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Responsible	Organisation	Contributing WP
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Abstract
This document details the work done on Task 2.5 “Integrated Controller”, which deals with the integrated controller (IC) of the energy generated by on-site RES in the Spanish demo of the project, enabling advanced control functionalities. The report evaluates the case study created by the expected energy generation and demand, and details the capabilities of the IC to cope with the requirements of the target plant. The developed prototype of the IC HMI-EMS is validated by means of tests designed with reference to the Spanish demo case study.

Keywords
Energy Management System, Model Predictive Control, System Dimensioning, SCADA

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EXECUTIVE SUMMARY

This document presents the work done on Task 2.5 “Integrated Controller”, covering the functionality of what will be the controller of the energy generated by the Renewable Energy Sources (RES) on site in the Spanish demo of the project. The role of the Integrated Controller in the Spanish demonstration, which enables advanced control functions, is discussed.

This report assesses the scenario created by the anticipated energy generation and demand, and outlines the capabilities of the Integrated Controller to address the requirements of the target plant.

By building a model of the Spanish demonstration, several plant sizing cases were tested in simulations. A self-sufficiency ratio of 50% was used as a constraint, resulting in a specific sizing case that was used as a reference. This case includes reference values for the power converter, Li-ion battery and PV system to be included in the Spanish demo plant.

Validation tests of the Human Machine Interface – Energy Management System (HMI-EMS) were carried out at CENER’s premises, in which the HMI-EMS governed a Li-ion battery with the aim of managing energy which is locally generated.

The validation demonstrates how the Integrated Controller allows the management of the produced renewable energy, using a Battery Energy Storage System (BESS), to optimise its local use in the demonstration plant. The test results also show that the EMS successfully calculates the operating profile of the current equipment to achieve the intended target.

During the tests, the Integrated Controller communicated effectively with the converter, which allows anticipating the correct operation of the different components of the system in the future Spanish demo. Besides, the configuration of the demo will be easily performed through the plant configuration screens on the Supervisory Control And Data Acquisition (SCADA) HMI, in accordance with the plug-and-play philosophy of the Integrated Controller presented in the report.

ACRONYMS AND ABBREVIATIONS

BESS	battery energy storage system
EMS	energy management system
ESS	energy storage system
HMI	human machine interface
IC	integrated controller
ICT	information and communications technology
MPC	model predictive control
RES	renewable energy sources
SCADA	supervisory control and data acquisition
SOC	state of charge

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1 Introduction

1.1 Purpose of the document

This document details the work done on task 2.5 “Integrated Controller”. This task deals with what will be the controller of the energy generated by on-site RES in the Spanish demo of the project, enabling advanced control functionalities.

In order to know in detail the future energy demands in the Spanish demo, results of the energy simulations carried out in Task 2.6 "Advancing simulation-based energy performance assessment for optimal PEB design" have been used as input.

1.2 Scope of the document

This report explores the role of the Integrated Controller (IC) in the Spanish demo. It evaluates the case study created by the expected energy generation and demand, and details the capabilities of the Integrated Controller to cope with the requirements of the target plant.

Finally, the developed prototype of the IC HMI-EMS is validated by means of tests designed with reference to the Spanish demo case study.

1.3 Structure of the document

Section 2 studies the demo plant performance according to the demand requirements provided by Task 2.6. through a series of simulations, different plant dimensioning cases are generated and one case is finally selected. This case matches the size of the power converter to be included in the IC, with the Li-ion battery and PV system to be installed in the Spanish demo, in order to produce the expected energy balance and economic performance.

Section 3 describes the Model Predictive Control (MPC) algorithm included in the HMI-EMS of the developed IC, and how this EMS layer coordinates with the different hierarchical control levels.

Section 4 presents the features of the SCADA included in the HMI-EMS. The different configuration screens are explained, showing the flexibility offered to the user to define the current system, and to access to the generated data.

Section 5 describes the hardware and Information and Communications Technology (ICT) architecture of the IC. The details of the equipment to be used in the Spanish demo are presented, including both the intelligence side (HMI-EMS) and the power conversion side.

Finally, section 6 presents the validation tests of the HMI-EMS carried out at CENER’s premises. Profiles generated in the selected case of section 2 are used to govern the HMI-EMS, managing a Li-ion battery with the role of dealing with energy which is locally generated.

2 Role of the integrated controller in the Spanish demo

2.1 Introduction

The Integrated Controller is responsible for managing the renewable energy locally generated in the PEB with the aim of maximising its benefit for the overall system.

The general features of the Integrated Controller are listed below:

- EMS based on a configurable HMI for microgrids and power plants;
- easy and configurable Front End for the selection of plant elements;
- integrates standard industrial communication protocols;
- integrates advanced smart strategies for power plant energy optimization;
- energy market and weather forecast availability for strategy definition;
- integrates the control for the power plant's elements;
- SCADA, energy strategy and control system embedded into the same HW and SW platform;
- automatic report generation;
- power plant alarms and warnings for safety shutdown;
- web interface for remote monitoring;
- different user configurations and access.

2.2 Preliminary system dimensioning for a PEB

The base case for the simulation was built considering a residential community in the city of Granada. The model considers only the electrical part of the system, including the electricity consumption derived from the central HVAC system of the residential community.

In order to generate a reference annual profile of the energy consumption two different data sources were used. First, a pre-set residential profile was selected from Homer Energy software to account for the domestic electricity demand of the dwellings. The annual profile is generated by adding to a common reference daily profile a random hourly variation based on adjustable parameters.

Second, to take into account the energy consumed by the equipment serving the thermal demands of the community, the resulting profile obtained in the simulations carried out within Task 2.6 was used. Figure 2-1 shows the daily average profile of both demand concepts, in January.

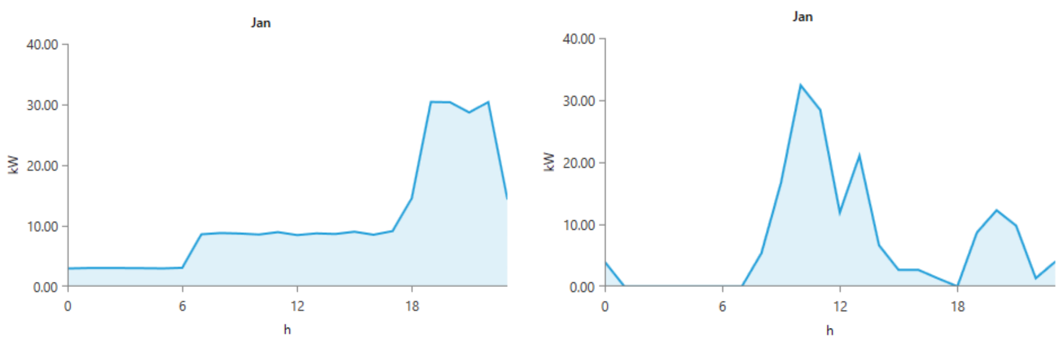

Figure 2-1. a) Domestic and b) HVAC electricity demand daily profiles in January

The general conditions used in the simulations, regarding energy local generation and demand, are listed in Table 2-1.

Table 2-1. General conditions used in the simulations

Parameter	Average	Peak
Solar horizontal irradiance	4.75 kWh/m^2/day	
Domestic electricity demand	267.9 kWh/day	43.4 kW
HVAC electricity demand	129.6 kWh/day	72.7 kW

The planned photovoltaic system will provide the local energy generation needed to obtain a PEB case. According to the calculations, that threshold is reached with a minimum of 85 kWp installed on-site. On the other hand, a BESS will enable the energy time-shift to match generation with consumption. This way, locally generated energy can be used without relying on energy exchange with the grid.

However, the energy lost in the charging and discharging inefficiencies of the BESS must be compensated by over-sizing the PV system accordingly, so a compromise between the two systems must be reached to obtain a balanced sizing of the overall system. The reference chosen as a compromise is a target self-sufficiency ratio of 50% over a year, i.e. limiting the electricity demand that can be covered by imports from the grid to 50%. The results obtained from the model are shown in Table 2-2.

Table 2-2. Dimensioning results from the simulations

Equipment	Size
Photovoltaic system	90 kWp
BESS	30 kW, 100 kWh

Figure 2-3 (part a) shows the resulting average daily profile in January of grid purchases once the PV system is installed, while Figure 2-2 shows the profile corresponding to the base case as a reference. As expected, the average energy import during the central hours of the day is practically zero. Certainly, that does not mean this will be case in cloudy days, taking into consideration that the figure is depicting an average profile in the month of January, which is taken as an example given its demanding climate conditions.

Due to the rapid rise and fall of PV power generation, in the morning and evening respectively, the grid will have to respond accordingly by supplying power to the system. While this is not a problem for the grid when dealing with a single user, this circumstance could jeopardize the operation and security of the grid when the number of users grows progressively.

This issue is addressed by the integration of BESS into the system. The resulting daily profile of the case PV+BESS is shown in Figure 2-3 (part b). In this case, the average purchase profile of the grid is slightly reduced, especially in the evening hours when residential consumption is generally at its highest. While this reduction does not seem to be relevant, it is enough to reach the self-sufficiency target set in the overall annual energy balance.

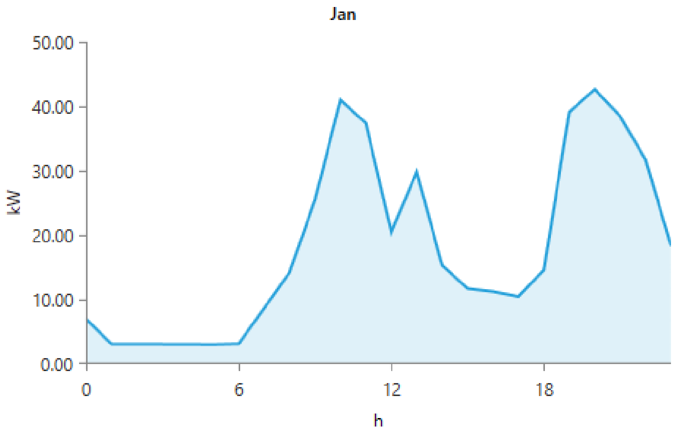

Figure 2-2. Total grid purchases daily profile in January: Base case

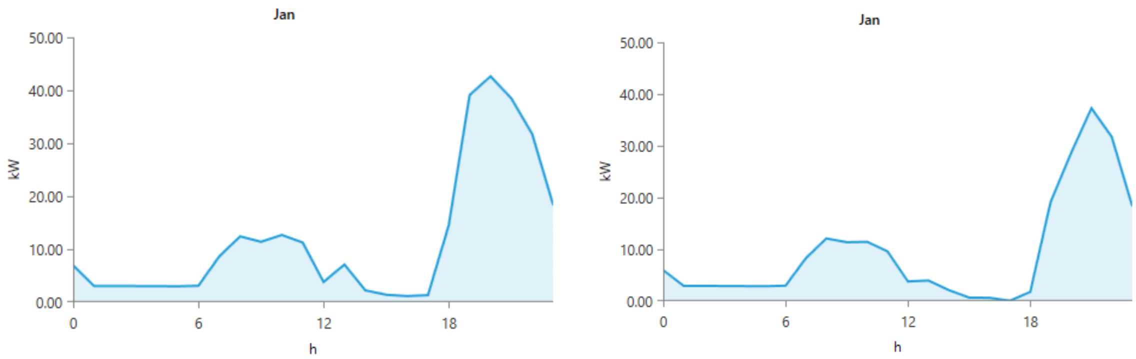

Figure 2-3. Grid purchases daily profile (kW) in January: a) PV case, b) PV+BESS case

In terms of surplus renewable energy exported to the grid, in the cases without and with BESS, we find a similar impact of BESS to that experienced in the purchase profiles. As Figure 2-4 shows, the inclusion of BESS reduces the impact of the building on the grid during the central hours of the day. Again, the aggregation of multiple systems can pose a considerable problem for urban low-voltage grids, if an increasing deployment of these local generation systems occurs. In the example month of January, the surplus energy fed into the grid is notably reduced from almost 40 kW to around 30 kW peak power on average.

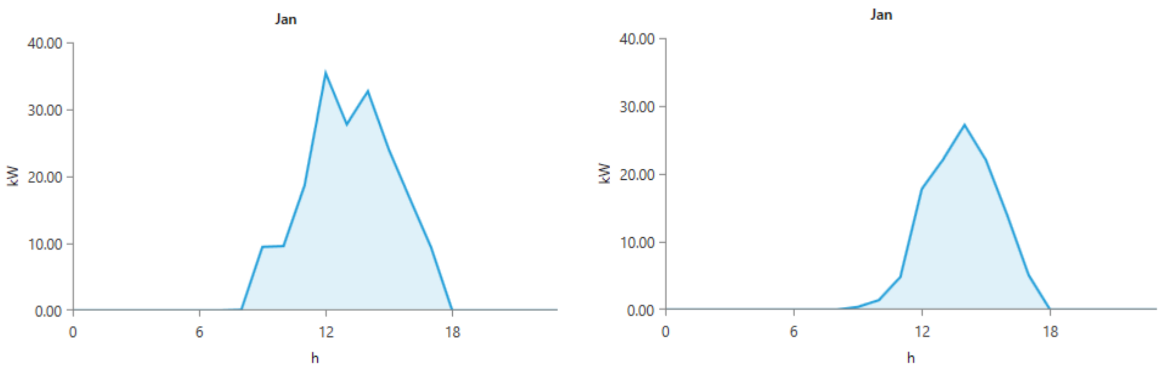

Figure 2-4. Grid sales daily profile (kW) in January: a) PV case, b) PV+BESS case

Table 2-3 shows the electricity balance in the different simulated cases. As can be seen, the incorporation of the BESS significantly reduces the energy exchange with the grid, both for purchasing and selling electricity. Energy exports are reduced by around 30% by locally storing energy in the BESS. As a consequence, energy purchases are reduced by around 26% annually.

Table 2-3. Annual electricity balance of the simulated case studies

	Electricity demand (MWh)	Renewable generation (MWh)	Grid purchases (MWh)	Grid sales (MWh)
Base case	145.02	0.00	145.02	0.00
PV case	145.02	154.02	93.48	102.49
PV+BESS case	145.02	154.02	68.94	72.60

Two indicators can be used to assess economic benefits for the user, namely, the self-consumption ratio and the self-sufficiency ratio. It is important to make clear the differences between self-consumption and self-sufficiency, although it is true that maximizing each of them is interesting for the user.

Self-consumption indicates the percentage of locally generated energy that is consumed by the user, which is calculated discounting from 100% the proportion of generation that is sold to the grid.

Meanwhile, self-sufficiency indicates the percentage of energy consumed by the user that is locally generated, which indicates the actual level of independence from the electricity grid. This ratio is calculated discounting from 100% the proportion of local demand that is satisfied from the grid.

In the end, it is this second indicator that gives a better idea of the system's ability to reduce the cost of the bill and reduce the system's dependence on the external grid.

Although renewable generation exceeds electricity demand, as Table 2-3 shows, the self-sufficiency ratio is only 35.5% if it is not possible to store this energy. This means using the electricity grid as a buffer to be able to shift the use of the energy generated over time, which implies buying back the energy previously sold, with the additional cost that this entails, and possibly saturating the distribution grid at specific times.

The incorporation of a BESS into the system allows part of the excess energy to be stored locally, reducing dependence on the grid and, as Table 2-4 shows, allowing the self-sufficiency ratio to be increased to 52.5%. In this way, a self-consumption ratio of 52.9% of the energy generated is achieved, minimising the amount to be exported to the grid.

Table 2-4. Self-consumption and self-sufficiency in the simulated case studies

	RES self-consumption (%)	System self-sufficiency (%)
Base case	0.0	0.0
PV case	33.5	35.5
PV+BESS case	52.9	52.5

3 EMS (Energy Management System)

3.1 Description of the predetermined MPC algorithm

The main objective of the Integrated Controller's EMS is to maximise the self-sufficiency ratio and reduce electricity bills by the smart utilization of the local renewable energy in a residential community. By using weather and load demand predictions, the system knows how much energy needs to be imported from the external grid in the next 24 or 48 hours; in this way, the EMS uses the electricity tariff schedule and linear programing optimization techniques to calculate when to charge or discharge energy from the BESS, in order to minimise the total amount and cost of the electricity consumed from the external grid.

The use of energy storage systems to shift high demand of electricity from high tariff periods to lower demand and lower tariff periods (load shifting) is a well-known practice and one of the fundamental functions of electrical energy storage systems. In this case, the focus is also on the minimisation of the energy exchange with the grid in order to reduce as much as possible the energy dependence of the PEB on the external grid.

Optimization problem

As mentioned above, the main objective of the EMS is to maximise the self-sufficiency ratio and reduce electricity bills through the integration of the renewable generation and the smart operation of the BESS.

A linear optimization program has been designed and implemented into the Integrated Controller to account for the optimal management of the energy. This program also incorporates considerations related to technical specifications of the equipment.

The objective function implemented in the EMS algorithm to solve the optimization problem is shown in Equation 1:

$$min\left(\sum_{i=0}^{24}\left(E_{grid\_in(i)}\cdot C_{grid\_in(i)}-E_{grid\_out(i)}\cdot C_{grid\_out(i)}\right)+\sum_{p=1}^{t}P_{max}\cdot C_{p}\right)$$

Equation 1. Objective function of the EMS algorithm

Where:

- i — Hour in the interval
- p — Tariff period
- t — Number of tariff periods
- E_{grid_in} — Energy imported from the grid (kWh)
- E_{grid_out} — Energy exported to the grid (kWh)
- P_{max} — Highest average power during 15 minute in each tariff period (kW)
- C_{grid_in} — Price of the energy imported from the grid during each tariff period (€/kWh)
- C_{grid_out} — Price of the energy exported to the grid (€/kWh)
- C_p — Demand charge cost (€/kW·day)

The optimization problem is subject to:

- the law of conservation of energy in the nodes of the grid of the consumer,
- technical limitations for an optimum use of the equipment.

In order to calculate the imported and exported energy flows, the MPC requires as input the predicted generation and consumption of energy in the system for the next 24-72 hours.

Generally, the weather forecast can be downloaded from web services, for which the IC must have an internet connection. Once the renewable resource forecast is known, the IC is able to calculate the expected power generation, knowing the technical characteristics of the available generation equipment.

Regarding the electricity demand, the IC is able to generate this prediction from the available historical records using machine learning techniques, which discriminate according to the day of the week, the season of the year, etc.

In any case, the IC allows the possibility of feeding these predictions externally whenever another system is available to provide them.

3.2 EMS vs control layer

The control layer interacts with the strategy level (EMS) that manages the energy generated by on-site RES, enabling advanced control functionalities. This dialog is based on a multilayer control scheme of assets. This architecture consists of different control layers based on the dynamics of each participating system. Thus, the complexity of the control problem is solved by separating processes into easier sub processes, with similar dynamics, which are approached as easier problems to solve (see Figure 3-1).

- The higher layer assigns the hourly energy exchanged with the grid through the common coupling connection point, and it is based on the communication with the EMS.
- The intermediate layer, called the supervisory layer, is able to distribute the requested power according to the upper layer to the available assets, respecting the specified limits. The power, energy and state of charge (SOC) limits in each control loop are based on the plant configuration received from the upper layer control and status signals from the lower layer assets.
- The lower layer consists of the local controllers of each individual device. In this particular case, the battery control units receive active power setpoints, while the PV system control sets the generation limits.

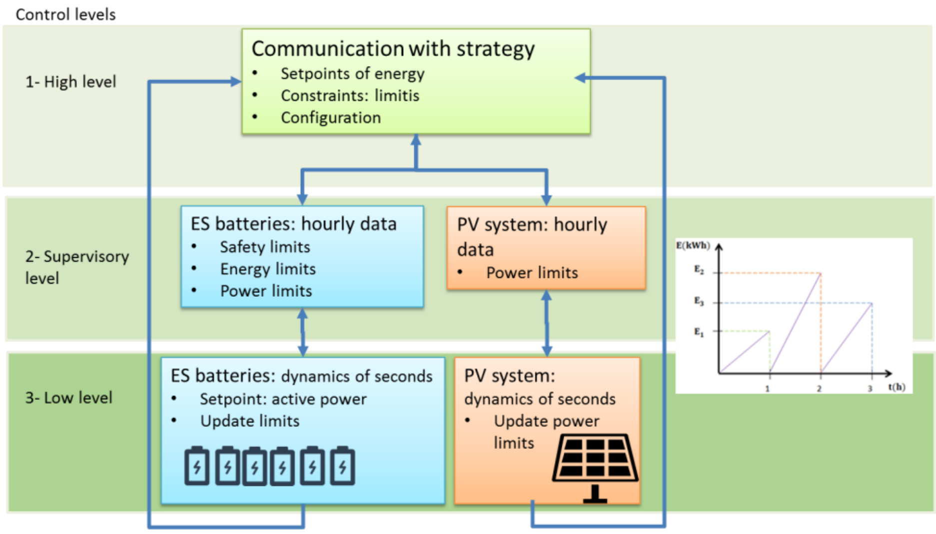

Figure 3-1. Hierarchical control with different levels

Lower level

An internal controller is responsible for enabling the regulation of the active power generation below a limited range. The regulation of the hourly power ramp is established through a constant active power setpoint for each hourly period. The active power regulation error between the target power measured at the Point of Common Coupling (PCC) and the result of the battery power level and the PV generation is compensated by the PI controller. Thus, the setpoints of each subsystem are updated according to the system state variables.

Supervisor level

At this level, the monitoring of the storage and generation capacity range is operated differently. Since batteries are bi-directional systems, the SOC, energy and energy limits are updated at each iteration time of the control loop with a specific battery supervisor.

High level

This level performs the management of the energy exchanged between the converter and the grid at the common coupling point of the grid according to the indications of the strategy. The daily plan calculated taking into account the forecast, flexibility, controllable and non-controllable loads, is loaded from the management algorithms. As a result, the generation and storage setpoints for the next 24 hours are read. Furthermore, if it is necessary to compensate for forecast errors or to recalculate the flexible compensation plan, at each new hour this high-level control updates the read setpoints.

Control model benchmark

The tested architecture is validated by considering a plant configured with a photovoltaic system and a grid-connected energy storage system. The management algorithms write the hourly setpoints. The battery is a lithium-ion battery that has been modelled considering a second-order-RC equivalent electrical circuit in discrete space-time. The PV model has been selected based on current-voltage (I-V) equations[1].

Simulation tests have been implemented and verified in MATLAB-SIMULINK language based models, with 0.5 s solver time step. After control model validation, the models have been translated into Lab-VIEW language. The results of the modelling in different software languages have been verified and therefore, the code has been validated.

Simulation results

In Figure 3-2 results of energy and power at the PCC, at the BESS and the PV generation are presented for 3.8 h of simulation. A multilayer structure control is provided by a high number of degrees of freedom. By maintaining a selection of degrees of freedom constrained, the rest allows to pursue different objectives involving efficient management of the energy storage system. Therefore, the flexibility of the control is proven.

The upper graph shows the evolution of the accumulated energy values for the different concepts within every hour. The control responds to the accumulated error generated along time comparing it to the generated energy predictions for that hour. That way, the instant power of the BESS is constantly updated with the aim of minimising the accumulated error at the end of each hour. Figure 3-2 shows the instant variation of the power for the different concepts in the figure.

Where:

Epcc	Hourly target energy at the point of common coupling
Egen	Accumulated energy at the generation equipment along the hour
Energia_bateria	Accumulated energy at the battery along the hour
Epcc_ref	Desired evolution of the accumulated energy at the pcc along the hour
Error	Accumulated control error along the hour
Pbat_ref	Power reference for the battery
Pgen_m	Measured power at the generation equipment
Pcc_m	Measured power at the point of common coupling
Pbat_m	Measured power at the battery

[1] Tian H., Mancilla-David F, Ellis K., Muljadi E., A detailed performance model for photovoltaic systems, NREL/JA-5500-54601, 2012

Figure 3-2. Energy (upper graph) and active power (lower graph) results of the control simulation of the plant during 3.8 hours.

4 SCADA system

4.1 Introduction

The SCADA is responsible for managing the reading and writing of variables in the system. On the one hand, it monitors and records all the data generated by the system, while on the other hand, it sends the setpoints generated by the EMS.

The screens generated in the SCADA allow for setting the operation parameters and monitoring the performance of any asset in the system.

4.2 Local grid system configuration

In the main menu (Figure 4-1), the elements that will be part of the plant can be configured. At the same time, it is possible to select the list of strategies that are desired to be part of the plant control. This can also be done in an option within the plant configuration. It is possible to establish user permissions (to start/stop the plant for the basic level, up to advanced plant configuration for the administrator level).

Available options in the main menu:

- plant configuration;
- strategies selection and tuning;
- user settings;
- user and configuration log.

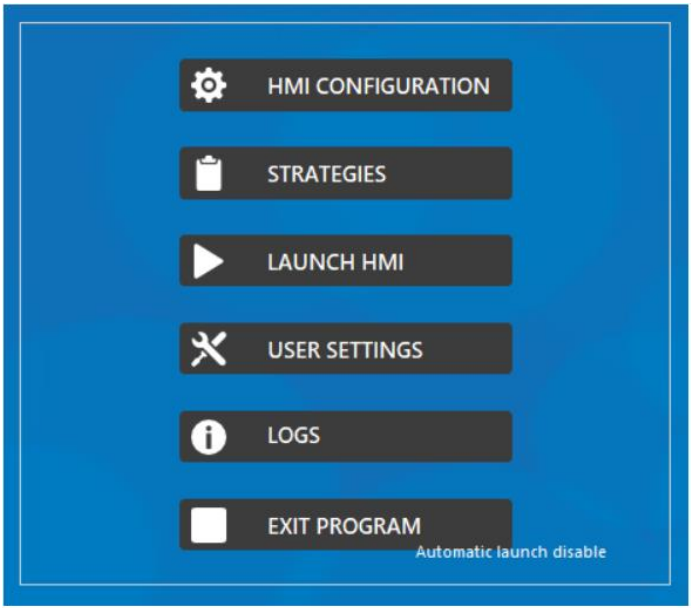

Figure 4-1. Main menu screen in the SCADA

The Integrated Controller allows for different plant topologies regarding its relation with the external grid. The available options for topologies are listed below:

- ON GRID: plant connected to the electricity network;

- OFF GRID: plant disconnected from the electricity network with different elements generating the local network;
- ON GRID + BACK UP: plant connected to the electricity network but with a backup generating set to supply power in case of power failure;
- DIESEL GRID: gen-set always generating the local network.

4.3 Selection and configuration of equipment

The integrated controller allows you to configure the plant (Figure 4-2) by adding the elements from a wide list of available options. For correct electrical operation, one of the elements must be selected as the master, which will be responsible for maintaining the voltage and frequency when the plant is isolated from the grid. Additionally, up to 6 other elements can be chosen, considering load, generation or measurement elements.

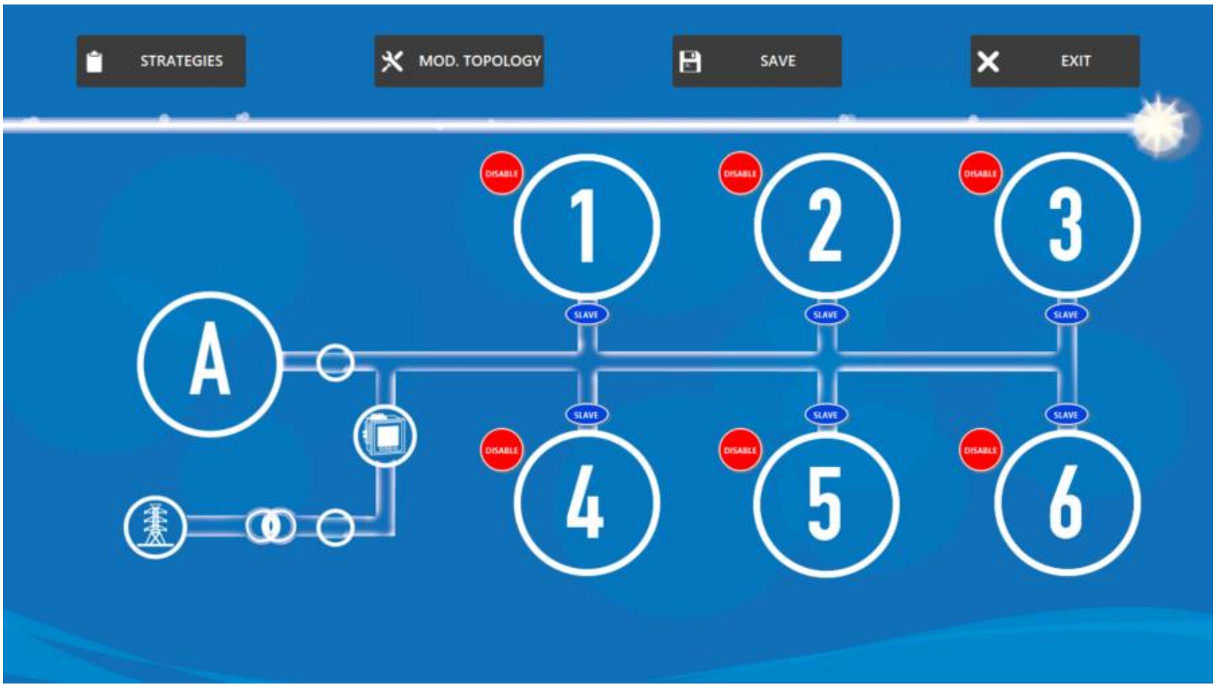

Figure 4-2. Plant configuration screen in the SCADA

The full list of eligible items is presented below (Figure 4-3):

- Renewable Generation:
  - Wind turbine
  - PV system
  - Hydraulic turbine
- Conventional:
  - Gen-set
- Energy storage:
  - Pb-acid
  - Lithium-ion
  - Redox flow

  - Fly-wheel
- Loads:
  - Industrial Load
  - Residential Load
- Converters
- Measurement (meteorological station, grid analyser)

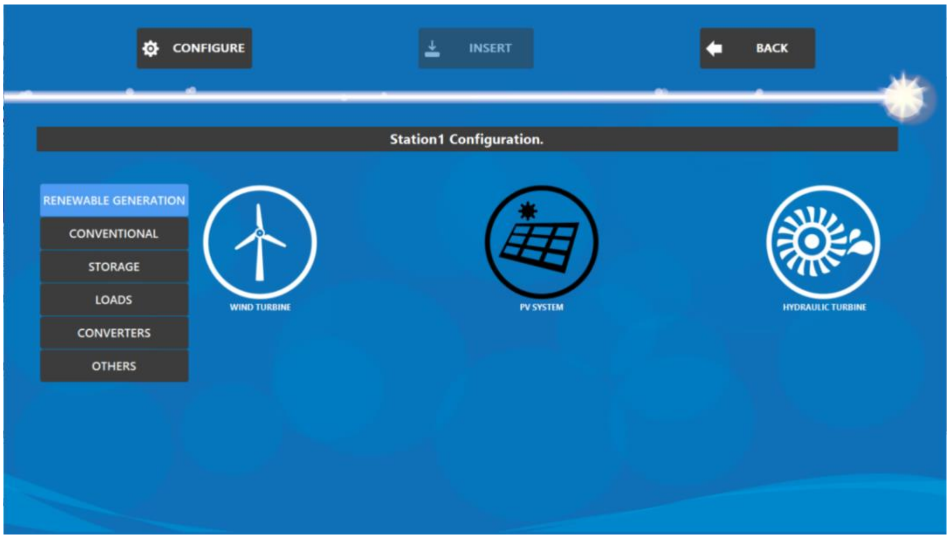

Figure 4-3. RES elements in the SCADA

Each time an element is selected, by clicking on the configure button, a personalised screen is displayed for each element (Figure 4-4), showing all the variables associated with that element that must be configured so that the plant can operate optimally from the point of view of both control and energy management.

The configuration screen of each element allows the next options:

- setting parameters for every technology;
- read and write parameters for elements control and smart strategy management;
- the communication protocols available:
  - MODBUS TCP/IP,
  - MODBUS RTU,
  - IEC 61850,
  - IEC 104,
  - OPC.

Those listed are the protocols currently implemented in the equipment. This flexibility in communications options facilitates the implementation of the system, minimising the development required to integrate the different equipment available. This allows a plug-and-play installation for which no specific training is required. However, there is the possibility of incorporating new ad-hoc protocols if any particular equipment in the Spanish demo site requires it.

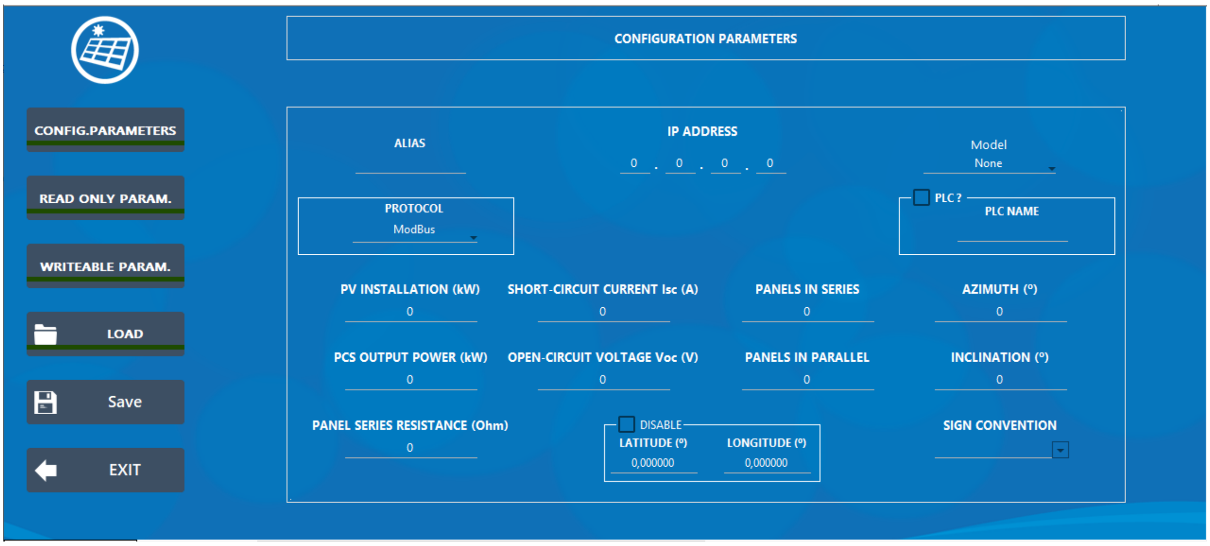

Figure 4-4. Configuration screen for an element in the SCADA

4.4 Strategy selection

The integrated controller has a number of predefined strategies for the most common applications of the target plants. In this way, the user only has to select the options that are of interest to him and the system acts accordingly. The list of available options is shown below:

- Self-consumption: the system stores surplus energy generated by RES for a later use during high tariff periods.
- Economic self-consumption: during the lowest cost tariff period, energy can be purchased to be stored, and consumed later in high price periods.
- Energy time-shift: the system consumes from the network in periods of cheap energy and from the Energy Storage System (ESS) or Renewable Enegy Sources (RES) generation in periods of high tariffs.
- Peak shaving: the system uses generation and storage elements to reduce network consumption at plant demand peaks, trying to minimise the demand charge in the electricity bill.
- Load following: the system tries to constantly follow the demand of the plant by reducing the exchange with the grid.
- V/f regulation: for very specific applications, the system is capable of participating in the regulation of the distribution and transmission grid.

4.5 Tariffs

The EMS makes decisions to optimise the import and export of energy through the grid based on the prices associated with each period. For this reason, it is essential to complete this information in detail in order for the system to make reliable decisions. To make this task easier for the user, the SCADA has templates (Figure 4-5) of the tariff period schedules associated with the different voltage and power levels. However, the user can always design another tariff schedule from scratch.

Then, the energy and demand charge prices need to be completed for each tariff period (Figure 4-6). This process can be manually performed in the HMI, or alternatively, prices can be externally provided via file.

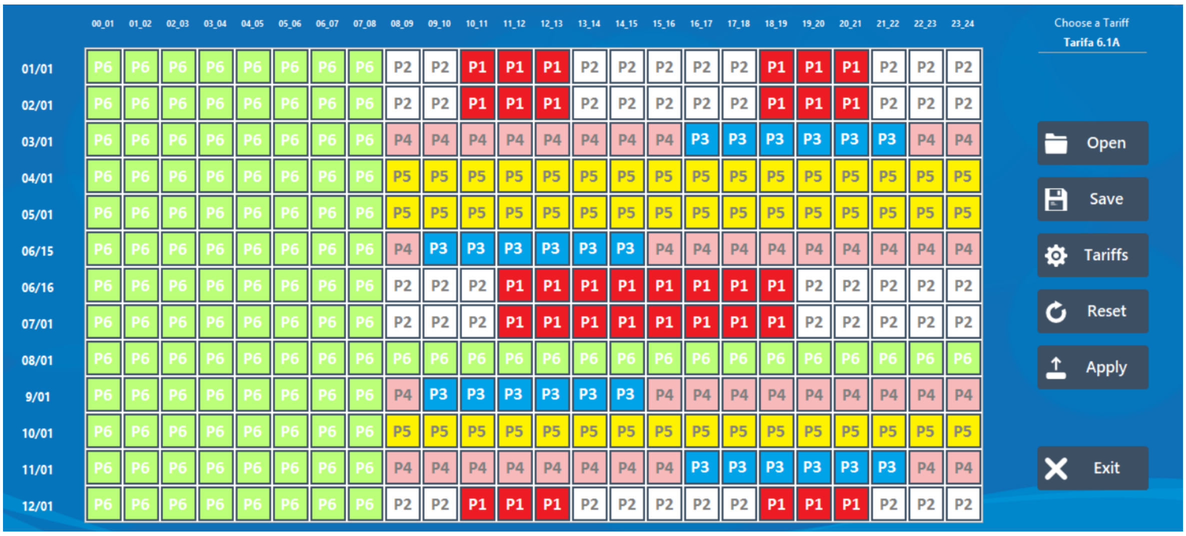

Figure 4-5. Tariff schedule template in the SCADA

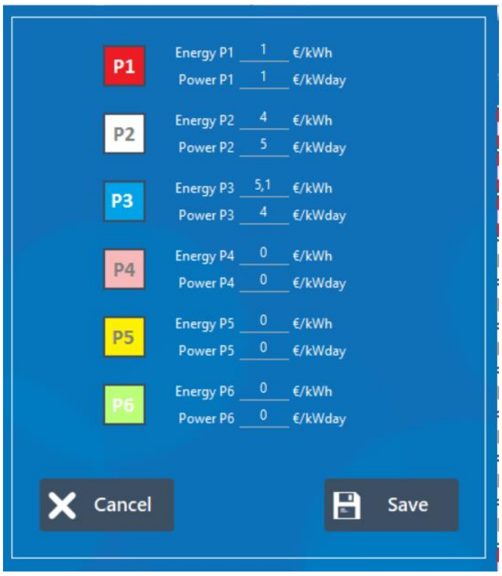

Figure 4-6. Energy and demand charge prices in the SCADA

4.6 Power plant monitoring

Once the application is started, a synoptic with the selected configuration can be seen (Figure 4-7). The power, SOC and consumption values of each element are shown. More detailed information about each element can be accessed by clicking on each element.

It is possible to monitor how the strategy and control behaves, consult historical plant data and generate performance reports, as well as a list of events and alarms registered in the plant.

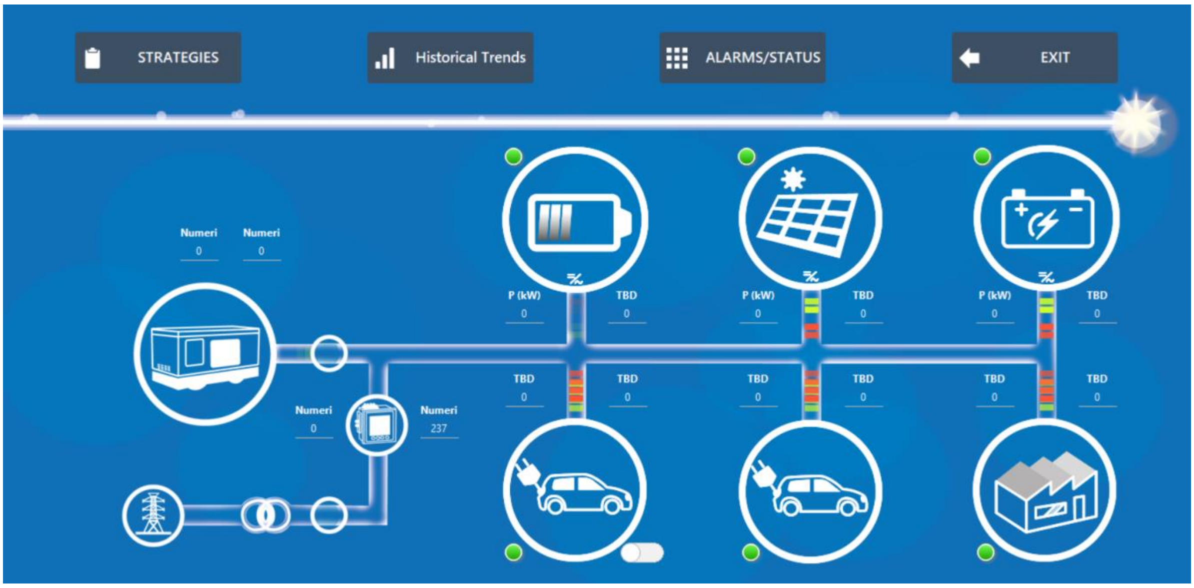

Figure 4-7. Main monitoring screen in the SCADA

5 Hardware and ICT architecture

5.1 Introduction

The Integrated Controller is composed by the integration of a power electronics converter and an HMI-EMS which includes the plant control algorithms and the energy management system for microgrids and hybrid plants.

5.2 Power Converter

The power side of the integrated controller includes a rectification stage and a DC/DC stage. The AC side is connected to the grid, while the DC side has three configurable outputs depending on the number of generation or storage devices connected to the system. In this way, it is possible to select to operate the plant with 1, 2 or 3 devices connected to this side. In the event that the plant only has 1 or 2 manageable devices, 3 or 2 branches can be short-circuited respectively to increase the deliverable power of the devices connected to that channel.

In addition, it can operate both as a power source and as a voltage source (at least one storage system is required to operate in this mode). In the case of operating in voltage source mode, the setpoints to be received are the amplitude and frequency of the network to be generated, while if it operates as a current source, a power setpoint must be given for each of the devices connected to the converter. The electrical diagram of the converter is shown in Figure 5-1.

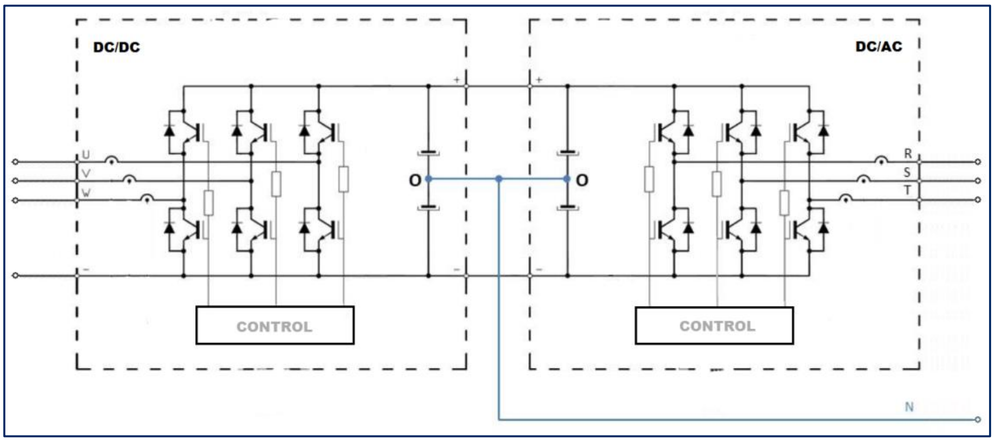

Figure 5-1. Electronic Power Converter Scheme

The main feature that differentiates the Integrated Controller from existing commercial equipment is that, by hybridising the power electronic converter and the EMS, the system provides an intelligence that allows it to manage a plant in an integrated way.

5.3 HMI-EMS

The software solution that has been implemented and that will respond to the proposed scope runs on an industrial PC with touch screen, so that the plant operator can make the settings and modifications of the application, without using any additional peripherals. Furthermore, as the touch screen has industrial protection, it reduces the likelihood of damage to the final product due to use or environmental factors of the plant where it is located. This hardware will have the ability to connect via Ethernet port with all external elements to establish communications, store and process data in the cloud, as well as for remote monitoring and remote management.

The software platform for the configuration, management and operation of a hybrid plant has been implemented in the LabVIEW development environment. This environment offers the possibility of developing applications and tools for data acquisition, control, storage and management without having to use third-party toolkits under normal operation conditions, thereby homogenising the software environment.

This application has the following functionalities:

- SCADA system
- Plant control module
- Energy management and optimisation module
- Module for communication, management and storage of data, errors and alarms
- Reports and historical data and events module

The configuration of the plant is carried out in a very simple and user-friendly environment made up of screens, through which the user has to navigate and select the devices to be included in the plant, the characteristics of each device, as well as its variables and communication parameters (see Figure 5-2).

PARÁMETRO	REGISTRO	UNIDADES	ESCALADO	TIPO DATO	HABILITAR
POTENCIA ACTIVA TRIFASICA	40001	kW	1	U16	HABILITADO
POTENCIA REACTIVA TRIFASICA	40002	kVAr	1	U16	DESHABILITADO

Figure 5-2. Modbus Configuration Parameters

The default communication protocol used to connect the HMI with other elements of the plant is Modbus TCP/IP and OPC UA. This means that all the elements have common characteristics, reflecting the name of the channel or the variables to be read or written, the units of the data, the type of data, the scaling, the register of the variable to be read or written and whether the channel is disabled or not. Communication between the HMI and the power electronics developed by CENER is carried out via "Network Streaming" technology, as it allows a large amount of information to be sent very quickly, improving on current technologies such as MODBUS or OPC.

5.4 Topology of the Spanish demo site in EXCESS

For the EXCESS project, the graphical interface of the HMI results as shown in Figure 5-3. It features a storage device, a PV generation plant, as well as residential loads and a weather station. More equipment can be added dynamically as the project progresses to include communications with third party equipment supplied by the other project partners.

The Spanish demo site will include both sides of the IC, the HMI-EMS and the power conversion side.

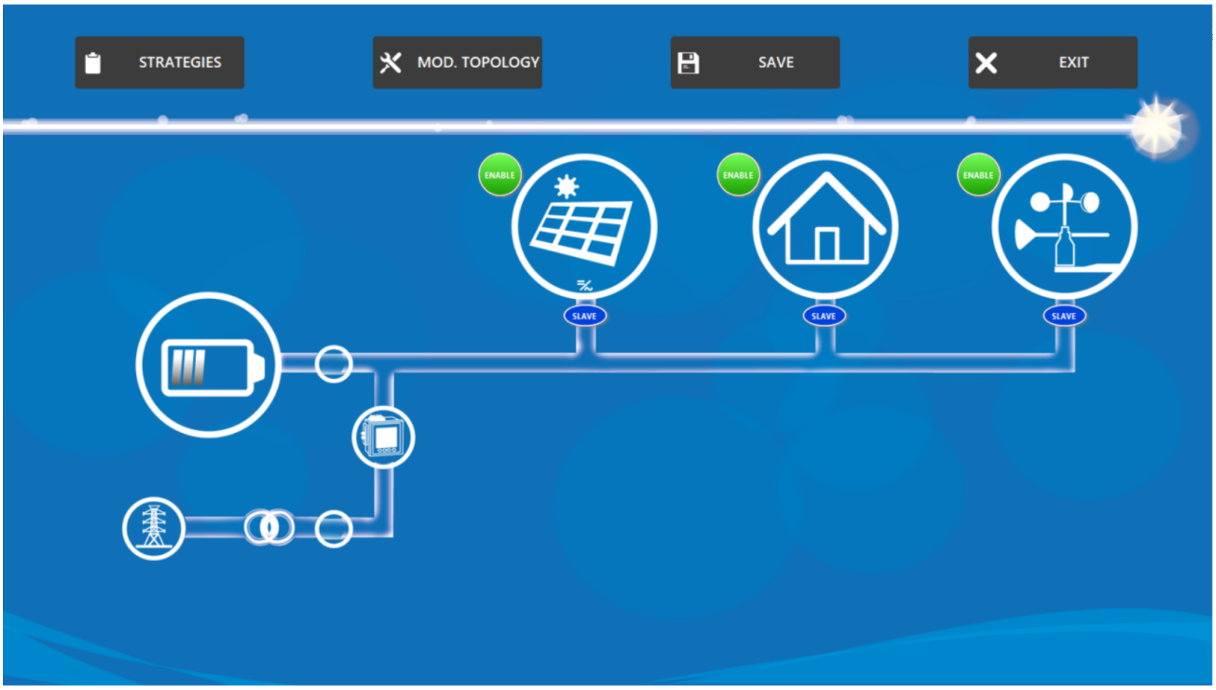

Figure 5-3. Main SCADA screen for the Spanish demo in EXCESS project

6 Validation testing

6.1 Test preparation

The validation test of the IC was carried out at CENER's ATENEA microgrid facilities (Figure 6-1). For this purpose, the HMI-EMS of the Integrated Controller was connected to a 4 kW nominal lithium battery available in the microgrid (see Figure 6-2), via a converter of the appropriate power.

Figure 6-1. CENER's ATENEA microgrid facilities

The tests have been carried out taking as a reference the simulations for the sizing of the system mentioned in section 2. The period chosen corresponds to a week in March of the generation and demand profiles (domestic and HVAC) used for the sizing. This week has been chosen because of the existing variability of generation and demand, which gives rise to days with excess and shortage of generated energy, and allows the behaviour of the Integrated Controller to be studied in different daily patterns.

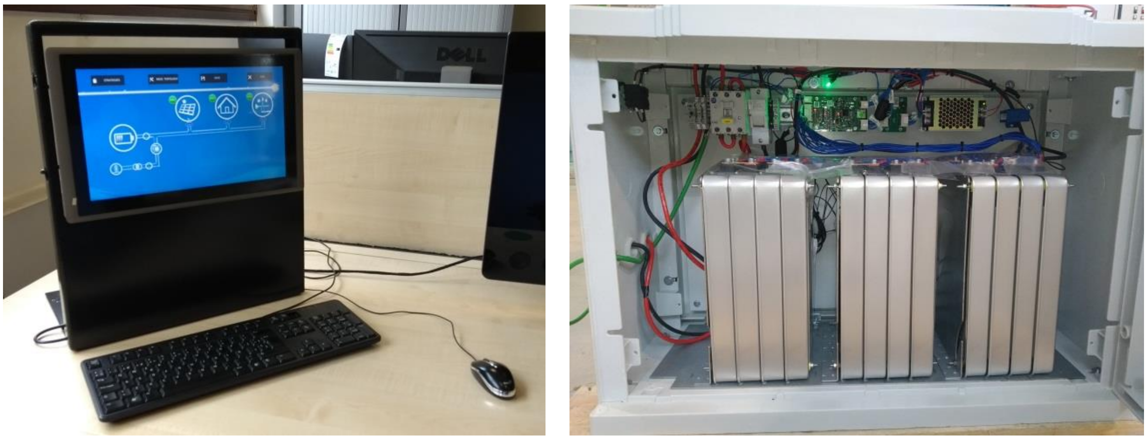

Figure 6-2. Test set-up: a) HMI-EMS of the IC; b) Test battery.

Figure 6-3 shows the detail of the reference week. Domestic and HVAC electricity demands are grouped under the concept “Demand”. The renewable contribution is provided by the generation of the photovoltaic system. As can be seen, the profile includes some days with a very low solar resource, where photovoltaic generation is practically negligible. Similarly, there are other days when there is a significant amount of surplus generation, which can be managed by the IC to optimise system performance.

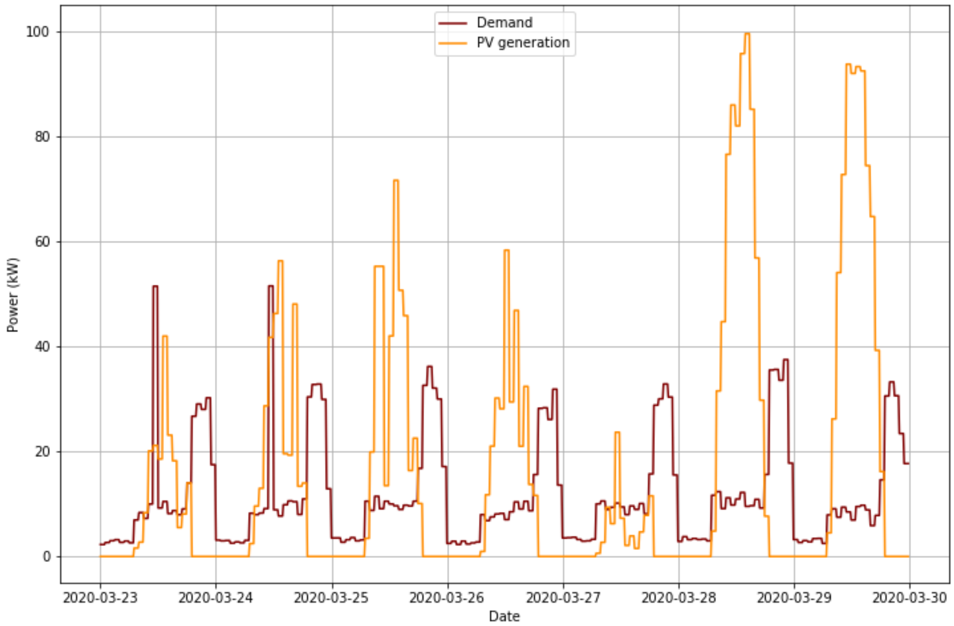

Figure 6-3. Generation and demand profile used as a reference for the IC validation

The system dimensions for the relevant test case are given below:

- PV system: 100 kWp;
- BESS: 30 kW – 100 kWh.

During normal operation, the EMS uses as input the generation and demand forecasts received every 24 hours. With this information, it runs the optimisation algorithm to produce the BESS operating profile. Since the predictions are not exact, the EMS must ensure throughout the day that the actual generation and demand measurements follow the expected profile within a reasonable margin. When it is deemed that the optimisation needs to be recalculated, as the BESS will have performed differently than expected following the control layer setpoints, the optimisation needs to be rerun with the updated SOC, to generate the BESS setpoint for the remaining hours of the day. This procedure is carried out automatically and is triggered by the optimisation layer.

In the case of this validation, the operation is simpler as a perfect prediction has been assumed. However, some deviations can accumulate during operation of the BESS due to variations of efficiency and capacity from nominal values.

The expected operation of the system, as generated by the EMS, is shown in Figure 6-4. It shows the grid consumption profile (PCC Imports) resulting from the operation of the BESS, which absorbs many power peaks that would otherwise be covered by this external grid. This behaviour is easily seen on the first day shown in the figure, where the PCC imports are avoided thanks to the BESS operation, until the BESS is fully discharged and the grid has to switch to covering the entire demand.

During the rest of the days, the behaviour is as expected for a self-consumption system: the BESS stores surplus PV energy during sunshine hours for use after sunset, whereby the BESS undergoes around one charge-discharge cycle per day. Depending on the electricity tariff schedule, which in Spain is different for each month in large installations, the EMS will prioritise the use of the stored energy during the highest cost hours. In addition, it will try to dampen power peaks to reduce the demand charge of the bill.

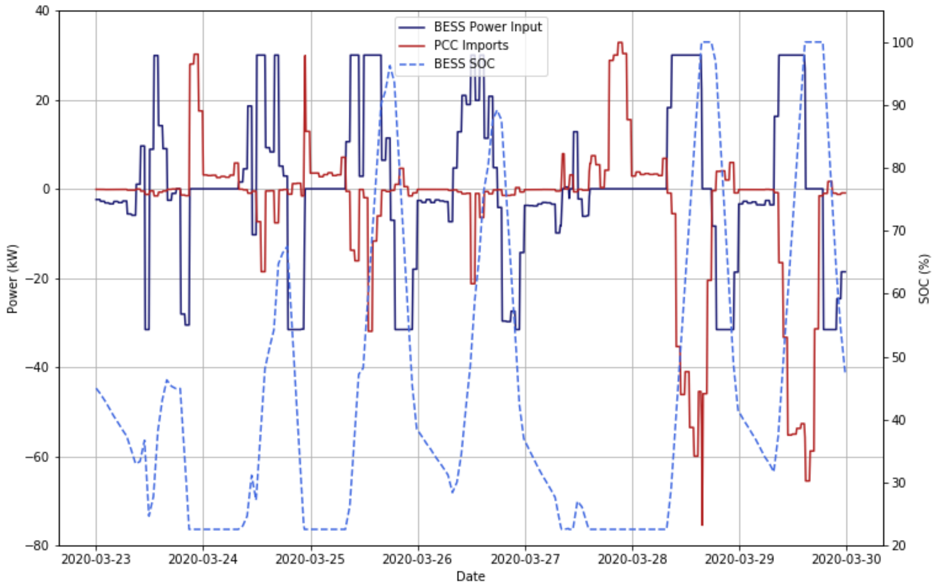

Figure 6-4. System operation according to EMS optimisation

Should the night-time electricity price be low enough to make it profitable, the EMS would take the decision to charge the BESS during this tariff period. Unfortunately, this is not the case with current electricity tariffs in Spain.

Although on the days with the lowest solar resource the BESS does not reach 100% charge, the values achieved on average days suggest that the sizing of the BESS is adequate for this demonstration plant.

6.2 Test results

The BESS operating profiles calculated according to the sizing of the demonstration plant in Spain had to be resized for the validation test to adjust to the nominal power of the lithium battery available in the microgrid. Thus, the validation results graph shows the values of the different variables already scaled for the development of the tests.

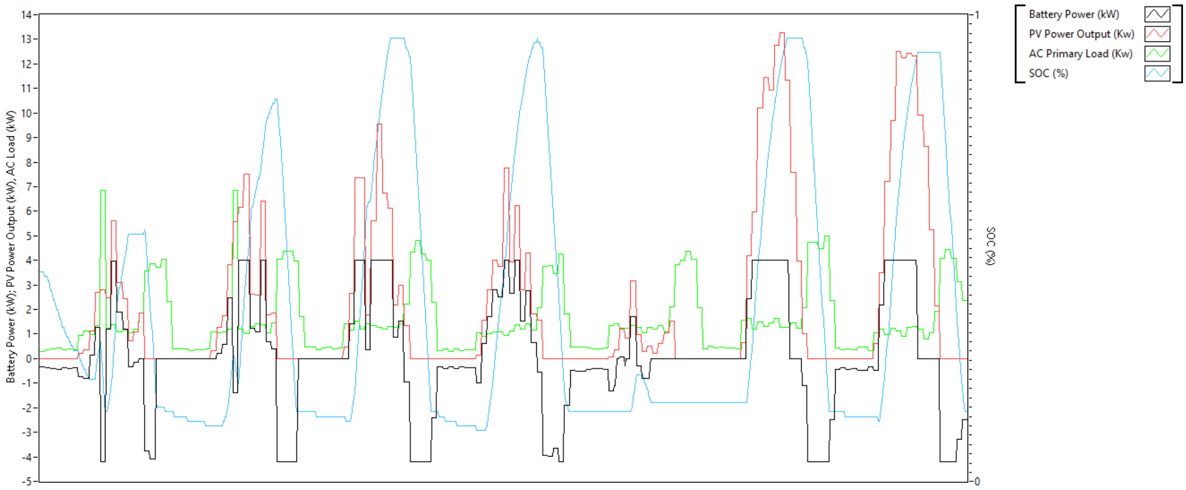

Figure 6-5. System operation during validation tests

Figure 6-5 shows the input profiles used, together with the power and SOC measurements of the battery throughout the test. The power supplied and absorbed by the battery closely follows the expected behaviour of Figure 6-4. Similarly, the evolution of the SOC is almost identical to the expected profile, although minor differences can be seen due to the inaccuracy of the efficiency and energy capacity assumed by the EMS, as mentioned above. This difference of the SOC measurement with respect to the one calculated by the optimisation could lead to a recalculation through the optimisation algorithm in case it reaches a considerable error along the day.

During the actual operation of the system including prediction errors, the control layer is responsible for making real-time decisions to enforce the setpoint received from the strategy layer, doing so in the smoothest possible way for the management of the system elements.

In the case at hand, the difference in SOC values may mean that the BESS depletes the stored energy sooner than expected. In this case, it will not be able to provide all the expected energy according to the optimisation result. In terms of energy, this may result in a small deviation of the energy cost on the bill from the expected one. However, the impact can be much larger if the peak power limitation according to the optimisation setpoint is not met. In this case, this deviation can penalise the maximum monthly power value, leading to a significant increase in the cost of the bill. For this reason, serious consideration should be given to the possibility of incorporating machine learning mechanisms that update the BESS capacity and efficiency values considered in the calculations to minimise the possibility of incurring in these errors.

In any case, it is to be expected that the largest contribution to the deviations between prediction and operation originates from forecast errors in power generation and demand.

6.3 Conclusion of the validation testing

The integrated controller enables the management of the renewable energy generated, making use of the BESS, to maximise its use locally within the user's system. The test results show that the IC is able to run the optimisation algorithm to generate the BESS operating profile according to the stipulated objective function.

According to validation tests, the IC is able to communicate effectively with the converter, sending the necessary setpoints for the correct operation of the storage system. This is all achieved by simply introducing the main parameters of the equipment to be controlled in the configuration screens of the IC, so that the start-up of the system is as simple as possible, according to a plug-and-play philosophy.

The BESS has successfully responded to the commands following the planned profile. In addition, the correct parameterisation of the BESS in the IC user application has ensured that the discharge duration is as expected, making it possible to accurately modify the resulting power at the PCC profile to optimise the energy use within the plant, and ultimately the economic performance.

7 Conclusion

By building a model of the Spanish demonstration site, several plant sizing cases were tested in simulations. A self-sufficiency ratio of 50% was used as a target, resulting in a specific sizing case that was used as a reference. This case includes reference values for the power converter, Li-ion battery and PV system to be included in the Spanish demo plant.

Validation tests of the HMI-EMS were carried out at CENER's premises, in which the HMI-EMS governed a Li-ion battery with the aim of managing locally generated energy.

The validation demonstrates how the integrated controller allows the management of the produced renewable energy, using a BESS to optimise its local use in the demonstration plant. The test results also show that the EMS successfully calculates the operating profile of the current equipment to achieve the intended target.

During the tests, the HMI-EMS communicated effectively with the converter, which allows anticipating the correct operation of the different components of the system in the future Spanish demo site. Besides, the configuration of the demo will be easily performed through the plant configuration screens on the SCADA HMI, in accordance with the plug-and-play philosophy of the IC presented in the report.