level control will be done at simulation level as only a huge number of devices under a common DSM strategy will have a significant impact in the grid in terms of power demand and/or energy storage.

4.5.1 Glen Dimplex devices DSM operation

The Glen Dimplex devices will be integrated in the Osimo demo as a virtual network for simulation purpose. The Smart Controller will take the role of an aggregator with the responsibility of provide the required thermal energy to the users and the capacity of shifting the electrical demand for the charging of the devices.
The algorithm used for the DSM strategy will be the same that was described in section 3.4 and that have been validated in La Plana.
At the same time the real operation of the SETS will be validated in ASTEA building as part of the Energy Management System.

4.5.2 EVs DSM operation

The flexibility of the EVs' batteries can be employed to carry out the following duties:

- optimize the loads: the dynamic controller of the EVSEs can regulate power profile delivered to the charging points to shave loads peak curve, avoiding congestions on the distribution (V2G) line or the passing of the POD limits (V2B);
- maximize the self-consumption of the of the PV production (V2B): the batteries can store the energy generated by the PV plant during the periods of high production and provide energy to the building when the load is higher than the production;
- secondary and tertiary regulation (V2G): the flexibility of the batteries can be used to regulate the operation voltage of the distribution grid. Furthermore, an aggregate cluster of EVs, connected to EVSEs enabled for the V2G operation, can participate to the ancillary service market in order to provide the above-mentioned service to the distribution/transmission network operator.

The DSM acts as high-level controller that will provide to the PM (low-level controller) the set-point of the overall available power at the POD as a power reference value. This constraint is calculated by means a day-ahead optimization performed by the DSM taking as inputs the forecast of the PV generation and building load, the

initial SoC of the batteries, provided by the EVs builder, and the scheduling of the EVs, given by the owner of the EVs.
In the V2B mode the power reference value can be both positive, if the EVs is absorbing power from the grid to charge the batteries, or negative, if the EVs is injecting power into the grid. The PM it is based on the reliability of the scheduling of the EVs, the PV plant's production and building's load forecasts. This tool will optimize the power, both delivered to or provided by each charging point, in function of the overall available power at POD accordingly with the day-ahead results provided by the DSM. Instead, if one of the main inputs is not reliable (e.g. change in the EVs scheduling or highly variable weather), the PM will optimize the power delivered to each charging point in function of the overall available power at POD not considering the day-ahead calculated power profile. Furthermore, the real-time tool will guarantee also the safe operation of the EVSEs.

4.6 Grid Diagnostic deployment

The main objective of this task is to devise predictive models, algorithms and tools that help to guarantee grid stability and resilience through a deep knowledge of the effects in the grid of a highly variable generation and demand (e.g. renewable and electric vehicles), faults in the grid facilities, faults in the distribution grid or attacks.

A Reliability Centred Maintenance (RCM) approach was utilised to evaluate and assess failure modes of assets and their components, which could be detected before functional failure occurs and the consequences of these failure modes. A multitude of applicable failure modes were identified, however the sensor inputs to the diagnostic module were limited to only sensor technology currently incorporated on the MUSE GRIDS system. The following failure modes were identified as suitable for development in the Osimo site:

- Battery Analysis of the BESS
- IGBT Analysis of the BESS
- Voltage related failure of the PV modules

As not previous data of fault modes is available, it was decided that the best approach for the development of the algorithms is through data driven rule-based approach. Anomaly detection algorithms are being developed based on the real time data which will identify outliers that are an indication of a potential fault in the system. Such algorithms have the advantage of being less complex with limited computational power, thus can be easily deployed within the controllers compared to more complex machine learning techniques. Also, due to the lack of historical data the idea of the development of machine learning techniques was abandoned. Machine learning techniques pre-require substantial amount of historical data in order to learn patterns that are representative of system faults. Machine learning techniques approach could be used once enough representative data that describes the behaviour of faulty system is gathered.

4.7 Grid codes deployment

Osimo electricity network has just one point of connection with the national grid/TSO, and it configures itself as a municipal microgrid. As explained previously, due to the high penetration of renewable energy generation (mostly PV), the municipal microgrid witnesses a huge variance in the net-load exchange with national grid throughout the year, swinging from 30 MW of peak absorption, when the renewable generation is not sufficient to cover for the local energy demand, down to 20 MW of peak injection towards the national grid, when the local generation exceeds the total loads.
In this situation the availability of controlling the exchanged energy in the PCC could be helpful to avoid instabilities and, in general, to facilitate the management of both local and main grid. As the main power sources in the case of injection episodes are the non-controllable PV panels installed at users dwellings it is not possible to apply the grid codes in real time controllers. So, in Osimo demo case they will be applied in the high-level controller as part of the boundary conditions of the optimization problem. Specifically, balance control, base load

and peak shaving strategies will be considered in the CHP control to fix operation conditions according to the desired energy exchange with the main grid.

4.8 Hardware configuration

The MUSE GRIDS Cloud will be installed in a dedicated server with the next specifications:

- Equipment: DELL OptiPlex 7070 Micro Form Factor
- Processor: Intel Core i7-9700T
- Memory: 8Gb RAM
- Storage: 256GB SSD M.2 PCIe NVMe
- Communications: 2 x 802.11ac Wi-Fi Dual Band
- Operating system: Windows 10 Pro

4.9 Smart Control deployment

Osimo CHP plant is a critical asset for supplying the thermal demand of the users. The same apply to the pumping station that supplies water to the users. In this sense the smart control deployment will be designed to avoid any unavailability of the plants or any of the systems.
First, a dedicated server will be set up to host the whole MUSE GRIDS Cloud architecture. This server will be completely independent to the ones used by ASTEA in their monitoring and control architecture. Also to avoid any risk it has been decided that all the tests in the real system will be done in open loop, so any control action decided by the high-level control will be always supervised by a human operator before it can be set up in the system.
For the cogeneration plant system, the optimization problem will provide three different outputs:

- Cogeneration engine switch on/off state
- Supply temperature to the DHN
- Tank charging/discharging operation

These outputs will be generated in a day-ahead basis so the operator/manager of the plant can decide the strategy in the next hours using this information.
Unlike a strategy based in a daily prediction at midnight, in the MUSE GRIDS control strategy the predictive control algorithm is executed every 15 minutes. This means that an updated recommended control profile will be continuously calculated according to the real evolution of the system and not only based in a daily prediction for the whole day.
The outputs of the algorithm will be available for the operator through a web interface that can be accessed using the user security credentials. This is a previous stage to the use of the API (also based in web services) in case the manager wants to close the loop and use the profiles as the setpoints for the devices without the previous supervision.
Regarding the pumping station the strategy for the deployment of the smart controller will be the same that the one explained above for the cogeneration plant. In this case only the recommended profile for the water flow (pump speed) will be generated as the output of the optimization problem.
Finally, the ASTEA building energy management system will be integrated in the control and DSM strategies of the EVs and charging station as explained in section 4.5.2 and D2.2. This control will provide a smart charging and V2B strategy for the EV taking into account the production forecast of the PV plant in the building and also the

building demand. So this part of the control will be deployed together with the deployment of the charging station in ASTEA building.

5 Oud-Heverlee controller deployment guideline

The Oud-Heverlee demosite is a street in Oud-Heverlee, Belgium with a typical rural grid problematic: the feeder of the street is a radial feeder that has seen a large influx of loads (electrical vehicle (EV) chargers, heat pumps) and decentralized production (small-scale rooftop PV). This situation leads to power quality problems in the street (see Section 5.1), which an energy community could solve, by matching the demand and production in the street.

Figure 45 The Oud-Heverlee demosite feeder.

The energy community that has been set-up in MUSE GRIDS consists of 20 participating households, where each of the household has received a gateway to measure the households consumption, either through reading the "*P1 port*" of the Belgian smart meter or by optical measurement of the Ferraris meter by ENGIE's "Gecko" Sensor.

Figure 46 GeckoSense sensor installed on a Ferraris meter.

The community also includes controllable assets to match demand and supply. The assets available in Oud-Heverlee are Glen Dimplex' electrical water storage heaters, an electrical storage heater, a neighbourhood battery and two "vehicle-to-grid" bidirectional EV chargers.

Table 4 gives an overview of the controllable assets with their most important parameters.

Table 4: Capacity and rated power of the flexible assets

Device	Power	Energy storage
Neighbourhood battery	54 kVA	120.0 kWh
Glenn Dimplex Quantum heater	2 kW	15.4 kWh
Glenn Dimplex	3 kW	7.5 kWh
V2X chargers and vehicles	7 kW	40.0 kWh

5.1 Optimization problem definition

The optimization problem for the Oud-Heverlee electricity network includes the next elements present in the demo:

- PV panels: that in this case is a non-controllable renewable power energy source. The use of the produced energy is locally managed at home level, so from the network control point of view only the aggregated excess of energy will be available. This energy needs to be managed at the moment it is fed into the grid so the low level control has a key role to avoid voltage instability.
- EVs: with V2G capabilities, the EVs are managed using the control chain composed by the SMATCH optimization algorithm developed by ENGIE Laborelec, EVERON charging point operator and the individual chargers control.
- Smart Electrical Thermal Storage (SETS) devices: heaters and water tanks used for thermal storage managed using the Glen Dimplex DSM API and whose electric charging load can be controlled and shifted.
- Neighbourhood battery: fully controllable electrical energy storage device that will support the balancing of generation and demand
- Electrical loads: the uncontrolled loads present in the households. These loads are computed as the community combined consumption.

Based on the general objectives of the Smart Controller, in Oud-Heverlee the main goals of the local energy controller are multiple: reduce the voltage fluctuation at the end of the line, increase the self-consumption and reduce the peak power taken form the utility grid. The basic actions of the designed controller for this purpose are:

- Forecasting community demand and production: forecast of the community combined consumption and production are calculated over a time horizon of 24 hours, with 30 minutes as time step. PV production and household consumption are forecasted separately.
- DSM control calculation: the different controllable devices in the street need to be dispatched to charge at the right time. The Glenn Dimplex heating devices will be activated for loading when the community predicted power is minimum
- Neighbourhood battery control: a peak shaving algorithm is applied to bring the aggregated load profile as close as possible to its average power. Figure 47 shows the main concept of this control in which power limits (red dotted lines) are calculated for the charging/discharging operation of the battery

A more detailed description of the low-level control can be found in D2.5.
As the low-level controller has already a predictive approach, the high-level control will have a double objective:

- To cover the global objectives not targeted in the low level control (eg. the operation cost minimization)

- To define a common strategy for all the controllable assets instead of the "cascaded" one used in the low level control.

The optimization problem will be based in a MILP formulation and will have a similar approach of the one explained in section 3.1 for La Plana controller. The outputs of the algorithm will be the optimal SOC of the battery and the optimal charging profile for SETS devices in a 24 hour prediction horizon.

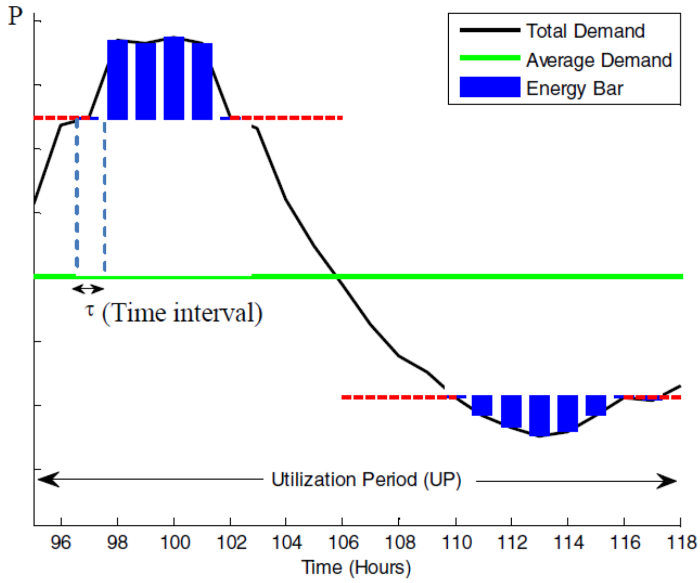

Figure 47. Low-level controller main concept

5.2 Data management and data base deployment

The data management in the Oud-Heverlee demo site consists of collecting the data from all devices deployed in the field (most importantly, the household consumption gateways) and storing them in a time-series database, which is called the "Historian". All services, such as the forecaster of the community production and consumption, as well as the MUSE GRIDS optimizer retrieve data from the Historian to perform their respective calculations. The results of those calculations are then again stored in the Historian, where they can be retrieved and send as set-points to the devices.

Figure 48 shows the integration and communication of low-level control with respect to the higher levels of control (forecaster and optimizer). The communication between the assets and the cloud is via 4G.

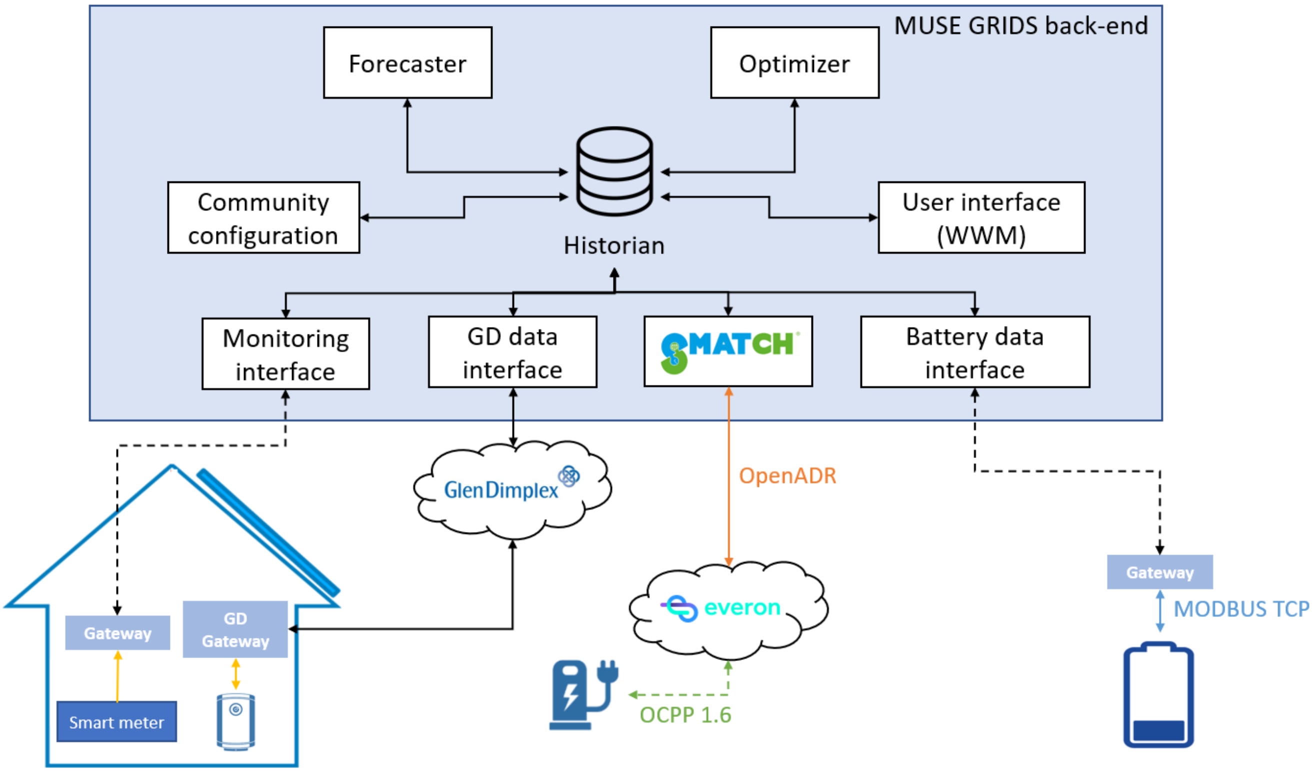

Figure 48. Communication of low-level control at Oud-Heverlee (dotted lines are 4G communication, black lines are RESTFUL APIs over HTTPS).

The monitoring of the electric meter is done with a local gateway which pushes the energy data into the Historian database in the cloud via 4G communication. The data stored in the historian is available for other MUSE GRIDS services in the cloud through APIs. For example, one important service that is constantly running, calculates the total consumption of the community every 30 minutes.

For the control of the **neighbourhood battery,** the MUSE GRIDS service (battery controller) communicates in 4G with the battery gateway with a RESTFUL API. The gateway communicates with the battery through MODBUS.

The battery data interface stores the most important parameters of the battery in the Historian and will read the power set-points for the battery from the Historian as well.

For the control of **Glen Dimplex** devices, the muse grid service (GD controller) communicates with Glen Dimplex API in HTTP. The Glen Dimplex devices receives the control setpoint from the Glen Dimplex platform through a Glenn Dimplex gateway installed in the home that is connected over the home's WiFi network. Communication between gateway and the device itself takes place over an encrypted radio-frequency protocol.

The GD controller service that runs in the cloud retrieves the most important data from the Glen Dimplex cloud per device, such as Incremental and Critical Run Times (the minimum time the devices have to be on to provide comfort), power consumption of the device and store them in the Historian. The optimizer will retrieve this information at the beginning of each optimization period and return a charge profile to the GD control service, which communicates this information back to the Glen Dimplex API.

The control of a V2X capable vehicle is performed through different actors, that have each their role in the value chain, with respective communication protocols and abstraction layers. For the MUSE GRIDS project, the actors are:

- The electrical vehicle (EV)
- The electrical vehicle supply equipment (EVSE), or simply the EV charging station. For the Oud-Heverlee site, the charger will be a MagnumCap.
- The Charging Point Operator (CPO), which operators a pool of EVSEs, which manages the access to different chargers and valorises the chargers' flexibility by allowing connection to E-Mobility Service Providers. Typical roles of the CPO are user identification, diagnostics and maintenance. For the Oud-Heverlee site, the CPO will be EVERON.
- The E-Mobility Service Provider (eMSP), which valorises the charger point flexibility, through tariff structures etc. In the MUSE GRIDS project, this would be the MUSE GRIDS controller which valorises the EV's charging flexibility by providing support to the distribution grid, together with SMATCH, an optimization algorithm developed by ENGIE Laborelec. The MUSE GRIDS controller and SMATCH both run on ENGIE Laborelec's OLAF foundation.

  Besides the information received from the CPO, SMATCH also has a phone application for the user that allows the user to communicate when the car needs to be fully charged.

Figure 49 shows the different roles on the EV value chain for the MUSE GRIDS project.

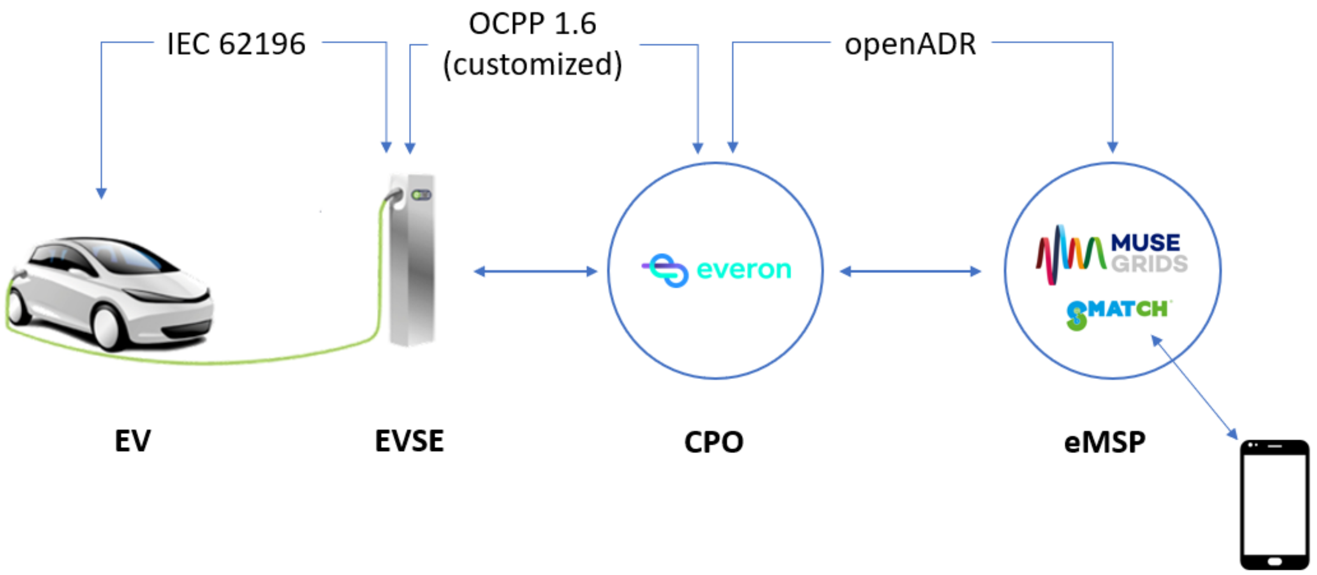

Figure 49. The different actor along the V2X value chain, with their respective communication protocols.

Concretely, the MUSE GRIDS optimizer will schedule the V2G setpoints and communicate these to SMATCH. SMATCH then runs it is own optimizer to inform the MUSE GRIDS optimizer what set-points are feasible. The set-points are then communicated to the CPO which in turn sends them to each EV charge point.

5.3 Demand Prediction module deployment

As explained in the previous sections, an electric meter sensor is installed at each community member. This electric meter sensor computes the number of clockwise (consumption) or contraclockwise (production) rotations of the Ferrari meter or the pulse at the P1 port for the digital meter.
This data is converted by the gateway in energy (kWh) and send by the gateway to the MUSE GRIDS Historian. This data is stored in the timeseries: ***site_id.site_total_energy.*** Where $site_id is a number assigned for each community member. This timeseries is presented on the upper graph in Figure 50.

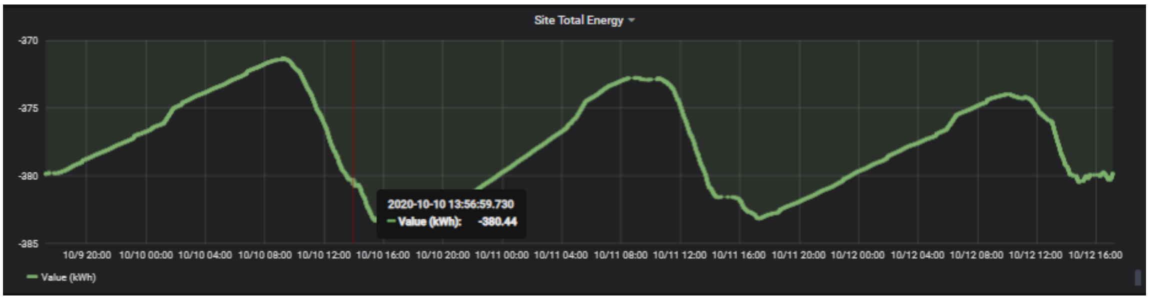

Figure 50. The raw energy measurements [kWh] of a site in the MUSE GRIDS community.

The frequency of data collected depends on the Ferrari disk rotation speed (from 75 to 600 tr/kWh) and the community member consumption. For the MUSE GRIDS community, it varies between several data per minutes to dozens of minutes between two samples. This means that the data of all community members is retrieved at different timestamps.
Therefore, every 30 minutes a community total is calculated to 'synchronize' all measurements. A timeseriesaggregates the data of the timeseries *site_total_energy* in time range of 30 minutes for each site. This value is computed every 30 minutes for the earlier 30 minutes. At 4pm the aggregated energy data are computed for the time period between 3pm and 3.30pm.

Note that this community total contains both household consumption as well as production, because production is not separately measured. This makes forecasting the future consumption a difficult to solve problem, since the irregular behaviour of the PV is mixed in with the household's consumption.
To solve this issue, an irradiance sensor is installed on a site of the MUSE GRIDS community. The gateway attached to this sensor pushed irradiance data every 2 minutes to muse grid historian in the timeseries ***$community_id.$site_id.site_irradiance.*** This timeseries is presented in Figure 51.

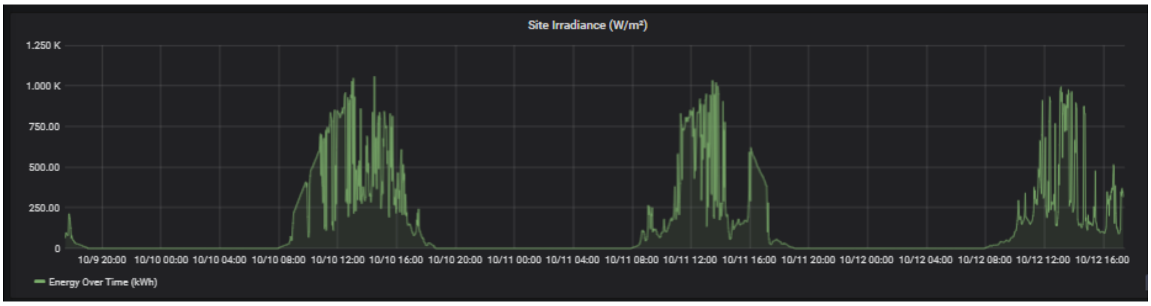

Figure 51 Site irradiance measurement in the MUSE GRIDS community.

This estimation is done as follows: the site irradiance is multiplied with the total PV power installed in the street and a correction factor, providing a total site production per half hour, called ***$community_id.$estimated_production_over_time***

```
estimated_production_over_time +=
  average(irradiance_in_kw_per_m2)
  * community.pv_config.production_scaling_factor_in_m2
  * PV_power_installed_in_kw
```

The community production is then substracted from the aggregated community consumption to obtain the demand only, called ***$community_id.$estimated_consumption_over_time***
Production and consumption are now split and can each individually be forecasted. The result is shown in Figure 52.

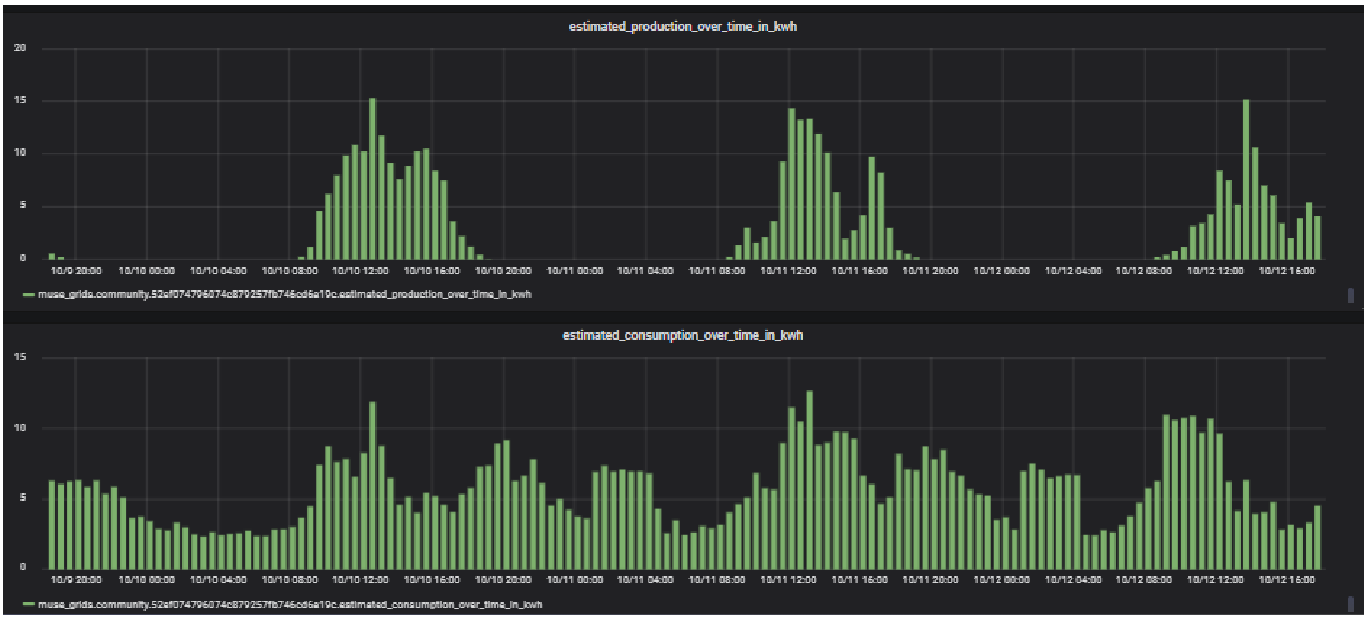

Figure 52. The community load profile split in an 'estimated consumption' and 'estimated production'.

For the forecast of the PV production, a freely available PV forecaster from the Belgian TSO *Elia* is used.
For the forecasting of the demand, a forecaster was developed by ENGIE Laborelec based on Random Forest Regression Learning.
First tests with the forecaster show a fairly good match with the actual load curve of the community. In Figure 53, the forecasted and actual load curve are shown. It is clear that the forecaster can predict the general shape of the load curve, but struggles with sudden and high consumption.

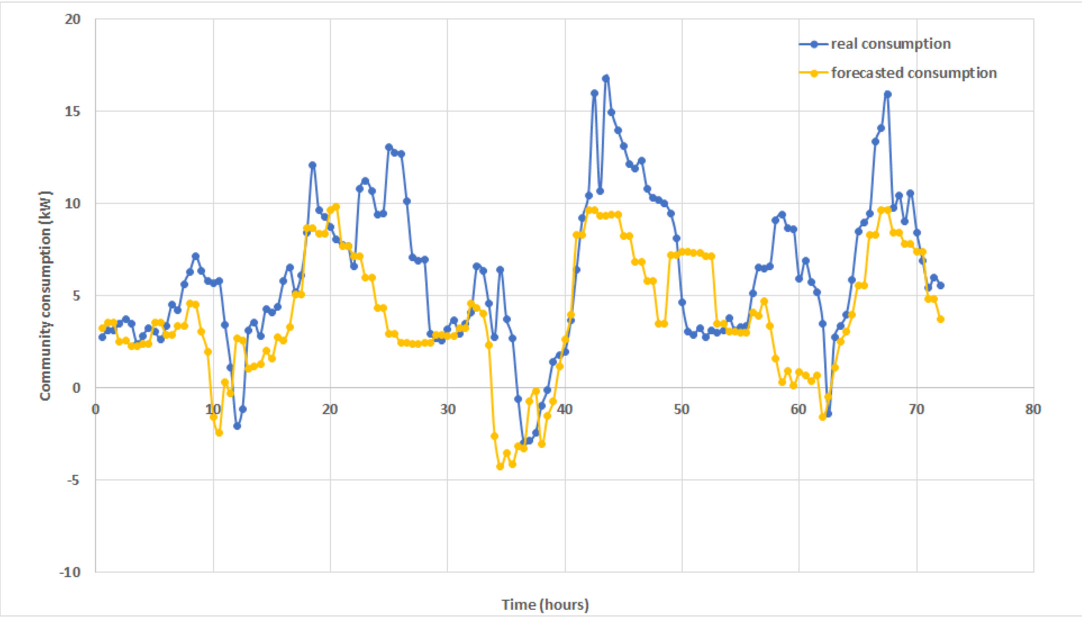

Figure 53. Comparison of the real load curve (blue) and forecasted load curve (yellow).

The overall flow diagram of the demand prediction module is shown in Figure 54.

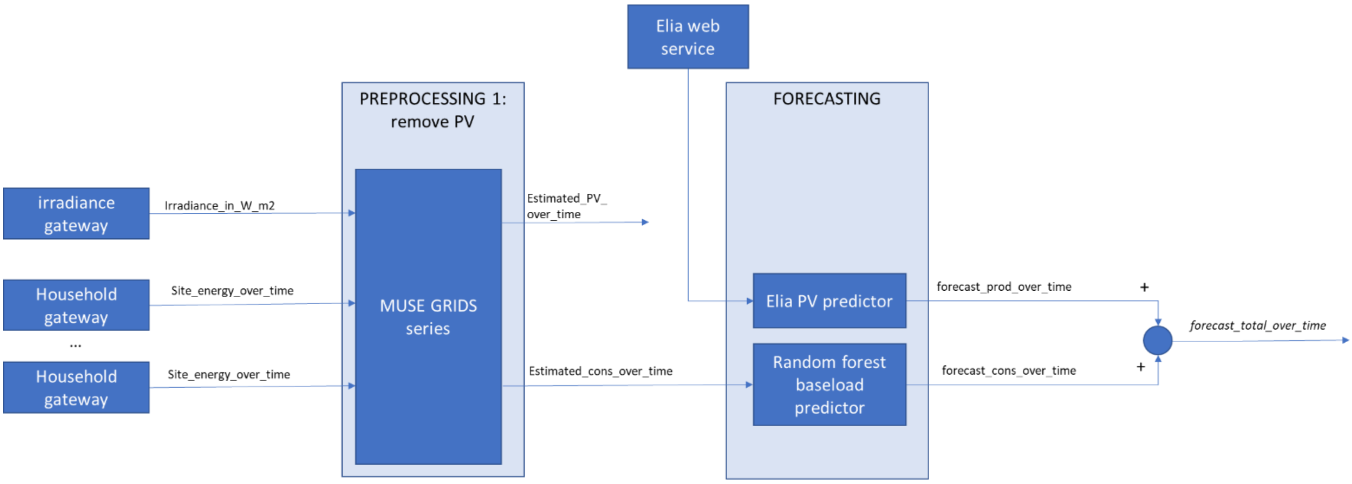

Figure 54 Flow diagram of the demand prediction module

5.4 Models module deployment

There is not a specific Models module in the Oud-Heverlee deployment of the MUSE GRIDS Cloud. As discussed in the previous section the PV models for power prediction are substituted by the Belgian TSO *Elia* forecaster service. No other models devoted to prediction are needed in this demo to be integrated in the optimization problem.

For the programming of the predictive and optimal control algorithm, also the battery model is needed. As explained in section 4.4 for the Osimo demo this simple model will be included in the control algorithm to define the so called boundary conditions of the optimization problem.

5.5 Demand side management deployment

The following section introduces how practically, the different assets will be steered by the MUSE GRIDS Optimizer. The main objective of the controller is to reduce the PV production in the street by displacing consumption of flexible assets to period with local production, consumption during periods with no local production should reduce, decreasing the dependence on external supply.
Concretely, for the Glen Dimplex devices, this problem reduces to charging the device when there is sun. For the EVs, this problem reduces to charging the car when there is sun and discharging at the moments when there is high consumption, for example the evening. Importantly, the household's comfort and energy consumption need to be taken into account for both.

5.5.1 Glen Dimplex devices DSM operation

The low-level control of the Glen Dimplex and the available control modes for DSM operation are detailed in D5.2. As explained in previous sections telemetry of the devices is available through Azure's Event Hubs, while the Glen Dimplex API allows to control charging profiles of cylinders and heaters.
In Oud-Heverlee the first approach for the control of the Glen Dimplex heating devices is straightforward. As it is a controllable load, the controller will activate this load when the community power is minimum.
The Glenn Dimplex device gives to information related to the device consumption CRT and DRT:

- **DRT (Daily Runtime)** –Runtime required for the next 24hours
- **CRT (Critical Runtime)** –Runtime required for the morning 12hours

Each day at 00.00 the controller sets the charging time windows in function of DRT, CRT and the load forecast. The charge of GD devices is planned when the load is minimum. The forecast is then updated taking in account the Glenn Dimplex load (cf. Figure 55).
In a second stage, the complementary optimization problem detailed in section 5.1 will include the SETS as controllable loads and will calculate the optimal charging profiles taking into account economic objectives too.

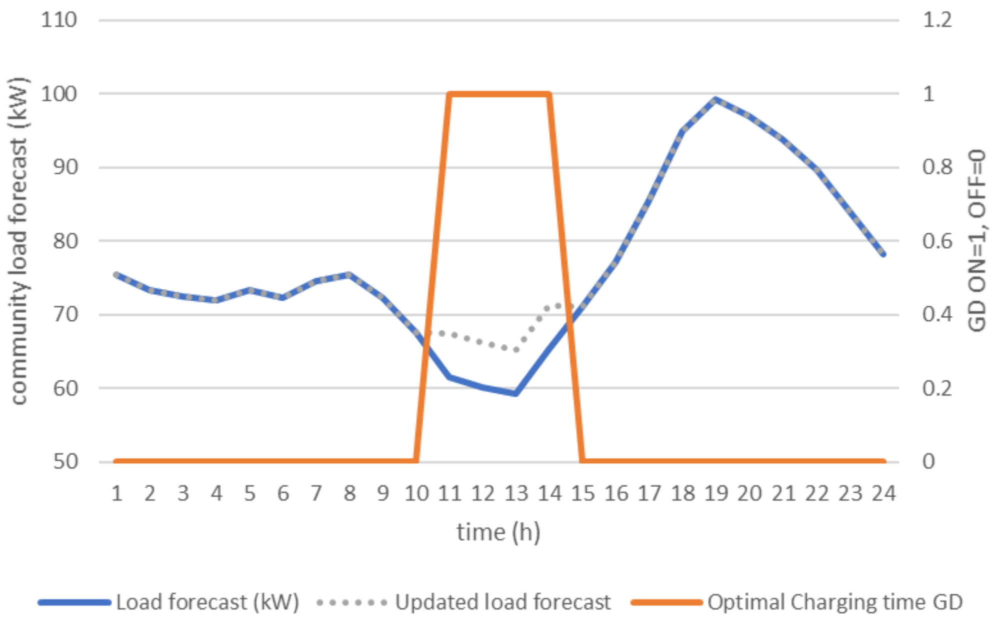

Figure 55: Control of GD devices

5.5.2 EVs DSM operation

For the V2G charger, an interface is foreseen with SMATCH platform. SMATCH will take care of the user needs constraint and optimize the control set-points to maximize self-consumption and peak shaving. The MUSE GRIDS EMS will send the load forecast to SMATCH and SMATCH will directly send the optimized charging setpoints. The forecast is then updated to take into account the electric vehicle load.

The interaction between MUSE GRIDS EMS, SMATCH, V2G chargers and final users are described in Figure 56. In a first step, the MUSE GRIDS EMS will send a charge profile to SMATCH, i.e. a load curve that has to be followed. SMATCH will then run it is own optimizer to schedule the charging of each EV to follow the load curve as best as possible, taking into account constraints such as the user needs (departure time of the vehicle), charger maximum power, expected state-of-charge and so on. This schedule is returned to the MUSE GRIDS EMS for information.

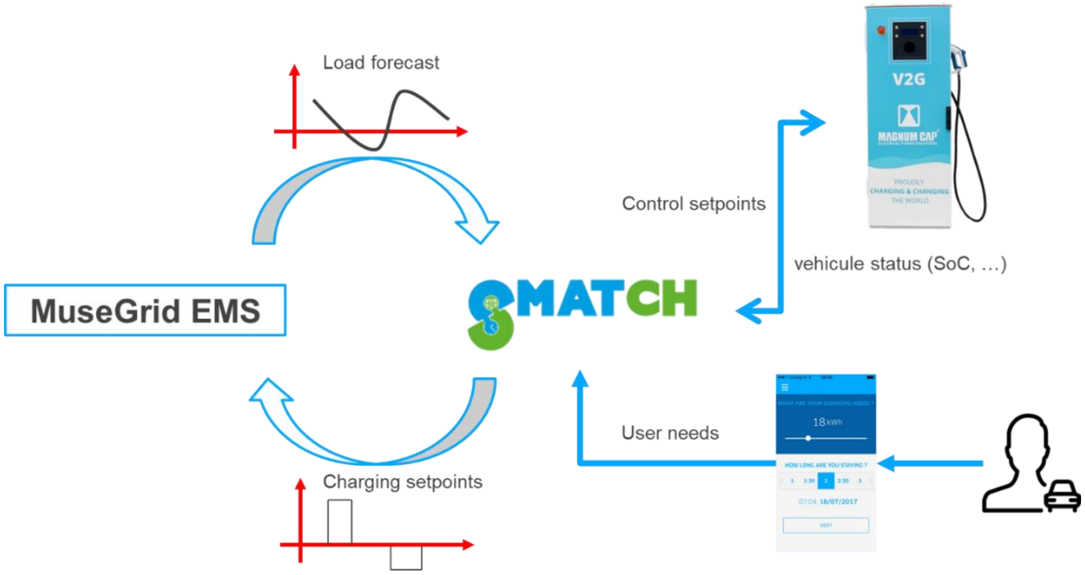

Figure 56 Interaction between the MUSE GRIDS EMS and the SMATCH optimizer.

5.6 Grid Diagnostic deployment

The objectives and approach of the Grid Diagnostic module is the same as explained in section 4.6.
Again a multitude of applicable failure modes were identified, however the sensor inputs to the diagnostic module were limited to only sensor technology currently incorporated on the MUSE GRIDS system. The following failure modes were identified as suitable for development in the Oud-Heverlee site:

- Battery Analysis of the BESS
- IGBT Analysis of the BESS
- Electrical Element Failure with water cylinder and Space heaters
- Voltage related failure of the PV modules

As explained in section 4.6 the algorithms will be developed using a data driven rule-based approach due to the lack of historical data.

5.7 Hardware configuration

All MUSE GRIDS services are Python scripts which run on ENGIE's OLAF foundation, which includes different development environments, the Historian database, authentication services, logging, notification tools, monitoring tools and AWS services. The OLAF foundation runs entirely in Amazon Web Services.

There are three independent environments in OLAF, called INT, PREPROD and PROD. The different environments are implemented to make sure that all changes in code are tested before they are released in the pilot site. The INT testing environment allows testing of the basic functionality of the code. In the PREPROD environment, the code can be tested in a small community of two friendly users, that are not in the MUSE GRIDS community. The MUSE GRIDS community is located in the PROD environment.

5.8 Smart Controller deployment

The core of the Smart Controller in Oud-Heverlee demo will be installed in the OLAF Foundation owned by EngieLab. This will include the demand and generation prediction modules and all the interfaces for communication among the different platforms (SMATCH, EVERON, Glen Dimplex) or with the devices (neighbourhood battery).

The high level control algorithm will be Python programmed what will allow its installation in the OLAF platform or in an external server in the cloud. Both options will be evaluated.

The communication between the Predictive and Optimal Control module and the other services installed in OLAF will be based in a RESTFUL API. The control module will receive the generation and demand day-ahead predictions and also the energy requirements of the SETS. It will return the energy profiles for the SETS, V2G chargers and the battery that satisfy the selected optimization strategy.

When the economic objective wants to be guaranteed, as this option is not available in the low level control, the generated profiles calculated by the high-level controller will be used straightforward as the setpoints of the installed devices. In case of self-consumption maximization the low-level control approach will have priority while the high-level solution will be used for management decisions and configuration of the low-level control (eg. shifting the SETS loading profiles to the one defined in the high-level control instead of just do it at the lowest demand point).

6 Conclusion

This deliverable is able to show the advance degree in the development of the control, deployment of the demos and the firsts tests carried out to validate the control architecture and control features.

Regarding the Smart Controller the advance degree is notable not only first versions of MUSE GRIDS Smart Controller and MUSE GRIDS Cloud have been fully developed. The whole architecture of the control solution for the project has been defined and the responsibilities have been distributed between all partners. The MUSE GRIDS Smart Controller features have been defined for each demo site and the communication with the MUSE GRIDS Cloud has been defined. In terms of MUSE GRIDS Cloud, it is able to communicate not only with all assets present in the three demos (La Plana, Osimo and Oud-Heverlee), but also with the MUSE GRIDS Smart Controller.

Regarding Ongrid Control Modes, which are explained in this document, all have been developed and tested at La Plana Hybrid facility with successful results. Some of the tests are described in this deliverable. These tests helped the control project partners to detect and solve some bugs not detected in the model, and in addition, it also helped the model to be improved.

Regarding the deployment at both demos, in both demos the installation and the commissioning of all assets, even though the COVID-19 delayed some tasks, are progressing, and all data collection software are completed. In addition, the partner knowledge about each demo is increasing and it helped to define a better control strategy for each demo. Lessons learnt on effective deployment will be analysed in T6.1 and reported in the deliverable D6.1.

In addition, this deliverable is able to show a high degree of collaboration between the project partners (demos and control partners) about control variables, assets and demo characteristics and control behaviour for each demo.

It is important to remark that thanks to some integration tests at La Plana hybrid facility, the MUSE GRIDS Smart Controller and the MUSE GRIDS Cloud has been tested and also some control features and behaviour have been improved in this preliminary control version. This will imply a quicker validation phase and a quicker development of the final control version. The full validation of the control will be included in the deliverable D2.10.