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Smart Island Energy Systems

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1 Introduction

The overall scope of the SMILE project is to demonstrate, in real-life operational conditions, a set of both technological and non-technological solutions adapted to local circumstances targeting distribution grids to enable demand response schemes, smart grid functionalities, storage, and energy system integration with the final objective of paving the way for the introduction of the tested innovative solutions in the market in the near future. To this end, three large-scale demonstrators have been implemented in three island locations in different regions of Europe with similar topographic characteristics but different policies, regulations, and energy markets: Orkneys (UK), Samsø (DK), and Madeira (PT).

The Madeira demonstrator involves five pilots addressing three main aspects:

- Optimization of self-consumption of PV production in domestic and commercial installations in self-consumption only regime – referred to in this report by UPACs – with the help of battery energy storage (pilots 1 and 2)
- EV smart charging (pilots 3 and 4)
- Battery storage for grid support at the substation level (pilot 5)

This document presents the deliverable D4.11 entitled "Installation report of the DSM demo (Final version)," which refers directly to pilots 1, 2, and 5 above mentioned [1].

The previous version (named D4.7[1]) covered all the aspects related to installing the different hardware and software components that comprised the three pilots. Namely, the Advanced Metering Infrastructure (AMI), the Battery Energy Storage System (BESS), and their integration with the Energy Management System (EMS). The previous version also reported on the task of selecting the five best candidates to receive a BESS from a pool of 27 recruited micro-producers. This was followed by a detailed explanation of the process of installing and integrating the BESS. Likewise, the previous version provides detailed descriptions concerning the installation of a BESS in one of the substations in Madeira.

The present version aims at complementing the previous report by providing an in-depth assessment of pilots 1, 3, and 5. More precisely, for each pilot, data from both the real-world deployments and simulations are put together to assess the effectiveness of the deployed storage control algorithms, each of which targeted a different purpose. To this end, several performance indicators have been considered, including rates of self-consumption (SC) and self-sufficiency (SS).

This document contains four additional chapters. Chapter 2 provides an update to the Energy Management System and the BESS that supported the three pilots. Chapter 3 provides an assessment of the first two pilots, namely optimization of self-consumption of PV production in domestic and commercial installations. Chapter 4, on the other hand, provides an assessment of pilot number 5, optimization of energy storage for providing grid stability at the substation level. Finally, chapter 5 concludes this report with an overview of the obtained results and their main implications for the implementation of smart grids in the real world.

[1] https://cordis.europa.eu/project/id/731249

2 Overview of Main Technologies

This chapter provides an overview of the main enabling technologies for these three pilots, namely the Energy Management System (from PRSMA) and the BESS (from Lithium Balance).

2.1 Energy Management System

The *EnergySpectrum* system, from now on referred to as EMS, is a proprietary platform from PRSMA that is the backbone of the Madeira demonstrator in the SMILE project. More precisely, the EMS provides data storage, access, processing, and remote control of the hardware components that supported the five pilots in Madeira Island, as shown in Figure 2.1.

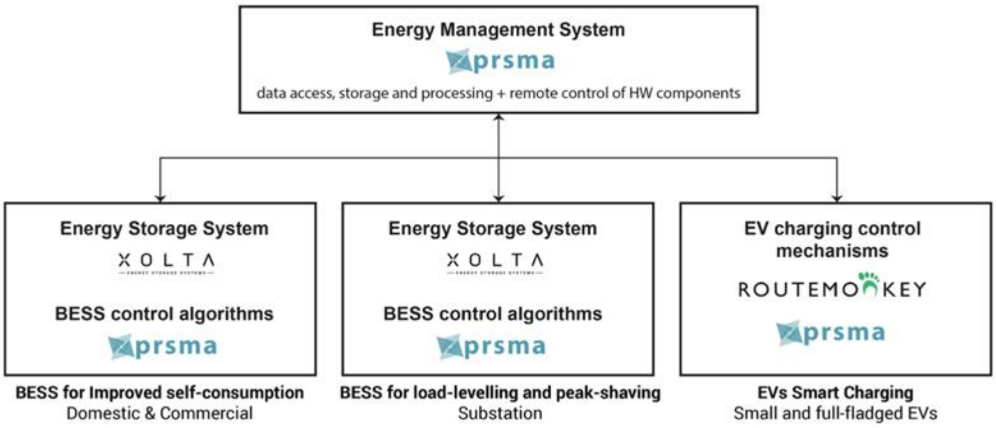


Figure 2.1: Overview of the organization of the five pilots in Madeira Island and their relation to the EMS.

This chapter provides an updated overview of the EMS main components and implementation details, with a particular focus on the aspects related to pilots 1 and 2 (BESS for improved self-consumption in domestic and commercial micro-producers), and 5 (BESS for load-levelling peak-shaving at the substation).

2.1.1 Main Components and Technical Specifications

The EMS has five main components. 1) the back-end, 2) the front-end, 3) the gateway, 4) storage control, and 5) EV charging control. Figure 2.2 illustrates the main components of the EMS and their respective interactions. Note that the only hardware that is part of the EMS package is an optional gateway to account for the situation in which the data is not already uploaded to a cloud-based system.

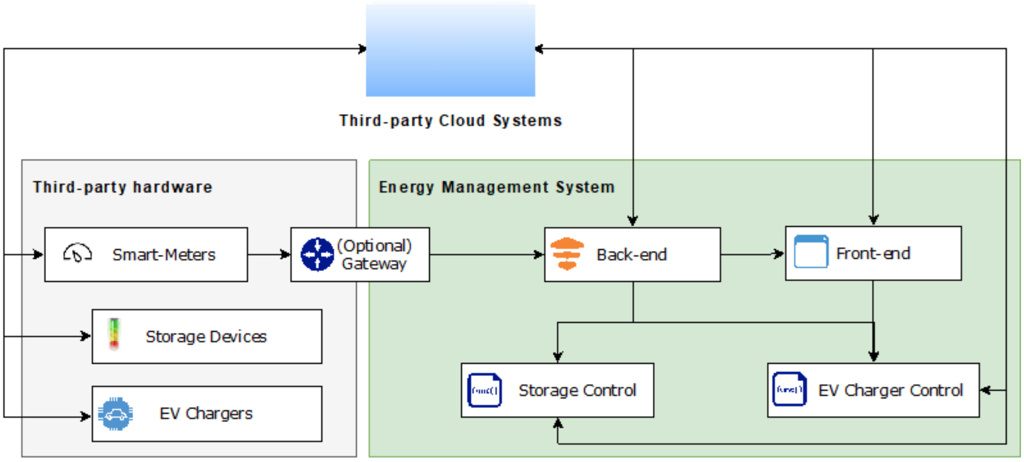


Figure 2.2: Diagram depicting the main components of the EMS and the respective interactions between each other.

From a technical perspective, the EMS consists of two main layers: the operational technology (OT) and the information technology (IT) layers. The former consists mostly of the hardware components (in this case, the smart meters, EV charging stations, and gateways), whereas the latter consists mostly of software components (e.g., databases, web services, and control algorithms). A simplified representation of the EMS architecture is provided in Figure 2.3, which also includes an illustration of the integration with third-party cloud services, namely the Route Monkey (RM) and XOLTA.

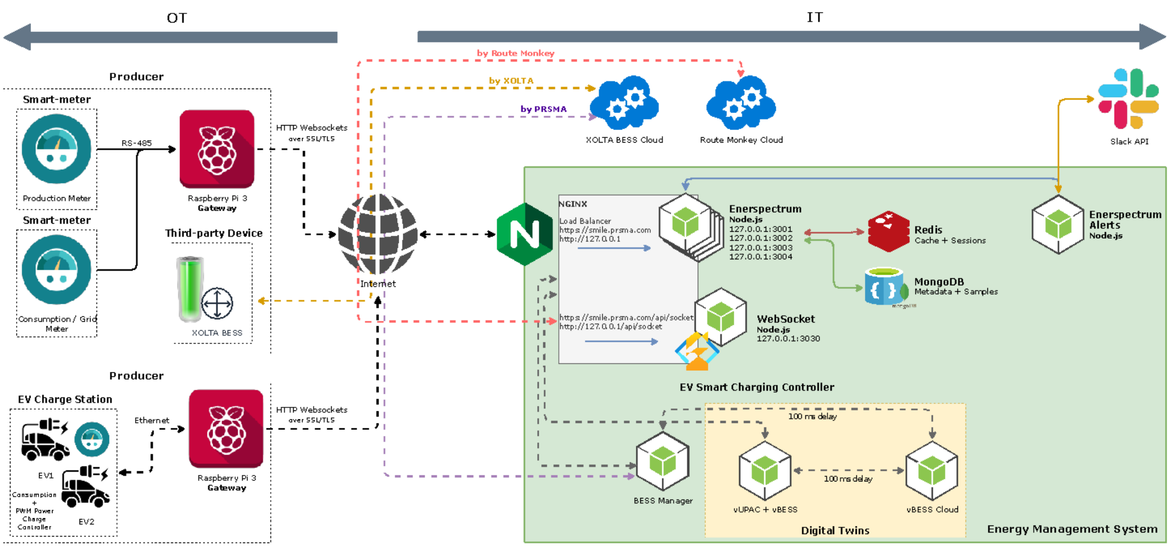


Figure 2.3: Representation of the EMS architecture, as deployed for SMILE in Madeira Island. In this diagram, only prosumers monitoring (pilots 1 and 2), and EV charging (pilot 3) are represented.

As it can be observed, the data is persisted using NoSQL databases, more precisely, MongoDB. Furthermore, in order to speed-up query operations, a cache mechanism has been put in place using Redis, which is an in-memory data structure store.

All the operations related to storage are performed on the **BESS Manager (BM)** entity. More precisely, this entity has three main responsibilities: 1) read telematic data from the XOLTA BESS cloud (XBC), e.g., SOC, 2) run the control strategies for each BESS (e.g., greedy control), and 3) send control commands to the XBC. All the communications between the XBC and the BESS are taken care of by XOLTA.

The operations related to EV charging, i.e., data access and control, are performed on the **EV Smart Charging Controller (EVSCC)** entity. This is, however, out of the scope of this document. The interested reader should refer to deliverable D4.11 [2].

Finally, to enable real-time simulations, the IT layer was upgraded with the integration of Digital Twins (DT) of the main components in the overall system. More concretely, the UPACs, BESS, and the XBC. Note that the BESS Manager communicates with the **Virtual BESS cloud** (vBC), which is a digital replica of the XBC. The vBC, in turn, communicates with the **Virtual UPACs** (vUPAC) and **Virtual BESS** (vBESS). Finally, the vUPACs are updated at the same rate as the "real" UPACs, thus enabling real-time simulations.

2.1.1.1 XOLTA BESS Cloud and Virtual BESS Cloud

The virtual BESS cloud platform was implemented following the specifications provided by XOLTA with respect to the API of the actual XBC. More precisely, the vBESS cloud allows two simulations modes: 1) single action and 2) multiple actions. In the single-action mode, only one setpoint can be sent at a time. This setpoint remains active until another one is sent or the battery reaches the minimum or maximum SOC. In contrast, in the multiple action mode, several setpoints are sent at a time. In this mode, the BESS controller will keep executing the last setpoint until either a new command is sent or the BESS cannot fulfil the request (i.e., the minimum or maximum SOC are reached).

A simplified overview of the requests is shown in Table 2.1. In ideal circumstances (e.g., no network or data failure), the two modes will produce the same results, i.e., the battery will charge 1kW between 12:00 and 12:01 and 2kW between 12:01 and 12:02. Yet, if something wrong happens, the modes will have different outputs. For example, if at 12:01 it is not possible to send the command (e.g., due to network error), at the single-action mode, the battery will continue to charge at 1kW unless the minimum or maximum SOC are reached, and at the multiple actions mode the battery would stop because of the 0kW setpoint sent for to account for situations in which that minute in not being updated.

Ultimately, and considering the real-world nature of our deployments, it was decided to use the multi-action strategy, where each calculated setpoint is followed by a reset setpoint (0kW). Furthermore, it was decided that a new control action would be sent every two minutes.

Table 2.1: Single vs Multiple actions mode - example of sequence of commands sent to the BESS cloud.

ID	Single Action	Multiple Actions
1	06-11-2019 12:00 | 1 kW	06-11-2019 12:00 | 1 kW 06-11-2019 12:05 | 0 kW
2	06-11-2019 12:01 | 2 kW	06-11-2019 12:01 | 2 kW 06-11-2019 12:06| 0 kW
3	06-11-2019 12:10 | 3 kW	06-11-2019 12:10 | 3 kW 06-11-2019 12:15 | 0 kW

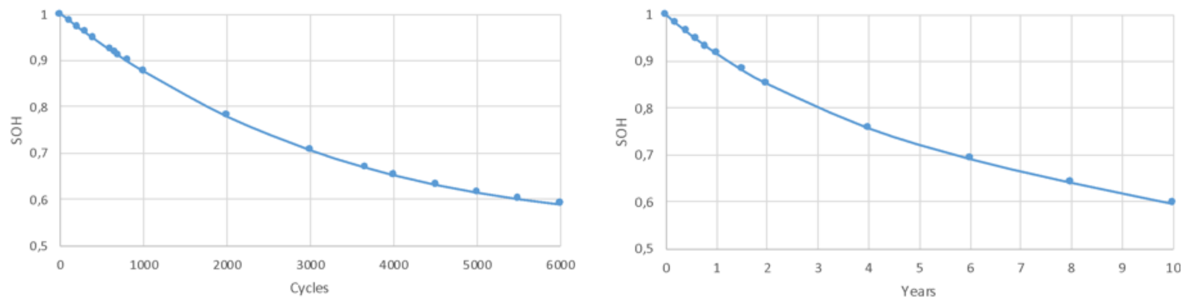
2.1.1.2 Virtual BESS

A simple BESS was modelled and used as virtual replicas of the deployed energy storage systems. The modelled BESS consists of two main components: 1) battery model and 2) inverter module.

Battery Module

The battery module has six tunable parameters, five of which remain unchanged for the simulation's entire duration: nominal capacity (kWh), rated power (kW), SOC_{min} (%), SOC_{max}(%), initial SOC (%), and initial SOH (%). The only setting that changes as the simulation proceeds is the battery capacity due to the SOH degradation.

Concerning the degradation model, XOLTA does not disclose this information. Therefore, the Tesla Powerwall ageing curves were used instead. More precisely, exponential functions were fitted to the data on the warranty sheet, similarly to what was done in SimSES [3]. Ultimately, two different ageing models were obtained: 1) cycles ageing 2) calendar ageing. The cycle and calendar ageing are illustrated in Figure 2.4



a) Cycles Aging

b) Calendar Aging

Figure 2.4: Cyclic and calendric battery degradation models.

As can be observed, after one year, the SOH will degrade by 8.4% (to 91.6%). In contrast, to achieve the same degradation due to cyclic ageing, the battery needs to perform approximately 650 cycles, which is almost 1.8 cycles per day, during one year. Therefore, to achieve a gradual reduction of the SOH, the degradation is calculated at each step of the simulation by taking the maximum value between cycle and calendar ageing.

Finally, it is essential to remark that this degradation model assumes that the battery reaches the end-of-life at 60% SOH, which is achieved after 6000 cycles at 90% depth of discharge (DoD) (cyclic Aging) or after ten years (calendar aging). Note, however, that as storage technology keeps evolving, in particular Lithium-Ion, it is expected that such devices will easily reach at least 15 years of calendric life, which much lower cycle degradation rates.

Inverter Module

The inverter module has two tuneable parameters, the rated power (kW) and efficiency (%). While the former is fixed according to the characteristics of the physical counterpart, the latter can be either fixed or based on the rated power.

In this case, it was decided to vary the inverter efficiency according to the rated power. More precisely, the power transfer efficiency of the inverter is obtained through the following Equation, where P is the power being transferred, andP_{inv} is the inverter rated power [4].

$$\eta = \frac{\frac{P}{P_{inv}}}{\frac{P}{P_{inv}} + 0.0072 + 0.0345 * \left(\frac{P}{P_{inv}}\right)^2} \qquad (1.1)$$

Figure 2.5 shows the efficiency in function of the inverter size and the amount of power to be transferred for inverters with rated power between 0.75 kW and 3 kW. As it can be observed, at lower power thresholds there is a considerable degradation of the inverter efficiency. In other words, lower inverter setpoints tend to be penalized over the higher ones. However, it can also be observed that as the setpoint reaches the rated power of the inverter, there is also a slight decrease in the inverter efficiency.

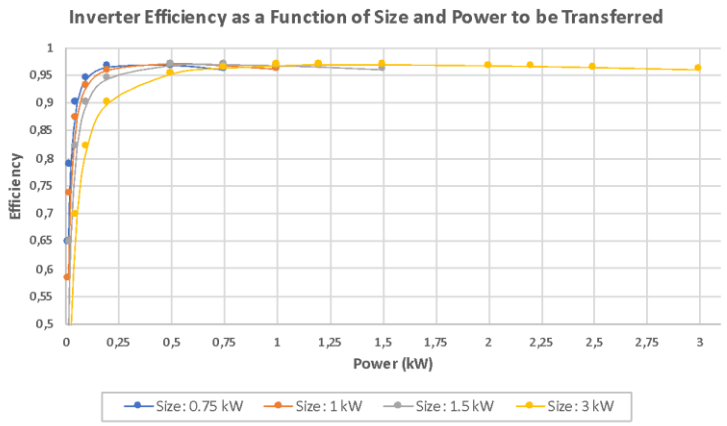


Figure 2.5: Inverter efficiency as a function of its size and the amount of power to be transferred.

2.2 Battery Energy Storage Systems

The SMILE partner Lithium Balance provided the energy storage hardware for the Madeira pilots. Next, a brief description of the BESS is provided. Details of the installation process are provided in deliverable D4.7, and thus omitted in this report.

2.2.1 Domestic and Commercial UPACs

In the concrete case of domestic and commercial UPACs, the following BESS were provided:

- 4 single-phase 3kW/8.6kWh residential BESS, to be deployed in four domestic UPACs as part of the pilot number 1.
- 3 single-phase 3kW/8.6kWh residential BESS, to be deployed on a three-phase commercial UPACs as part of the pilot number 2.

Overall, the residential BESS provided by Lithium Balance consists of the following components:

- Interconnected battery cells making up the battery system;
- The battery protection unit (BPU) – a set of switching and current sensing devices controlled by the underlying battery management system (BMS)
- The BMS, responsible for battery safety, control of BPU, monitoring and diagnostic of the BESS;
- The inverter – a bidirectional power converter DC/AC. Single phase inverters are used for 3kW/8.6kWh systems.
- A site controller – a local controller responsible for inverter control and its safe connection and disconnection, collecting all relevant data and transferring them to the EMS (e.g., SOC) and receiving control signals from the EMS (e.g.., active power setpoints) using cloud-to-cloud communication protocols.

The following block diagrams represent the different components that comprise the domestic BESS. Figure 2.6 represents the single-phase BESS deployed in pilot number 1, whereas Figure 2.7 represents the three single-phase BESS deployed in pilot number 2.

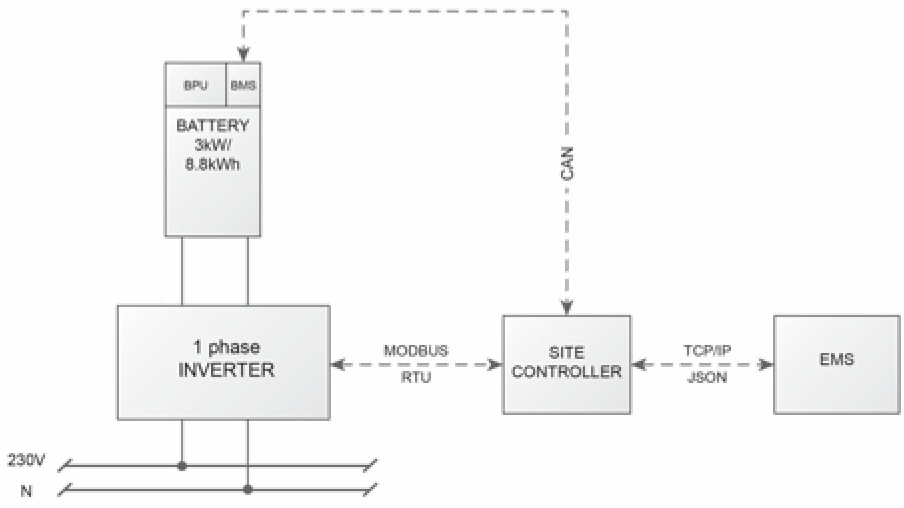


Figure 2.6: Block diagram of the single-phase LIBAL 3kW/8.6kWh BESS and communication with the EMS. (Application: improving self-consumption of the domestic UPACs – pilot study 1).

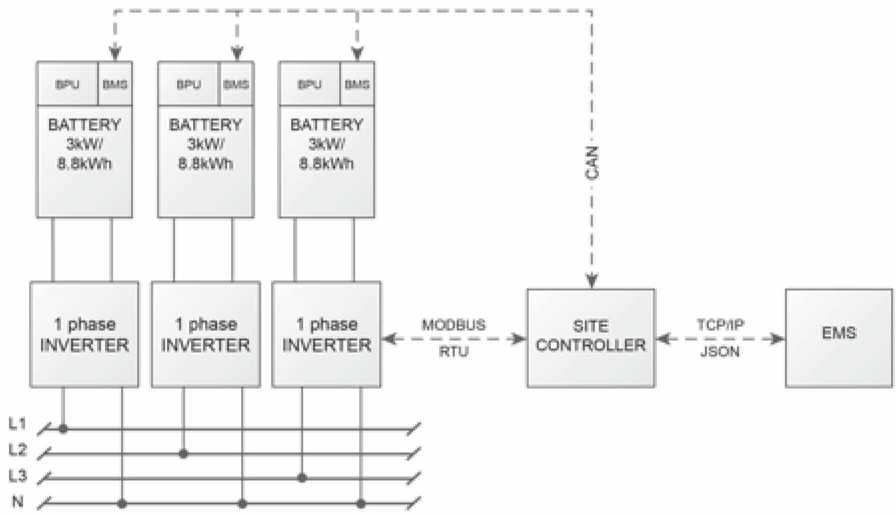


Figure 2.7: Block diagram of the three single-phase Lithium Balance 3kW/8.6kWh BESS and communication with the EMS. (Application: improving self-consumption on commercial UPACs – pilot study 2).

The main parameters of the residential systems are presented in Table 2.2.

Table 2.2: Main parameters of the residential battery.

Item	Value	Unit
Dimensions (height*width*depth))	40*44*29.5	cm
Battery type	LPF	-
Power	3.0	kW
Nominal battery DC voltage	48	V
Maximum rack voltage	54.75	V
Minimum rack voltage	42	V
Energy content	8.6	kWh

Regarding, the inverter hardware, the Victron MultiPlus-II 48/50/75-50[2] was the selected option. The main parameters of this device are listed in Table 2.3.

Table 2.3: Main parameters of the residential inverter.

Item	Value	Unit
Dimensions (height*width*depth)	56.5*32.8*24	cm
Weight	30	Kg
Type	MultiPlus-II 48/50/75-50	-
Mounting type	Wall mounted	-
Nominal power	3	kW
Max Input Current	50	A
Nominal network voltage	48	V
Maximum Efficiency	96	%
Output Voltage	230 – 2%	V
Output Frequency	50	Hz
Main features	Dynamic power control (P) and reactive power control (Q)	
	Power Control and Power Assist	
	Remote ON/OFF	

2.2.2 Distribution Substation

Regarding the distribution substation, the following BESS was installed:

- One 40kW/80 kWh LIBAL BESS (1 rack) with a three-phase ABB inverter deployed on the selected distribution station in Madeira Island.

The BESS provided by Lithium Balance consists of:

- Interconnected battery cells making up the battery system;
- The battery protection unit (BPU) – a set of switching and current sensing devices controlled by the underlying battery management system (BMS)
- The BMS, responsible for battery safety, control of BPU, monitoring and diagnostic of the BESS;
- The inverter – a bidirectional power converter DC/AC. A three-phase inverter will be used for this 40kW/80kWh system.
- A site controller – a local controller responsible for inverter control and its safe connection and disconnection, collecting all relevant data and transferring them to the EMS (e.g., SOC) and receiving control signals from the EMS (e.g.., active power setpoints) using cloud-to-cloud communication protocols.

The block diagram in Figure 2.8 presents the BESS structure:

[2] https://www.victronenergy.com/inverters-chargers/multiplus-ii

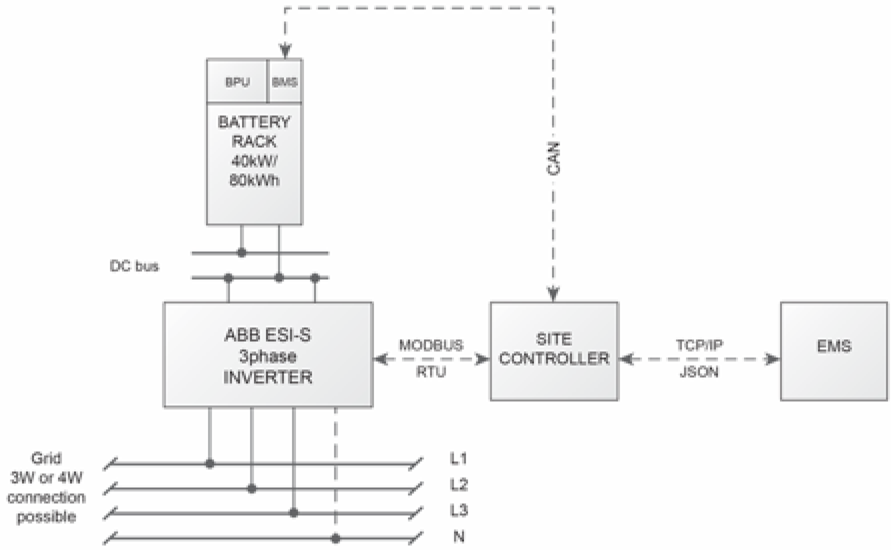


Figure 2.8: Block diagram of the Lithium Balance 40kW/80kWh BESS and communication with EMS (application: grid support)

The main parameters of the grid support system are presented in Table 2.4.

Table 2.4: Main parameters of the substation BESS

Item	Value	Unit
Dimensions (height*width*depth)	Not Available	cm
Battery type	NMC	-
Number of racks	1	-
Power	50	kW
Nominal battery DC voltage	700.8	V
Maximum rack voltage	806.4	V
Minimum rack voltage	499.2	V
Energy content	80	kWh

The grid support BMS is provided by an ABB ESI-S[3] inverter, with the unique function of reducing power losses for improving system economy (very low standby power consumption). Lithium Balance provides the inverter together with AC side grid filter and AC contactors. The main parameters of the inverter are presented in Table 2.5.

Table 2.5: The main parameters of the ABB ESI-S inverter

Item	Value	Unit
Dimensions (height*width*depth)	58.5*32.6*75.5	cm
Type	ESI-S – IP30	-
Mounting type	Wall mounted	-
Nominal power	40	kW
Rating	60	Arms

[3] ABB ESI-S inverter, https://new.abb.com/high-voltage/capacitors/lv/energy-storage-inverters-esi

Item	Value	Unit
Nominal network voltage	400	V
DC voltage control range	585 – 830	V
Main features	Dynamic power control (P) and reactive power control (Q)	
	Individual power control per phase *	
	Harmonic mitigation up to the 50^{th} *	
	Stepless reactive power compensation	
	Load balancing (3-Phases/ 3-Phases + Neutral) *	
	Islanding mode	
	Black start (as an option)	
	LVRT (Low Voltage Ride Through)	
	Modularity (several units can be put in parallel) for high-current applications	
* available only for 4-W device	Full redundancy and flexibility (master/master configuration and independent DC busses) *	

3 Pilot Assessment: Domestic and Commercial UPACs

This chapter presents the technical assessment of the pilots conducted in the domestic and commercial UPACs, namely pilot 1 and 2. The chapter is organized in four main sections. Section 3.1 provides the content and background information necessary to understand the remaining sections of the chapter. Section 3.2 presents and describes the storage control algorithms that were used in the two pilots. Section 3.3 describes the assessment methodology, including the considered performance indicators. Finally, the assessment results are presented and discussed in section 3.4.

3.1 Context and Background Information

3.1.1 Low Voltage Peak Power Contract and Power Tariffs

In Portugal, the electricity supply contracts and tariffs are defined by the national energy services regulator (ERSE[4]). For low-voltage (LV) consumers, the electricity bill consists of two components: a fixed component that depends on the peak contracted power (kVA), and a dynamic part governed by the actual energy consumption (kWh).

The customers select the peak power contract (PPC) based on their estimated electricity needs. The available PPCs range from 3.45 to 20.70 kVA, each of which has an associated daily fee [5]. Changes to the PPC require a formal request to the DSO, and, if accepted, a certified electrician performs the change in the customers' energy meter.

Concerning the dynamic component, there are three tariffs available: a single-rate (SR), a Two Time-of-Use (2-TOU), and a Three TOU (3-TOU). The active energy rates, in Euros per kWh, according to each tariff and billing period are presented in Table 3.1. The daily variations of the active energy prices are illustrated in Figure 3.1.

Table 3.1: Active energy prices, in Euros per kWh, according to each tariff and billing period as of 2018.

<table>
<tr><th>Period</th><th>Single-Rate</th><th>2-TOU</th><th>3-TOU</th></tr>
<tr><td>Off-peak</td><td rowspan="3">0.1629 €</td><td>0.0982 €</td><td>0.0982 €</td></tr>
<tr><td>Half-peak</td><td rowspan="2">0.1894 €</td><td>0.1716 €</td></tr>
<tr><td>Peak</td><td>0.2153 €</td></tr>
</table>

4 https://www.erse.pt/en/home

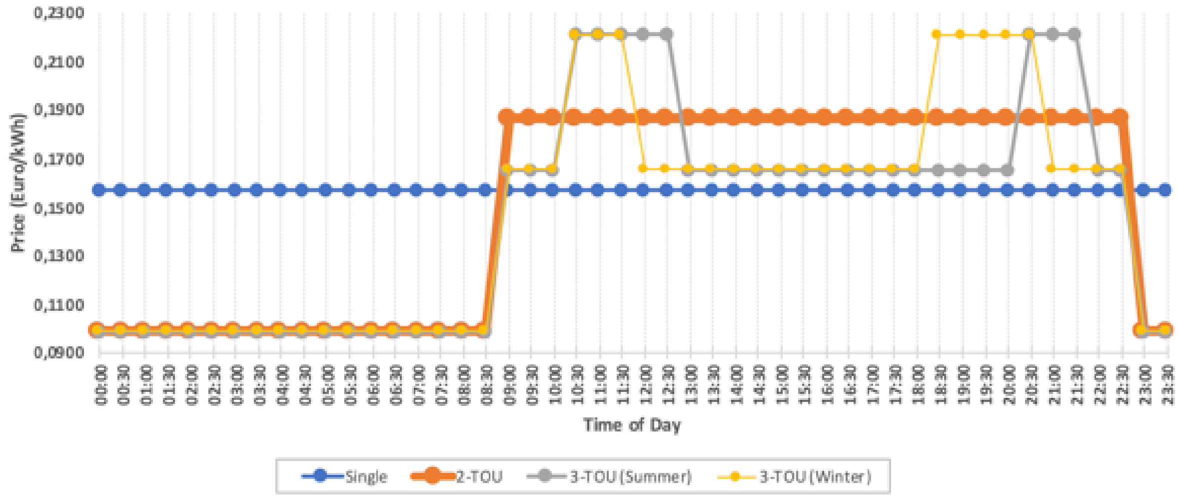


Figure 3.1: Daily variation of active energy rates per kWh according to the available tariffs as of 2018.

3.1.2 Overview of the Selected UPACs

The first version (D4.7) of this deliverable provides detailed description of the selection process for the UPACs that were the best candidates to receive a BESS. More precisely, one year of consumption and production data (2018-10-01 00:00:00 to 2019-09-30 23:59:59) were used to conduct simulations considering the presence of storage devices. Ultimately, this led to the pre-selection of six UPACs, that were later narrowed down to the four UPACs that ended up received the BESS. The details of the selected UPACs are presented in Table 3.2.

Table 3.2: Final disposition of the selected UPACs. PPC: Peak Power Contract, IPV: Installed PV, D: Domestic, C: Commercial.

UPAC	Type	PPC (kVA)	IPV (kWp)	Tariff	BESS Configuration
U9	D	6.9	4.5	Single Rate	3 kW / 8.6 kWh Single-phase
U6	D	10.45	2.7		
U2	D	6.9	2.25		3 kW / 8.6 kWh Single-phase [a]
U13	D	10.45	4.5		
U8	C	20.7	3.92	2 TOU	3 kW / 8.6 kWh Three-phase [b]

[a] Since U2 and U13 have three-phase consumption and single-phase solar PV production, the BESS were installed in same phase as the solar PV.

[b] U8 has three-phase consumption and solar PV production. Thus, one BESS system will be installed in each phase. Note that despite the total installation amounts to 9 kW / 28.8 kWh, the upper limits in each phase are still 3 kW / 8.6 kWh.

3.2 Battery Control Algorithms

Two control algorithms have been implemented in the case of the domestic UPACs: 1) greedy control, and 2) greedy control with pre-charge.

The *greedy control algorithm* is a standard operation strategy in self-consumption scenarios, shown to be optimal in self-consumption only scenarios with a flat-rate energy price. It works by determining the net-load (i.e., the difference between production and consumption) and actuating the battery accordingly. I.e., storing excess production until the upper State of Charge (SOC) limit is reached or supplying the excess demand from the battery until the lower SOC is reached, as described in detail in deliverable D4.5, section 2.2.1 [6].

The *greedy control with pre-charge algorithm* uses the greedy strategy during peak hours, i.e., from 9AM to 11PM. During the off-peak hours, 11PM and 9AM, the battery is charged to a pre-calculated SOC and is not allowed to discharge until the peak period starts.

The amount of pre-charge depends on the battery's capacity and on the electricity demand during the peak periods. It is calculated using Equation (3.1), rounded to the next multiple of 5. $P_{G\_L}(PH)$ is the daily average consumption from the grid during the peak hours (PH), P_{PV_G} is the daily average PV production that is injected in the grid, and *BNC* is the battery nominal capacity in kWh. Both $P_{G\_L}(PH)$ and P_{PV_G} were calculated using one year of historical data.

$$SOC_{pc} = min\left(\frac{P_{G\_L}(PH) - P_{PV\_G}}{BNC} + SOC_{min}, SOC_{max}\right) \quad (3.1)$$

3.3 Assessment Methodology

The assessment is made on top of the data collected from the real-world deployment, for a period of 12 consecutive months. The data was then grouped by month and season, to enable a more granular analysis of the results. Particularly, by analyzing the results per season it is possible to understand the effects of the weather changes.

For each UPAC, the following KPIs are calculated in both real-world and simulation settings:

- *Degree of self-supply* before and after the BESS installation (%): Measures the percentage of PV generation which is used for self-supply, and not sold to the grid / curtailed. This is the same as *Self-Consumption (SC)*, which is the term that is used in this report.
- *On-site energy ratio* before and after the BESS installation (%): Measures the relation between the energy supply from local renewable sources and the total energy demand. This is the same as *Self-Sufficiency (SS)*, which is the term that is used in this report.
- *Monetary Savings* before and after the BESS installation (Euros): Measures the saving in Euros from owning just a PV or a PV + BESS, taking into consideration the rates in place during the deployment.
- Number of *battery cycles*: This is an estimate of the number of cycles performed by the battery and provides a very good indication of the degree of usage of a BESS. One cycle refers to a full charge and discharge cycle, at 70% DoD.

For the real-world deployment, the following indicators are also calculated:

- *Available data:* refers to the ratio between the consumption and PV production data that is available and what was expected. This is an indicator of the AMI stability.
- BESS uptime: refers to ratio between the amount of data points available and what was expected. This is an indicator of the stability of the cloud-2-cloud infrastructure for storge control.

3.4 Results and Discussion

3.4.1 Domestic: UPAC 2

UPAC 2 has a single-phase power contract and owns a single-phase PV installation with a kWp of 2.25. The tariff in place is the single-rate, therefore, it was only possible to deploy the greedy control strategy.

For this UPAC, the year-long analysis was done for the period between September 2020 and August 2021. The results of the real-world deployment are summarized in Figure 3.2.

Year	Season	Month	Available Data (%)	PV (kWh)	Load (kWh)	PV Only					PV + BESS							
						SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	Estimated Cycles	Uptime	Savings (€) BESS	Savings (€) Total
2020	Autum	Sep	99.67%	291.55	487.32	143.06	148.49	49.1%	29.4%	23.30	260.57	36.64	89.4%	53.5%	21.2	97.0%	19.14	42.45
		Oct	99.15%	260.36	479.84	128.76	131.60	49.5%	26.8%	20.97	167.63	95.54	64.4%	34.9%	7.3	92.2%	6.33	27.31
		Nov	100.00%	218.70	534.30	120.80	97.89	55.2%	22.6%	19.68	195.39	28.46	89.3%	36.6%	14.7	97.0%	12.15	31.83
			99.61%	**770.6**	**1501.5**	**392.6**	**378.0**	**50.9%**	**26.1%**	**64.0**	**623.6**	**160.7**	**80.9%**	**41.5%**	**43.2**	**95.4%**	**37.6**	**101.6**
2021	Winter	Dec	99.99%	205.34	721.00	141.14	64.20	68.7%	19.6%	22.99	185.99	22.81	90.6%	25.8%	9.0	90.3%	7.31	30.30
		Jan	54.19%	97.77	456.29	76.47	21.31	78.2%	16.8%	12.46	91.69	7.15	93.8%	20.1%	2.9	99.2%	2.48	14.94
		Feb	79.98%	251.74	513.11	154.79	96.95	61.5%	30.2%	25.22	230.76	27.67	91.7%	45.0%	14.6	99.9%	12.38	37.59
			78.05%	**554.9**	**1690.4**	**372.4**	**182.5**	**67.1%**	**22.0%**	**60.7**	**508.4**	**57.6**	**91.6%**	**30.1%**	**26.5**	**96.4%**	**22.2**	**82.8**
	Spring	Mar	99.25%	330.46	399.76	140.15	190.30	42.4%	35.1%	22.83	253.29	101.63	76.6%	63.4%	25.5	92.5%	18.43	41.26
		Apr	100.00%	302.95	349.03	120.77	182.18	39.9%	34.6%	19.67	240.42	73.01	79.4%	68.9%	22.8	89.6%	19.49	39.16
		May	97.38%	346.66	362.00	124.82	221.84	36.0%	34.5%	20.33	263.81	95.60	76.1%	72.9%	25.8	99.9%	22.64	42.97
			98.87%	**980.1**	**1110.8**	**385.7**	**594.3**	**39.4%**	**34.7%**	**62.8**	**757.5**	**270.2**	**77.3%**	**68.2%**	**74.2**	**94.0%**	**60.6**	**123.4**
	Summer	Jun	44.22%	131.91	206.22	58.45	73.46	44.3%	28.3%	9.52	97.79	37.90	74.1%	47.4%	7.8	100.0%	6.41	15.93
		Jul	99.94%	356.46	412.03	144.40	212.06	40.5%	35.0%	23.52	252.16	112.33	70.7%	61.2%	19.7	99.0%	17.55	41.08
		Aug	99.85%	327.08	356.53	141.31	185.77	43.2%	39.6%	23.02	280.51	54.53	85.8%	78.7%	26.0	99.9%	22.68	45.70
			81.33%	**815.5**	**974.8**	**344.2**	**471.3**	**42.2%**	**35.3%**	**56.1**	**630.5**	**204.8**	**77.3%**	**64.7%**	**53.5**	**99.6%**	**46.6**	**102.7**
Grant Total			**89.47%**	**3121.0**	**5277.4**	**1494.9**	**1626.0**	**47.9%**	**28.3%**	**243.5**	**2520.0**	**693.3**	**80.7%**	**47.8%**	**197.4**	**96.4%**	**167.0**	**410.5**

Figure 3.2: Year-long real-world results for UPAC 2 considering the greedy strategy.

Regarding the uptime of the systems, both AMI and BESS, the results show an average of 89.5% and 96.4%, respectively. With respect to the AMI, the overall uptime is heavily affected by the months of January and June, where due to issues with the Internet and the AMI gateway. Concerning the estimated number of cycles, the results show a total of less than 200, which corresponds to less that one cycle per day. Furthermore, the results also show that in October, January and June, the number of cycles is much lower than in the others months. There are two main reasons for this, first, the missing data in January and June, and second, an internal (random) issue with the inverter device that was not able to accommodate the requests sent from the control algorithms.

Considering the year-around results, it is possible to observe an increase of self-consumption from 48% to 81% (an increase in the order of 41%.). Nevertheless, it is also possible to observe that even with a SC rate of 81%, the SS rate is still less than 50%, which is a clear indicator that in the UPAC the PV installation is slightly under-sized.

Looking at the results from the different seasons, it is possible to observe that Winter is the most complicated season, since this is when the PV production is lower, and the consumption is higher, due to the Holliday's seasons. Ultimately, this is reflected by a much lower rate of self-sufficiency, despite the increase in the self-consumption rates.

To further understand the results obtained in the real-world deployment, **Figure 3.3** shows the energy flows and battery SOC for one week in December (left), and the month of August (right). As it can be observed, the amount of surplus of PV production is very low during the winter, which leads to an under-use of the BESS. In contrast, during August the amount of surplus PV production is considerably high, still not enough to produce at least of one battery cycle per day. Ultimately, this suggest that under the current PV installation and average demand, a slightly lower battery (~80% of the current nominal capacity) would suffice. Alternatively, this installation could benefit from increasing the PV installation, but this solution alone would not be sufficient to compensate the lower levels of PV production in the winter months.

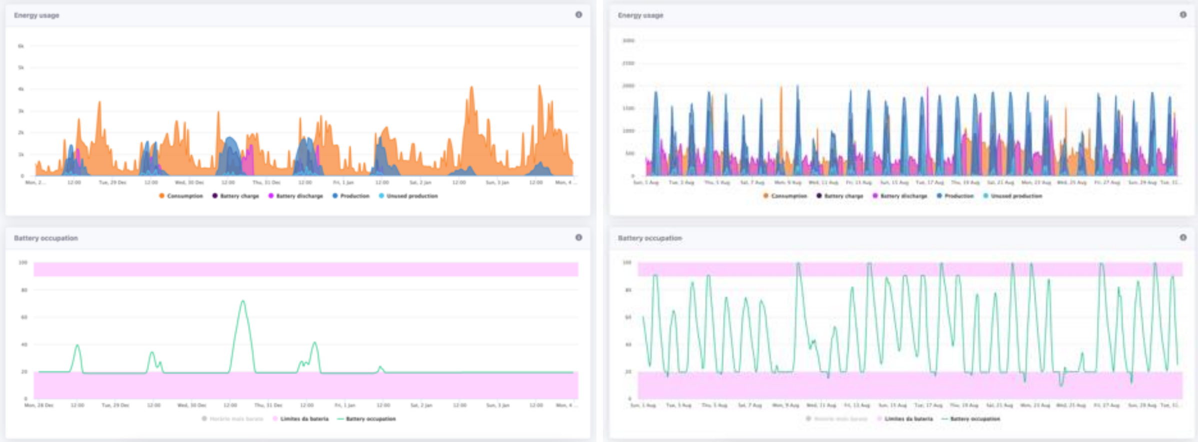


Figure 3.3: Energy flows and battery SOC for one week in December (left) and August (right) in UPAC 2

Simulations with Digital Twins

In order to understand the full potential of BESS in this UPAC, simulations were also conducted using the Digital Twins platform. The simulations were conducted using data for the same period, considering one-minute averages of PV production and consumption. Ultimately, such simulations correspond to an approximation of the optimal solution where the storage control would be performed locally.

The first simulation corresponds to the greedy control strategy that was deployed in the real-world. The obtained results and shown in Figure 3.4.

Year	Season	Month	PV (kWh)	Load (kWh)	PV Only					PV + BESS						
					SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	Estimated Cycles	Savings (€) BESS	Savings (€) Total
2020	Autum	Sep	291.89	489.34	152.53	139.36	52.3%	31.2%	24.85	278.00	13.90	95.2%	56.8%	23.0	20.44	45.29
		Oct	270.66	496.39	140.38	130.28	51.9%	28.3%	22.87	258.42	12.24	95.5%	52.1%	21.0	19.23	42.10
		Nov	217.76	533.45	129.51	88.24	59.5%	24.3%	21.10	215.34	2.41	98.9%	40.4%	15.3	13.98	35.08
			780.3	**1519.2**	**422.4**	**357.9**	**54.6%**	**27.9%**	**68.8**	**751.8**	**28.6**	**96.5%**	**49.8%**	**59.3**	**53.6**	**122.5**
	Winter	Dec	216.16	742.58	152.00	64.16	70.3%	20.5%	24.76	216.16	0.00	100.0%	29.1%	11.3	10.45	35.21
2021		Jan	233.16	687.02	176.69	56.48	75.8%	25.7%	28.78	233.16	0.00	100.0%	33.9%	9.9	9.20	37.98
		Feb	284.46	573.62	194.62	89.84	68.4%	33.9%	31.70	282.54	1.92	99.3%	49.3%	15.6	14.32	46.03
			733.8	**2003.2**	**523.3**	**210.5**	**71.5%**	**26.7%**	**85.2**	**731.9**	**1.9**	**99.8%**	**37.4%**	**36.8**	**34.0**	**119.2**
	Spring	Mar	347.29	413.76	158.95	188.34	45.8%	38.4%	25.89	314.01	33.28	90.4%	75.9%	27.4	25.26	51.15
		Apr	307.15	347.26	129.23	177.92	42.1%	37.2%	21.05	265.11	42.03	86.3%	76.3%	24.3	22.13	43.19
		May	360.89	376.54	140.44	220.45	38.9%	37.3%	22.88	284.94	75.95	79.0%	75.7%	25.9	23.54	46.42
			1015.3	**1137.6**	**428.6**	**586.7**	**42.3%**	**37.6%**	**69.8**	**864.1**	**151.3**	**85.2%**	**76.0%**	**77.6**	**70.9**	**140.8**
	Summer	Jun	297.49	476.46	179.85	117.64	60.5%	37.7%	29.30	283.06	14.43	95.1%	59.4%	18.1	16.81	46.11
		Jul	377.66	423.51	162.47	215.19	43.0%	38.4%	26.47	315.56	62.10	83.6%	74.5%	27.0	24.94	51.40
		Aug	340.95	369.96	155.81	185.14	45.7%	42.1%	25.38	298.63	42.32	87.6%	80.7%	25.6	23.27	48.65
			1016.1	**1269.9**	**498.1**	**518.0**	**49.7%**	**39.4%**	**81.1**	**897.3**	**118.9**	**88.8%**	**71.5%**	**70.7**	**65.0**	**146.2**
Grand Total			**3545.5**	**5929.9**	**1872.5**	**1673.0**	**54.5%**	**32.9%**	**305.0**	**3244.9**	**300.6**	**92.6%**	**58.7%**	**244.4**	**223.6**	**528.6**

Figure 3.4: Year-long simulation results for UPAC 2 considering the greedy strategy.

It can be observed that through simulation there is an increase in both SC and SS rates, much of which happens due to the faster storage control (once per minutes vs. two per minute in the real-world).

Again, similar to the real-world case, in the Autumn and Winter the levels of SC are much higher, but this does not correspond to a large increase in the SS.

Concerning the number of cycles, a natural increase is observed, both due to the stability of the simulation that is free of hardware errors, but also due to the fact that through simulation one control setpoint is considered every minute.

Finally, considering the fact that this UPAC has a considerably high level of consumption for the size of the PV installation, it was also interesting to assess the effects of pre-charging the storage device in the off-peak periods. To this end, the second simulation corresponds to the pre-charge algorithm with a calculated pre-charge percentage of 40%, and assumes that the 2-TOU tariff is in place. The obtained results are presented in Figure 3.5.

Year	Season	Month	PV (kWh)	Load (kWh)	PV Only					PV + BESS								
					SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	OPE (€)	OPE	Estimated Cycles	Savings (€) BESS	Savings (€) Total
2020	Autum	Sep	291.89	489.34	152.53	139.36	52.3%	31.2%	34.69	256.66	35.23	87.9%	52.5%	51.60	10.5%	25.3	23.74	58.44
		Oct	270.66	496.39	140.38	130.28	51.9%	28.3%	31.83	242.96	27.70	89.8%	48.9%	53.32	10.7%	26.1	24.71	56.54
		Nov	217.76	533.45	129.51	88.24	59.5%	24.3%	29.10	208.94	8.82	96.0%	39.2%	51.60	9.7%	22.7	20.88	49.99
			780.3	**1519.2**	**422.4**	**357.9**	**54.6%**	**27.9%**	**95.6**	**708.6**	**71.8**	**91.2%**	**46.9%**	**156.52**	**10.3%**	**74.1**	**69.3**	**165.0**
2021	Winter	Dec	216.16	742.58	152.00	64.16	70.3%	20.5%	34.45	215.86	0.30	99.9%	29.1%	53.32	7.2%	20.0	17.81	52.27
		Jan	233.16	687.02	176.69	56.48	75.8%	25.7%	38.10	233.16	0.00	100.0%	33.9%	53.32	7.8%	18.9	15.91	54.01
		Feb	284.46	573.62	194.62	89.84	68.4%	33.9%	42.10	280.29	4.18	98.5%	48.9%	48.16	8.4%	22.7	21.18	63.28
			733.8	**2003.2**	**523.3**	**210.5**	**71.5%**	**26.7%**	**114.7**	**729.3**	**4.5**	**99.5%**	**37.3%**	**154.80**	**7.8%**	**74.1**	**54.9**	**169.6**
	Spring	Mar	347.29	413.76	158.95	188.34	45.8%	38.4%	34.10	273.89	73.40	78.9%	66.2%	53.32	12.9%	23.6	24.31	58.41
		Apr	307.15	347.26	129.23	177.92	42.1%	37.2%	28.04	222.32	84.82	72.4%	64.0%	51.60	14.9%	19.1	18.68	46.72
		May	360.89	376.54	140.44	220.45	38.9%	37.3%	30.20	236.22	124.67	65.5%	62.7%	53.32	14.2%	19.1	18.94	49.13
			1015.3	**1137.6**	**428.6**	**586.7**	**42.3%**	**37.6%**	**92.3**	**732.4**	**282.9**	**72.3%**	**64.3%**	**158.24**	**14.0%**	**74.1**	**61.9**	**154.3**
	Summer	Jun	297.49	476.46	179.85	117.64	60.5%	37.7%	39.09	268.46	29.03	90.2%	56.3%	51.60	10.8%	21.9	20.04	59.13
		Jul	377.66	423.51	162.47	215.19	43.0%	38.4%	34.93	266.28	111.38	70.5%	62.9%	53.32	12.6%	21.4	20.06	54.99
		Aug	340.95	369.96	155.81	185.14	45.7%	42.1%	33.86	243.44	97.51	71.4%	65.8%	53.32	14.4%	17.9	17.51	51.37
			1016.1	**1269.9**	**498.1**	**518.0**	**49.7%**	**39.4%**	**107.9**	**778.2**	**237.9**	**77.4%**	**61.7%**	**158.24**	**12.6%**	**74.1**	**57.6**	**165.5**
Grand Total			**3545.5**	**5929.9**	**1872.5**	**1673.0**	**54.5%**	**32.9%**	**410.5**	**2948.5**	**597.0**	**85.1%**	**52.5%**	**627.80**	**11.2%**	**296.4**	**243.8**	**654.3**

Figure 3.5: Year-long simulation results for UPAC 2 considering the pre-charge strategy.

As it can be observed, the number of cycles during the Winter months have increased considerably, but only slightly on the remaining seasons. Furthermore, it is also possible to observe that in this second scenario there is a slight decrease in the SC and SS rates, due to the fact that, especially in the summer months, pre-charge implies that the early morning excess PV production will not be stored in the battery.

Nevertheless, it is clear that pre-charge can also be a solution for domestic UPACs, especially when they have high consumption and lower PV installations. For example, in this particular case, it was possible to cover an average of 11% of the total demand with energy acquired during the off-peak periods. Ultimately, this not only provides a benefit to the UPAC owner, but also to the grid operator that sees more demand being shifted to off-peak periods.

3.4.2 Domestic: UPAC 6

UPAC 6 has a tri-phase power contract but owns a single-phase PV system with 2.7 kWp. The PV was connected to the phase that has the highest average demand, and consequently the BESS also had to be connected to this phase. The only appliance connected to the remaining two-phases is a motor that is used for irrigation. The tariff in place is also the single-rate, therefore, the greedy control strategy was deployed.

For this UPAC, the year-long analysis was done for the period between September 2020 and August 2021. The obtained results are summarized in Figure 3.6.

Regarding the uptime of the systems, both AMI and BESS, the results show an average of 89.6% and 81.1%, respectively. With respect to the AMI, the overall uptime is heavily affected by the months of September and October due to changes in the electrical infrastructure of UPAC 6, which were unrelated to the SMILE project. Concerning the estimated number of cycles, the results show a total of less than 90, which is a very low number of cycles. Still, the number of cycles is hardly affected by issues will the inverter, similarly to what happened in the previous examined UPAC.

Year	Season	Month		PV (kWh)	Load (kWh)	PV Only					PV + BESS							
						SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	Estimated Cycles	Uptime	Savings (€) BESS	Savings (€) Total
2020	Autum	Sep	61.94%	181.10	104.54	41.39	139.71	22.9%	39.6%	6.74	104.85	78.81	57.9%	100%	10.9	88.6%	10.34	17.08
		Oct	17.33%	36.27	22.88	8.68	27.59	23.9%	37.9%	1.41	22.75	15.18	62.7%	99.4%	2.5	72.4%	2.29	3.71
		Nov	99.89%	198.36	138.34	43.16	155.20	21.8%	31.2%	7.03	98.45	111.66	49.6%	71.2%	11.8	99.8%	9.01	16.04
			59.72%	415.7	265.8	93.2	322.5	22.4%	35.1%	15.2	226.1	205.7	54.4%	85.1%	25.2	86.8%	21.6	36.8
	Winter	Dec	99.95%	181.88	163.20	46.90	134.98	25.8%	28.7%	7.64	95.24	92.30	52.4%	58.4%	9.4	90.3%	7.87	15.51
2021		Jan	99.66%	181.40	171.88	50.37	131.02	27.8%	29.3%	8.21	55.61	125.79	30.7%	32.4%	0.5	98.7%	0.85	9.06
		Feb	99.93%	287.18	149.18	64.50	222.68	22.5%	43.2%	10.51	68.88	218.65	24.0%	46.2%	0.7	99.8%	0.71	11.22
			99.84%	650.5	484.3	161.8	488.7	24.9%	33.4%	26.4	219.7	436.7	33.8%	45.4%	10.6	96.2%	9.4	35.8
	Spring	Mar	98.34%	328.53	144.24	59.06	269.47	18.0%	40.9%	9.62	66.87	280.05	20.4%	46.4%	5.5	98.6%	1.27	10.89
		Apr	99.97%	347.38	139.21	63.45	283.93	18.3%	45.6%	10.34	125.40	228.90	36.1%	90.1%	11.5	89.6%	10.09	20.43
		May	99.98%	395.02	156.03	74.63	320.39	18.9%	47.8%	12.16	140.81	260.97	35.6%	90.2%	12.2	99.9%	10.78	22.94
			99.43%	1070.9	439.5	197.1	873.8	18.4%	44.9%	32.1	333.1	769.9	31.1%	75.8%	29.1	96.1%	22.1	54.3
	Summer	Jun	99.93%	354.50	137.11	66.78	287.71	18.8%	48.7%	10.88	118.29	252.60	33.4%	86.3%	11.7	98.9%	8.39	19.27
		Jul	99.98%	405.69	146.20	69.27	336.42	17.1%	47.4%	11.28	99.56	309.23	24.5%	68.1%	5.6	36.6%	4.93	16.22
		Aug	98.26%	365.05	137.47	68.31	296.74	18.7%	49.7%	11.13	68.31	296.74	18.7%	49.7%	0.0	1.62%	0.00	11.13
			99.39%	1125.2	420.8	204.4	920.9	18.2%	48.6%	33.3	286.2	858.6	25.4%	68.0%	17.3	45.1%	13.3	46.6
Grant Total			89.60%	3262.3	1610.3	656.5	2605.9	20.1%	40.8%	106.9	1065.0	2270.9	32.6%	66.1%	82.3	81.1%	66.6	173.5

Figure 3.6: Year-long real-world results for UPAC 6 considering the greedy strategy.

Considering the year-around results, it is possible to observe an increase of self-consumption from 20% to 31% (an increase in the order of 38%.). Still, unlike the case of UPAC 2, even such low rates of SC enable considerably high rates of SS. This aspect is particularly visible in the months of September, October, April and May, and is a very good indicator that this household has a very over-sized PV installation (another good indicator is the very low number of cycles, that represent around 1 cycle every 3 days).

To further understand the results, Figure 3.7 shows the energy flows and SOC for one week (left), and one day (right) in April. As it can be observed, in the first five days of the week this UPAC is almost 100% of the time off-grid, using less that 30% of the battery nominal capacity. Ultimately, this suggest that in normal conditions (i.e., fully operational equipment), a battery device with a nominal capacity around 5.6 kWh would enable this UPAC to be operating off-grid more that 90% of the time.

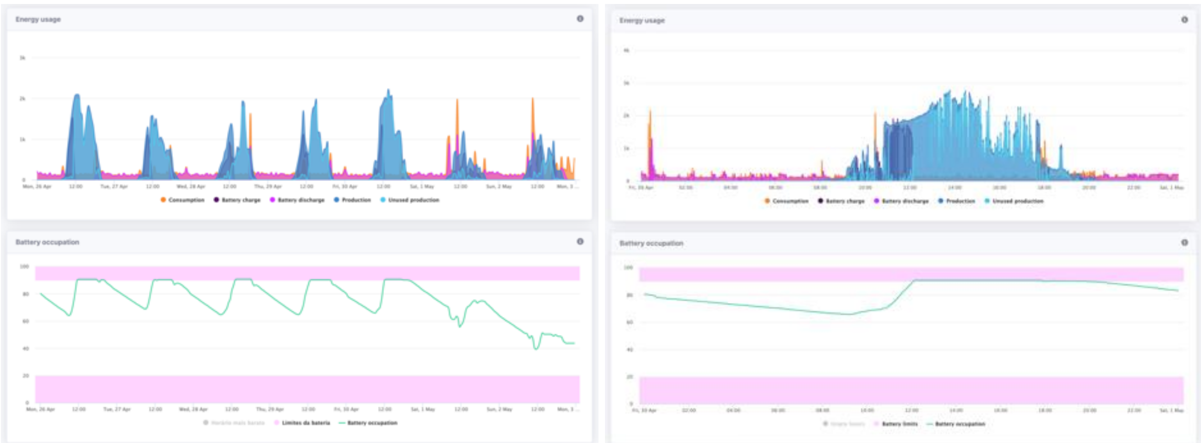


Figure 3.7: Energy flows and battery SOC for one week (left), and one day (right) in April for UPAC 2.

Simulations with Digital Twins

In order to understand the full potential of BESS in UPAC 6, a simulation of the greedy control strategy was conducted using the same data as in the real-world scenario. The simulation results are presented in Figure 3.8.

Year	Season	Month	PV (kWh)	Load (kWh)	PV Only					PV+BESS						
					SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	Estimated Cycles	Savings (€) BESS	Savings (€) Total
2020	Autum	Sep	297.76	160.97	73.88	223.88	24.8%	45.9%	12.04	169.70	128.06	57.0%	100.0%	17.7	15.61	27.64
		Oct	310.13	154.36	79.29	230.84	25.6%	51.4%	12.92	169.09	141.04	54.5%	100.0%	16.0	14.63	27.54
		Nov	199.68	138.18	46.60	153.07	23.3%	33.7%	7.59	145.12	54.55	72.7%	100.0%	17.4	16.05	23.64
			807.6	**453.5**	**199.8**	**607.8**	**24.6%**	**43.7%**	**32.5**	**483.9**	**323.7**	**61.4%**	**100.0%**	**51.1**	**46.3**	**78.8**
	Winter	Dec	196.45	156.60	41.14	155.31	20.9%	26.3%	6.70	152.39	44.06	77.6%	97.3%	19.7	18.12	24.82
2021		Jan	193.51	176.93	55.04	138.48	28.4%	31.1%	8.97	169.50	24.02	87.6%	95.8%	20.3	18.65	27.61
		Feb	268.66	140.34	61.73	206.93	23.0%	44.0%	10.06	151.39	117.26	56.4%	100.0%	15.9	14.61	24.66
			658.6	**473.9**	**157.9**	**500.7**	**24.1%**	**33.8%**	**25.7**	**473.3**	**185.3**	**73.9%**	**97.7%**	**55.9**	**51.4**	**77.1**
	Spring	Mar	342.16	150.12	63.81	278.35	18.6%	42.5%	10.39	162.93	179.23	47.6%	100.0%	17.7	16.15	26.54
		Apr	355.15	137.46	66.07	289.07	18.6%	48.1%	10.76	152.22	202.93	42.9%	100.0%	15.3	14.03	24.80
		May	409.08	161.58	81.00	328.09	19.8%	50.1%	13.19	174.65	234.43	42.7%	100.0%	16.7	15.26	28.45
			1106.4	**449.2**	**210.9**	**895.5**	**19.0%**	**46.9%**	**34.4**	**489.8**	**616.6**	**44.4%**	**100.0%**	**49.7**	**45.4**	**79.8**
	Summer	Jun	360.53	135.05	70.20	290.33	19.5%	52.0%	11.44	148.68	211.86	41.2%	100.0%	13.9	12.78	24.22
		Jul	424.36	149.72	73.21	351.15	17.3%	48.9%	11.93	164.60	259.76	38.8%	100.0%	16.3	14.89	26.81
		Aug	382.43	144.78	72.96	309.47	19.1%	50.4%	11.89	159.41	223.02	41.7%	100.0%	15.3	14.08	25.97
			1167.3	**429.6**	**216.4**	**951.0**	**18.6%**	**50.4%**	**35.2**	**472.7**	**694.6**	**40.6%**	**100.0%**	**45.5**	**41.8**	**77.0**
Grand Total			**3739.9**	**1806.1**	**784.9**	**2955.0**	**21.6%**	**43.7%**	**127.9**	**1919.7**	**1820.2**	**55.1%**	**99.4%**	**202.2**	**184.9**	**312.7**

Figure 3.8: Year-long simulation results for UPAC 6 considering the greedy strategy.

As it can be observed, the SS rate is near 100% even though the SC rates is just above 55%. Furthermore, this is obtained with roughly one battery cycle every two days. Ultimately, this validates the previous assumption that a battery with 65% of the nominal capacity would suffice to achieve considerable levels of SS. Furthermore, in a scenario that a feed-in tariff is available, there is still 45% of PV production to consider.

Finally, it is important to remark that since 100% SS is achieved with the greedy control strategy, a strategy with pre-charge is not necessary. Hence, this simulation was not performed.

3.4.3 Domestic: UPAC 9

UPAC 9 has a single-phase power contract and owns a 4.5 kWp PV installation. As with the other UPACs, the tariff in place is the single-rate, which limited the control strategy to the greedy operation.

For this UPAC, the year-long analysis was done for the period between September 2020 and August 2021. The obtained results are summarized in Figure 3.9. As it can be observed, this was a very stable installation both in terms of AMI and BESS, with average uptimes of 99% and 91%, respectively.

Considering the year-around results, it is possible to observe an increase of self-consumption from 26% to 50% (an increase in the order of 49%.). Furthermore, it is also possible to observe that a SC of 50% corresponds to a SS rate of around 77%. This is an indicator that the PV installation is slightly over-estimated in this UPAC.

Looking at the results from the different seasons, it is possible to observe that Autumn and Winter are the most complicated seasons since this is when the PV production is lower. Interestingly, in this UPAC, the highest consumption occurs in November and not in December, which is reflected by a SS rate of around 50% vs 65%. On the other hand, May was the month with higher PV production and lower consumption, hence the SS rate of 98%.

Year	Season	Month	Available Data (%)	PV (kWh)	Load (kWh)	PV Only					PV + BESS							
						SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	Estimated Cycles	Uptime	Savings (€) BESS	Total
2020	Autum	Sep	100.00%	560.74	397.77	158.88	401.87	28.3%	39.9%	25.88	321.31	281.08	57.3%	80.8%	32.1	97.7%	26.46	52.34
		Oct	87.11%	468.98	338.53	127.54	341.45	27.2%	37.7%	20.78	253.50	287.84	54.1%	74.9%	26.2	82.1%	20.52	41.30
		Nov	99.95%	426.07	424.20	113.88	312.19	26.7%	26.8%	18.55	212.60	257.21	49.9%	50.1%	23.0	91.1%	16.08	34.63
			95.69%	**1455.8**	**1160.5**	**400.3**	**1055.5**	**27.5%**	**34.5%**	**65.2**	**787.4**	**826.1**	**54.1%**	**67.9%**	**81.3**	**90.4%**	**63.1**	**128.3**
	Winter	Dec	99.97%	431.35	374.33	117.40	313.95	27.2%	31.4%	19.12	244.68	200.71	56.7%	65.4%	23.4	89.3%	20.73	39.86
2021		Jan	99.99%	358.64	389.49	112.51	246.14	31.4%	28.9%	18.33	245.10	128.85	68.3%	62.9%	25.1	98.1%	21.60	39.93
		Feb	99.99%	610.90	350.36	142.05	468.85	23.3%	40.5%	23.14	298.63	329.96	48.9%	85.2%	28.1	99.8%	25.51	48.65
			99.98%	**1400.9**	**1114.2**	**372.0**	**1028.9**	**26.6%**	**33.4%**	**60.6**	**788.4**	**659.5**	**56.3%**	**70.8%**	**76.5**	**95.6%**	**67.8**	**128.4**
	Spring	Mar	99.05%	629.87	311.36	138.01	491.86	21.9%	44.3%	22.48	264.62	394.94	42.0%	85.0%	27.1	92.6%	20.63	43.11
		Apr	99.99%	594.28	317.54	144.28	450.00	24.3%	45.4%	23.50	277.50	330.78	46.7%	87.4%	25.1	89.7%	21.70	45.20
		May	100.00%	664.79	336.43	171.91	492.88	25.9%	51.1%	28.00	329.05	351.88	49.5%	97.8%	28.5	99.9%	25.60	53.60
			99.68%	**1888.9**	**965.3**	**454.2**	**1434.7**	**24.0%**	**47.1%**	**74.0**	**871.2**	**1077.6**	**46.1%**	**90.2%**	**80.7**	**94.1%**	**67.9**	**141.9**
	Summer	Jun	99.99%	595.16	334.74	156.76	438.40	26.3%	46.8%	25.54	280.10	337.95	47.1%	83.7%	25.2	98.9%	20.09	45.63
		Jul	99.99%	661.78	330.59	161.01	500.77	24.3%	48.7%	26.23	274.60	397.47	41.5%	83.1%	20.4	62.9%	18.50	44.73
		Aug	99.76%	647.08	331.76	148.41	498.67	22.9%	44.7%	24.18	300.48	360.09	46.4%	90.6%	28.6	92.9%	24.77	48.95
			99.91%	**1904.0**	**997.1**	**466.2**	**1437.8**	**24.5%**	**46.8%**	**75.9**	**855.2**	**1095.5**	**44.9%**	**85.8%**	**74.2**	**84.7%**	**63.4**	**139.3**
Grant Total			**98.82%**	**6649.7**	**4237.1**	**1692.6**	**4957.0**	**25.5%**	**39.9%**	**275.7**	**3302.2**	**3658.8**	**49.7%**	**77.9%**	**312.7**	**91.2%**	**262.2**	**537.9**

Figure 3.9: Year-long real-world results for UPAC 9 considering the greedy strategy.

To further understand these results, Figure 3.10 presents the energy flows and battery SOC for the months of January (left) and May (right). As it can be observed, in some days of January, the PV production is very low, and hence not enough to perform a complete battery cycle. In contrast, in May, the PV production is consistently high, meaning that it is possible to reach the maximum SOC every day. In fact, it is interesting to observe that in a couple of days, the minimum SOC is around 40%, which again indicates that similar results can be achieved with a slightly smaller battery in terms of nominal capacity (around 7 kWh).

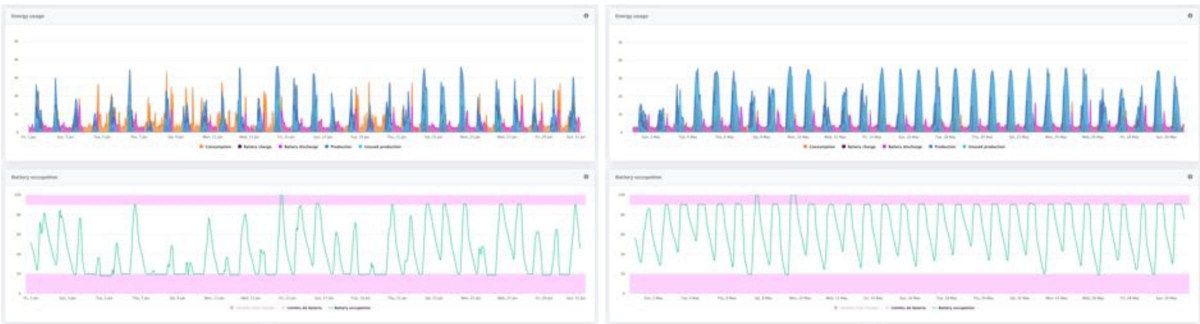


Figure 3.10: Energy flows and battery SOC for January (left), and May (right) for UPAC 9.

Simulations with Digital Twins

In order to understand the full potential of BESS in UPAC 9, a simulation of the greedy control strategy was conducted using the same data as in the real-world scenario. The simulation results are presented in Figure 3.11.

As it can be observed, the results of the simulation follow a very similar trend, with an increase in the SC rate in the order of 50%. Still, one thing that is observable is a considerable increase in the number of cycles which in part happens due to the fact that in the simulation mode, the storage setpoints are updated every minute, whereas, in the real-world deployment, this was done every two minutes.

Finally, we can also conclude that, unlike UPAC 6, where almost 100% SS would be possible just by introducing storage (as a result of the considerably low demand), in UPAC 9, this will not be possible without a change in the consumption habits. For example, shifting more consumption to the periods with higher sun exposure and avoiding reaching net-load values higher than 3 kW (the maximum power that can be supplied by the inverter). This would be particularly helpful in the Autumn and

Winter periods, which is when the SS drops despite the fact that there is more PV production than consumption (with the sole exception of January).

Year	Season	Month	PV (kWh)	Load (kWh)	PV Only					PV + BESS						
					SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	Estimated Cycles	Savings (€)	
															BESS	Total
2020	Autum	Sep	560.74	397.89	177.16	383.58	31.6%	44.5%	28.86	348.09	212.65	62.1%	87.5%	31.7	27.84	56.70
		Oct	580.34	400.01	176.52	403.82	30.4%	44.1%	28.76	349.49	230.85	60.2%	87.4%	30.7	28.18	56.93
		Nov	426.07	424.41	131.23	294.84	30.8%	30.9%	21.38	281.82	144.25	66.1%	66.4%	27.1	24.53	45.91
			1567.2	**1222.3**	**484.9**	**1082.2**	**30.9%**	**39.8%**	**79.0**	**979.4**	**587.8**	**62.8%**	**80.4%**	**89.5**	**80.6**	**159.5**
	Winter	Dec	453.06	385.98	132.82	320.24	29.3%	34.4%	21.64	289.90	163.17	64.0%	75.1%	27.9	25.59	47.22
2021		Jan	382.73	398.88	127.89	254.83	33.4%	32.1%	20.83	286.48	96.24	74.9%	71.8%	28.3	25.83	46.67
		Feb	566.43	330.01	139.85	426.58	24.7%	42.4%	22.78	283.77	282.66	50.1%	86.0%	25.6	23.44	46.23
			1402.2	**1114.9**	**400.6**	**1001.7**	**29.1%**	**36.3%**	**65.3**	**860.2**	**542.1**	**63.0%**	**77.6%**	**81.8**	**74.9**	**140.1**
	Spring	Mar	647.30	326.09	151.16	496.14	23.4%	46.4%	24.62	313.96	333.34	48.5%	96.3%	29.1	26.52	51.14
		Apr	594.28	317.62	153.50	440.78	25.8%	48.3%	25.01	309.77	284.51	52.1%	97.5%	28.0	25.46	50.46
		May	676.76	348.70	187.75	489.02	27.7%	53.8%	30.58	352.98	323.79	52.2%	100.0%	29.4	26.92	57.50
			1918.3	**992.4**	**492.4**	**1425.9**	**25.6%**	**49.5%**	**80.2**	**976.7**	**941.6**	**50.9%**	**97.9%**	**86.5**	**78.9**	**159.1**
	Summer	Jun	595.22	334.81	165.92	429.29	27.9%	49.6%	27.03	327.54	267.68	55.0%	97.8%	28.9	26.33	53.36
		Jul	686.90	341.20	171.46	515.44	25.0%	50.3%	27.93	335.74	351.16	48.9%	98.4%	29.4	26.76	54.69
		Aug	670.79	344.17	162.37	508.42	24.2%	47.2%	26.45	328.06	342.73	48.9%	95.3%	29.7	26.99	53.44
			1952.9	**1020.2**	**499.8**	**1453.2**	**25.7%**	**49.0%**	**81.4**	**991.3**	**961.6**	**50.9%**	**97.2%**	**88.0**	**80.1**	**161.5**
Grand Total			**6840.6**	**4349.8**	**1877.6**	**4963.0**	**27.9%**	**43.7%**	**305.9**	**3807.6**	**3033.0**	**56.9%**	**88.3%**	**345.8**	**314.4**	**620.3**

Figure 3.11: Year-long simulation results for UPAC 9 considering the greedy strategy.

3.4.4 Domestic: UPAC 13

UPAC 13 also has a three-phase power contract and owns a 4.5 kWp PV installation. Like with the case of UPAC 6, the PV system was connected to the phase with the highest demand, and so was the BESS. Again, this UPAC has a single-rate power tariff, and therefore the greedy control strategy was employed. It is also important to stress that this UPAC has a considerably high consumption with respect to the others.

For this UPAC, the year-long analysis was done for the period between March 2020 and February 2021. The obtained results are summarized in Figure 3.12. Note that these results refer to the phase where the PV and BESS are installed.

Naturally, the first observation concerns the missing data during four consecutive months. The reason behind this situation is the fact that in April 2020, there were works being developed to upgrade the PV installation from 1.5 kWp to 4.5 kWp, by adding a new 3 kWp installation. Unfortunately, this is when Covid-19 reached Madeira, and it was only in August 2020 that it was possible to conclude the upgrade of the AMI to support the additional PV capacity. Besides that, it is possible to observe that this system is fairly stable, with 99% of available data and a BESS uptime of around 90%.

Regarding the SC and SS rates, it is possible to observe that before the installation of the additional PV capacity, there was an increase of 42% in the SC rate (from 51% to 87%). O the other hand, after installing the additional 3 kWp of PV, the SC rate increased on average 37% (from 43% to 68%).

Year	Season	Month	Available Data (%)	PV (kWh)	Load (kWh)	PV Only					PV + BESS							
						SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	Estimated Cycles	Uptime	Savings (€) BESS	Savings (€) Total
2020	Spring	Mar	99.95%	171.99	323.39	87.74	84.93	51.0%	27.1%	14.29	150.23	21.76	87.0%	46.5%	13.5	95.6%	10.18	24.47
		Apr																
		May																
			99.95%	**171.99**	**323.39**	**87.74**	**84.93**	**51.0%**	**27.1%**	**14.29**	**150.23**	**21.76**	**87.0%**	**46.5%**	**13.5**	**95.6%**	**10.18**	**24.47**
	Summer	Jun																
		Jul																
		Aug	99.63%	447.79	442.15	161.84	272.95	36.1%	36.6%	26.36	283.30	164.50	63.0%	64.1%	21.9	98.6%	19.79	46.15
			99.63%	**447.8**	**442.2**	**161.8**	**273.0**	**36.1%**	**36.6%**	**26.4**	**283.3**	**164.50**	**63.0%**	**64.1%**	**21.9**	**98.6%**	**19.8**	**46.1**
	Autum	Sep	99.95%	534.84	522.32	232.38	303.30	43.4%	44.5%	37.85	325.41	209.43	61.0%	62.3%	23.4	86.3%	15.15	53.01
		Oct	99.95%	405.41	490.20	202.17	204.64	49.9%	41.2%	32.93	287.89	117.52	71.0%	58.7%	20.2	92.2%	13.96	46.90
		Nov	99.96%	369.15	533.40	166.20	204.53	45.0%	31.2%	27.07	226.23	142.92	61.0%	42.4%	14.1	99.7%	9.78	36.85
			99.95%	**1309.4**	**1545.9**	**600.8**	**712.5**	**46.1%**	**39.0%**	**97.9**	**839.5**	**469.87**	**64.3%**	**54.5%**	**57.8**	**92.7%**	**38.9**	**136.8**
	Winter	Dec	99.98%	363.13	457.58	147.70	211.72	40.7%	32.3%	24.06	248.01	115.12	68.0%	54.2%	20.3	90.3%	16.34	40.40
2021		Jan	99.38%	363.81	491.39	147.70	214.09	40.6%	30.1%	24.06	260.79	103.02	72.0%	53.1%	22.0	98.1%	18.42	42.48
		Feb	99.96%	484.28	511.22	234.01	247.95	48.3%	45.8%	38.12	356.77	127.51	74.0%	69.8%	23.7	99.3%	20.00	58.12
			99.77%	**1211.2**	**1460.2**	**529.4**	**673.8**	**43.2%**	**36.1%**	**86.2**	**865.6**	**345.65**	**71.3%**	**59.0%**	**66.1**	**95.9%**	**54.8**	**141.0**
Grant Total 1.5 kWp			**99.95%**	**171.99**	**323.4**	**87.74**	**84.93**	**51.0%**	**27.1%**	**14.29**	**150.23**	**21.76**	**87.0%**	**46.5%**	**13.5**	**95.6%**	**10.18**	**24.47**
Grant Total 4.5 kWp			**99.78%**	**2968.4**	**3448.3**	**1292.0**	**1659.2**	**41.8%**	**37.2%**	**210.5**	**1988.4**	**980.0**	**66.2%**	**59.2%**	**145.7**	**95.7%**	**113.4**	**323.9**
Grant Total			**99.83%**	**3140.4**	**3771.7**	**1379.7**	**1744.1**	**43.9%**	**36.6%**	**224.8**	**2138.6**	**1001.8**	**71.4%**	**56.0%**	**159.2**	**95.7%**	**123.6**	**348.4**

Figure 3.12: Year-long real-world results for UPAC 13 (PV and BESS Phase only) considering the greedy strategy.

One important aspect to consider is the fact that after installing the additional PV capacity, there was also an increase in the demand due to the acquisition of an EV. Consequently, despite having more PV production, the SS rate remained fairly low.

To further explore the results in UPAC 13, Figure 3.13, shows the energy flows and battery SOC during April (left) and September (right). Note that the energy flows correspond to the total values, i.e., the sum of the three phases.

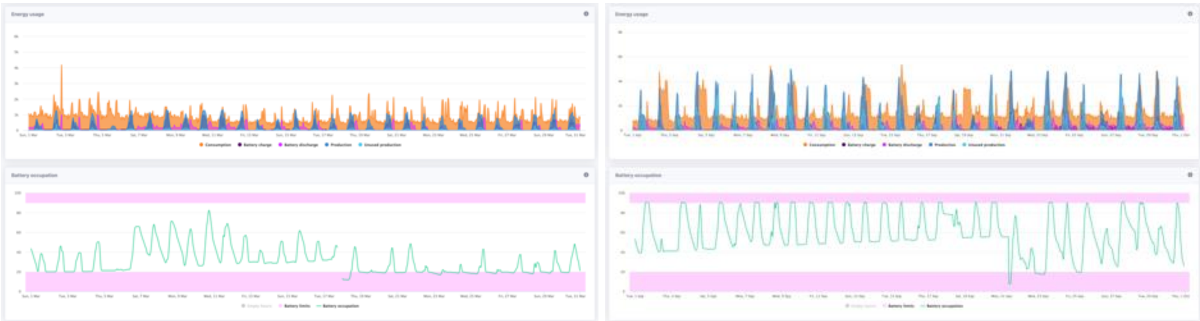


Figure 3.13: Energy flows and battery SOC for April (left), and September (right) for UPAC 13. Note that the energy flows correspond to the sum of the three phases, whereas the SOC is only for one of the phases.

As it can be observed, the number of cycles during April (1.5 kWp of PV) is very low due to the small size of the PV installation. On the other hand, in September (4.5 kWp), it is possible to observe a slight increase in the number of cycles. However, the most interesting aspect is the fact that for a large portion of the month, the BESS does not fully discharge despite the heavy dependence on energy from the grid (orange area). Ultimately, this illustrates the limitation of connecting the PV system to one single consumption phase instead of the three phases.

Simulations with Digital Twins

In order to understand the full potential of BESS in UPAC 13, a simulation of the greedy control strategy was conducted using the same data as in the real-world scenario. The simulation results are presented in Figure 3.14.

Year	Season	Month	PV (kWh)	Load (kWh)	PV Only SC (kWh)	PV Only To Grid (kWh)	PV Only SC	PV Only SS	PV Only Savings (€)	PV + BESS SC (kWh)	PV + BESS To Grid (kWh)	PV + BESS SC	PV + BESS SS	PV + BESS Estimated Cycles	Savings (€) BESS	Savings (€) Total
2020	Spring	Mar	172.28	323.47	97.18	75.10	56.4%	30.0%	15.83	172.28	0.0	100.0%	53.3%	13.4	12.23	28.06
		Apr														
		May														
			172.28	323.47	97.18	75.10	56.40%	30.0%	15.83	172.3	0.0	100.0%	53.3%	13.4	12.23	28.06
	Summer	Jun														
		Jul														
		Aug	448.50	443.36	146.16	302.34	32.6%	33.0%	23.81	286.48	162.02	63.9%	64.6%	25.0	22.86	46.67
			448.50	443.36	146.16	302.34	32.6%	33.0%	23.8	286.5	162.0	63.9%	64.6%	25.0	22.86	46.67
	Autum	Sep	534.84	522.47	243.66	291.18	45.6%	46.6%	39.69	399.33	135.50	74.7%	76.4%	27.9	25.36	65.05
		Oct	405.41	490.31	212.49	192.92	52.4%	43.3%	34.61	346.98	58.43	85.6%	70.8%	23.6	21.91	56.52
		Nov	369.15	533.43	172.52	196.63	46.7%	32.3%	28.10	305.10	64.05	82.6%	57.2%	23.9	21.60	49.70
			1309.4	1546.2	628.7	680.7	48.2%	40.7%	102.4	1051.4	258.0	81.0%	68.1%	75.4	68.9	171.3
	Winter	Dec	363.13	457.63	150.86	212.27	41.5%	33.0%	24.58	298.30	64.83	82.1%	65.2%	26.3	24.02	48.59
2021		Jan	363.81	493.83	160.61	203.19	44.1%	32.5%	26.16	307.35	56.46	84.5%	62.2%	25.9	23.90	50.07
		Feb	484.28	511.29	249.56	234.72	51.5%	48.8%	40.65	381.93	102.35	78.9%	74.7%	23.9	21.56	62.22
			1211.2	1462.8	561.0	650.2	45.7%	38.1%	91.4	987.6	223.6	81.8%	67.4%	76.1	69.5	160.9
Grant Total 1.5 kWp			172.3	323.5	97.2	75.1	56.40%	30.00%	15.8	172.3	0.0	100.00%	53.30%	13.4	12.2	28.1
Grant Total 4.5 kWp			2969.12	3452.32	1335.86	1633.25	42.18%	37.28%	217.61	2325.47	643.64	75.57%	66.70%	176.50	161.21	378.82
Grant Total			3141.4	3775.8	1433.0	1708.4	45.73%	35.46%	233.4	2497.8	643.6	81.68%	63.35%	189.9	173.4	406.9

Figure 3.14: Year-long simulation results for UPAC 13 (PV and BESS Phase only) considering the greedy strategy.

Ultimately, by simulating local control of the storage, a 44% increase in self-consumption is achieved in both scenarios (i.e., 1.5 kWp and 4.5 kWp). Furthermore, a direct comparison between the real-world and simulated case (only possible due to the 99% availability of data in the real-world test) shows an increase in SC rate around 13% (from 71.4% to 81.7%). A difference that can in part be explained by the fact that in the simulated case, the storage control is performed every minute, in contrast to the two minutes in the real-world version. While the difference of one minute between storage control updates may seem small, in the case of this UPAC, there are several refrigeration units with sharp start-up transients that affect the average consumption within a given minute. Ultimately, updating the storage control thresholds helps to compensate twice as fast to those rapid changes in the actual consumption.

As a final exercise, in order to understand even further the potential of storage in this UPAC, simulations were conducted assuming that the power installation was also single-phase (by summing the load from the three phases). The simulations were then conducted considering only the months where the PV capacity was already 4.5 kWp (from August to 2020 to February 2021). The simulation results are summarized in Figure 3.15.

Year	Season	Month	PV (kWh)	Load (kWh)	PV Only SC (kWh)	PV Only To Grid (kWh)	PV Only SC	PV Only SS	PV Only Savings (€)	PV + BESS SC (kWh)	PV + BESS To Grid (kWh)	PV + BESS SC	PV + BESS SS	PV + BESS Estimated Cycles	Savings (€) BESS	Savings (€) Total
2020	Summer	Aug	450.99	887.83	273.63	177.36	60.7%	30.8%	44.57	403.31	47.68	89.4%	45.4%	23.0	21.12	65.70
			450.99	887.83	273.63	177.36	60.7%	30.8%	44.57	403.31	47.68	89.4%	45.4%	23.0	21.12	65.70
	Autum	Sep	537.21	1133.88	383.19	154.02	71.3%	33.8%	62.42	527.65	9.55	98.2%	46.5%	25.9	23.53	85.95
		Oct	408.17	1160.63	330.72	77.45	81.0%	28.5%	53.87	400.51	7.66	98.1%	34.5%	12.3	11.37	65.24
		Nov	371.31	1114.30	266.57	104.74	71.8%	23.9%	43.42	366.52	4.78	98.7%	32.9%	17.9	16.28	59.71
			1316.7	3408.8	980.5	336.2	74.7%	28.7%	159.7	1294.7	22.0	98.3%	38.0%	56.1	51.2	210.9
	Winter	Dec	365.38	1053.07	255.56	109.82	69.9%	24.3%	41.63	357.99	7.40	98.0%	34.0%	18.3	16.69	58.32
2021		Jan	365.82	846.33	225.40	140.42	61.6%	26.6%	36.72	357.09	8.73	97.6%	42.2%	23.4	21.45	58.17
		Feb	486.20	883.02	329.04	157.15	67.7%	37.3%	53.60	462.72	23.48	95.2%	52.4%	23.9	21.78	75.38
			1217.4	2782.4	810.0	407.4	66.4%	29.4%	131.9	1177.8	39.6	96.9%	42.9%	65.6	59.9	191.9
Grand Total 4.5 kWp			2985.1	7079.1	2064.1	921.0	67.3%	29.6%	336.2	2875.8	109.3	94.9%	42.1%	144.7	132.2	468.5

Figure 3.15: Year-long simulation results for UPAC 13 (assuming single phase) considering the greedy strategy.

As expected, by summing all the three phases, the PV only SC rate increased immediately, from 42% to 67%. This is expected because the demand for these seven months increased from 3.45 MWh to 7.1

MWh (an increase of around 50%). As for the instruction of the BESS, it would represent an increase of 20% in the SC rate (from 76% to 95%).

Still, in such a scenario, the BESS would lose some preponderance since the number of cycles would be reduced (from ~173 to ~145) as a result of having less excess PV production. Ultimately, this situation would resemble that of UPAC 2, where the PV installation is undersized. Therefore, pre-charge would also be a good alternative in UPAC 13 in case both systems were single-phase.

3.4.5 Commercial: UPAC 8

UPAC 8 is a family-owned commercial activity operating seven days a week, from early morning to late evening.

This UPAC has a three-phase power installation with a contracted power of 20.7 kVA, as well as 4.95 kWp of PV, also in a three-phase installation. One battery/inverter pair was installed in each phase. The tariff currently in place is the 2-TOU, with two different prices, a lower during off-peak periods and higher during peak hours (see Figure YY).

Considering the very large difference between the consumption and production rates, the only reasonable control approach was to apply pre-charge. In this case, the calculated pre-charge was 80% in each of the three phases. The results obtained in the real-world deployment are shown in Figure 3.16, Figure 3.17, and Figure 3.18. These results refer to the period between March 2020 and February 2021.

Year	Season	Month	Available Data (%)	PV (kWh)	Load (kWh)	PV Only					PV + BESS									
						SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	OPE (kWh)	OPE (%)	Estimated Cycles	Uptime	Savings (€) BESS	Savings (€) Total
2020	Spring	Mar	99.98%	172.40	986.10	132.02	40.39	76.6%	13.4%	31.20	152.02	38.43	88.2%	15.4%	159.96	16.2%	31.3	95.7%	12.60	43.81
		Apr	99.97%	182.41	684.98	116.97	65.44	64.1%	17.1%	26.58	144.18	49.02	79.0%	21.0%	154.80	22.6%	22.5	87.4%	10.72	37.30
		May	99.98%	222.46	593.69	149.67	72.79	67.3%	25.2%	34.98	178.97	56.28	80.4%	30.1%	159.96	26.9%	18.3	78.1%	8.92	43.90
			99.98%	**577.3**	**2264.8**	**398.7**	**178.6**	**69.3%**	**18.6%**	**92.8**	**475.2**	**143.7**	**82.6%**	**22.2%**	**474.72**	**21.9%**	**72.1**	**87.1%**	**32.2**	**125.0**
	Summer	Jun	99.90%	198.76	923.86	163.95	34.81	82.5%	17.7%	37.16	175.37	38.02	88.2%	19.0%	154.80	16.8%	22.3	69.0%	9.02	46.19
		Jul	100.00%	257.11	928.91	212.58	44.53	82.7%	22.9%	49.70	230.51	45.45	89.7%	24.8%	159.96	17.2%	30.5	94.5%	11.96	61.66
		Aug	99.92%	210.29	827.09	158.69	51.60	75.5%	19.2%	37.51	183.54	49.06	87.3%	22.2%	159.96	19.3%	29.8	98.9%	10.75	48.25
			99.94%	**666.2**	**2679.9**	**535.2**	**130.9**	**80.2%**	**19.9%**	**124.4**	**589.4**	**132.5**	**88.4%**	**22.0%**	**474.72**	**17.8%**	**82.7**	**87.5%**	**31.7**	**156.1**
	Autum	Sep	99.89%	170.73	674.27	112.96	57.77	66.2%	16.8%	25.69	146.30	51.85	85.7%	21.7%	154.80	23.0%	32.1	99.0%	11.87	37.57
		Oct	99.98%	148.62	724.09	95.97	52.66	64.6%	13.3%	22.83	123.96	56.37	83.4%	17.1%	159.96	22.1%	32.4	97.8%	10.36	33.21
		Nov	99.97%	124.32	763.36	76.90	47.42	61.9%	10.1%	17.38	101.62	55.66	81.7%	13.3%	154.80	20.3%	33.2	98.9%	9.18	26.58
			99.95%	**443.7**	**2161.7**	**285.8**	**157.9**	**64.2%**	**13.4%**	**65.9**	**371.9**	**163.9**	**83.6%**	**17.4%**	**469.56**	**21.8%**	**97.7**	**98.6%**	**31.4**	**97.4**
	Winter	Dec	99.97%	113.39	761.41	71.96	41.43	63.5%	9.5%	16.91	85.39	65.78	75.3%	11.2%	159.96	21.0%	28.9	90.3%	6.67	23.58
2021		Jan	99.98%	100.44	835.59	66.84	33.60	66.5%	8.0%	15.61	75.56	61.86	75.2%	9.0%	159.96	19.1%	29.5	94.3%	6.18	21.79
		Feb	99.82%	168.77	740.05	100.77	67.99	59.7%	13.6%	20.53	128.41	81.95	76.1%	17.4%	144.48	19.5%	31.9	93.6%	8.32	28.86
			99.92%	**382.6**	**2337.0**	**239.6**	**143.0**	**63.2%**	**10.4%**	**53.1**	**289.4**	**209.6**	**75.5%**	**12.5%**	**464.40**	**19.9%**	**90.3**	**92.7%**	**21.2**	**74.2**
Grant Total			**99.95%**	**2069.7**	**9443.4**	**1459.3**	**610.4**	**70.5%**	**15.5%**	**336.1**	**1725.8**	**649.7**	**83.4%**	**18.3%**	**1883.40**	**20.3%**	**342.8**	**91.5%**	**116.6**	**452.7**

Figure 3.16: Year-long real-world results for UPAC 8 (Phase 1) considering the pre-charge strategy.

Year	Season	Month	Available Data (%)	PV (kWh)	Load (kWh)	PV Only					PV + BESS									
						SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	OPE (kWh)	OPE (%)	Estimated Cycles	Uptime	Savings (€) BESS	Savings (€) Total
2020	Spring	Mar	99.98%	167.77	614.96	124.52	43.25	74.2%	20.2%	29.24	151.05	27.18	90.0%	24.6%	159.96	26.0%	29.3	95.7%	14.22	43.46
		Apr	99.97%	178.43	557.00	120.92	57.51	67.8%	21.7%	27.37	144.74	41.93	81.1%	26.0%	154.80	27.8%	21.7	87.2%	10.64	38.02
		May	99.98%	218.06	441.56	145.09	72.97	66.5%	32.9%	33.69	174.26	48.18	79.9%	39.5%	159.96	36.2%	13.2	78.2%	8.92	42.62
			99.98%	564.3	1613.5	390.5	173.7	69.5%	24.9%	90.3	470.0	117.3	83.7%	30.0%	474.72	30.0%	64.2	87.0%	33.8	124.1
	Summer	Jun	99.90%	193.79	498.41	143.66	50.13	74.1%	28.8%	32.45	167.75	31.37	86.6%	33.7%	154.80	31.1%	15.7	69.1%	9.63	42.08
		Jul	100.00%	251.80	526.85	185.63	66.17	73.7%	35.2%	43.25	226.04	31.32	89.8%	42.9%	159.96	30.4%	18.7	94.5%	11.87	55.12
		Aug	99.92%	206.00	548.42	158.07	47.93	76.7%	28.8%	37.23	186.06	26.97	90.3%	33.9%	159.96	29.2%	24.3	98.9%	12.60	49.83
			99.94%	651.6	1573.7	487.4	164.2	74.9%	31.0%	112.9	579.8	89.6	88.9%	36.8%	474.72	30.2%	58.7	87.5%	34.1	147.0
	Autum	Sep	99.89%	165.69	539.65	126.32	39.37	76.2%	23.4%	28.62	149.80	23.04	90.4%	27.8%	154.80	28.7%	24.4	88.6%	12.14	40.76
		Oct	99.98%	144.41	501.05	103.07	41.34	71.4%	20.6%	24.34	128.30	28.00	88.8%	25.6%	159.96	31.9%	28.3	99.0%	13.48	37.83
		Nov	99.97%	120.14	474.09	82.91	37.23	69.0%	17.5%	18.59	105.86	28.95	88.1%	22.3%	154.80	32.7%	28.2	99.1%	9.73	28.33
			99.95%	430.2	1514.8	312.3	117.9	72.2%	20.5%	71.6	384.0	80.0	89.1%	25.2%	469.56	31.1%	80.8	95.6%	35.4	106.9
	Winter	Dec	99.97%	110.36	443.17	73.98	36.38	67.0%	16.7%	17.24	93.98	30.92	85.2%	21.2%	159.96	36.1%	24.0	90.3%	10.53	27.77
2021		Jan	99.98%	98.47	425.18	66.96	31.51	68.0%	15.7%	15.27	85.42	28.43	86.7%	20.1%	159.96	37.6%	25.9	94.3%	10.34	25.62
		Feb	99.82%	166.90	447.93	99.21	67.69	59.4%	22.1%	20.01	135.79	45.36	81.4%	30.3%	144.48	32.3%	22.7	88.6%	10.38	30.40
			99.92%	375.7	1316.3	240.2	135.6	64.8%	18.2%	52.5	315.2	104.7	84.4%	23.9%	464.40	35.3%	72.6	91.0%	31.3	83.8
Grant Total			99.95%	2021.8	6018.3	1430.3	591.5	70.7%	23.8%	327.3	1749.0	391.6	86.5%	29.1%	1883.40	31.7%	276.3	90.3%	134.5	461.8

Figure 3.17: Year-long real-world results for UPAC 8 (Phase 2) considering the pre-charge strategy.

Year	Season	Month	Available Data (%)	PV (kWh)	Load (kWh)	PV Only					PV + BESS									
						SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	OPE (kWh)	OPE (%)	Estimated Cycles	Uptime	Savings (€) BESS	Savings (€) Total
2020	Spring	Mar	99.98%	149.63	688.60	98.08	51.55	65.5%	14.2%	21.34	110.40	83.33	73.8%	16.0%	159.96	23.2%	24.4	100.0%	1.98	23.32
		Apr	99.97%	168.01	585.38	97.41	70.60	58.0%	16.6%	22.98	123.09	98.16	73.3%	21.0%	154.80	26.4%	29.9	95.6%	2.87	25.85
		May	99.98%	177.44	470.17	99.32	78.13	56.0%	21.1%	22.54	125.89	103.41	70.9%	26.8%	159.96	34.0%	23.2	87.3%	0.62	23.15
			99.98%	495.1	1744.2	294.8	200.3	59.8%	17.3%	66.9	359.4	284.9	72.7%	21.3%	474.72	27.9%	77.5	94.3%	5.5	72.3
	Summer	Jun	99.90%	218.55	548.47	127.89	90.67	58.5%	23.3%	29.81	157.96	104.56	72.3%	28.8%	154.80	28.2%	21.6	78.1%	2.08	31.90
		Jul	100.00%	194.42	630.62	121.56	72.86	62.5%	19.3%	27.48	141.83	97.73	72.9%	22.5%	159.96	25.4%	21.7	69.0%	1.66	29.15
		Aug	99.92%	251.90	627.96	144.76	107.14	57.5%	23.1%	33.78	184.73	120.91	73.3%	29.4%	159.96	25.5%	27.2	94.4%	2.79	36.57
			99.94%	664.9	1807.1	394.2	270.7	59.5%	21.9%	91.1	484.5	323.2	72.9%	26.9%	474.72	26.4%	70.4	80.5%	6.5	97.6
	Autum	Sep	99.89%	206.42	642.27	121.57	84.86	58.9%	18.9%	28.83	150.83	114.11	73.1%	23.5%	154.80	24.1%	30.5	98.9%	1.85	30.69
		Oct	99.98%	166.70	653.04	100.69	66.01	60.4%	15.4%	22.88	124.81	102.52	74.9%	19.1%	159.96	24.5%	33.1	99.0%	2.76	25.64
		Nov	99.97%	137.30	673.74	88.60	48.70	64.5%	13.2%	21.00	105.48	78.74	76.8%	15.7%	154.80	23.0%	25.6	75.2%	1.03	22.04
			99.95%	510.4	1969.0	310.9	199.6	61.3%	15.8%	72.7	381.1	295.4	74.9%	19.4%	469.56	23.9%	89.2	91.1%	5.6	78.4
	Winter	Dec	99.97%	112.83	671.73	77.96	34.87	69.1%	11.6%	17.59	86.62	63.98	76.8%	12.9%	159.96	23.8%	22.9	70.2%	0.96	18.55
2021		Jan	99.98%	109.02	664.91	75.45	33.57	69.2%	11.3%	17.78	79.99	66.36	73.4%	12.0%	159.96	24.1%	26.7	90.2%	4.82	22.59
		Feb	99.82%	98.05	614.87	71.19	26.87	72.6%	11.6%	16.58	73.82	52.23	75.3%	12.0%	144.48	23.5%	20.9	69.2%	3.79	20.36
			99.92%	319.9	1951.5	224.6	95.3	70.3%	11.5%	52.0	240.4	182.6	75.1%	12.3%	464.40	23.8%	70.5	76.5%	9.6	61.5
Grant Total			99.95%	1990.3	7471.8	1224.5	765.8	61.5%	16.4%	282.6	1465.4	1086.1	73.6%	19.6%	1883.40	25.5%	307.6	85.6%	27.2	309.8

Figure 3.18: Year-long real-world results for UPAC 8 (Phase 3) considering the pre-charge strategy.

Again here, the first comment goes to the high stability of both the AMI and BESS infrastructures with around 99% uptime in the AMI and 90% up-time in the BESS. The exception to this trend was mostly the months of December 2020 and February 2021 where we experienced some issues with the system installed on the third-phase.

Regarding the SC and SS, it can be observed that all the phases have very high SC and low SS, since the PV installation is undersized. This, and the fact that the calculated pre-charge is 80%, are clear indicators that this UPAC would take very good benefits from upgrading the PV installation to at least twice of the currently installed capacity.

Ultimately, in the current scenarios, the highest share of the savings arrives from the arbitrage operation, enabling to cover an average of 26% of the total demand with energy acquired at a lower price (Phase 1: 20.3%, Phase 2: 31.7%, Phase 3: 25.5%).

It is also possible to observe a decrease in consumption in April and May due to the Covid-19 lockdowns, which also lead to a decrease in the SC rate. This is especially visible in Phases 1 and 3, where equipment's for the UPAC commercial activity are installed.

It is also possible to observe that the unlike the domestic UPACs that see an increase of demand during the Holidays seasons, in the commercial UPAC the consumption is very stable throughout the year. Nevertheless, a decrease in the SS rates is also observed in Winter, mostly due to the reduction in the number of sun hours. This effect can be observed in Figure 3.19 that shows the energy flows and SOC during one week in August (left), and another in December (right).

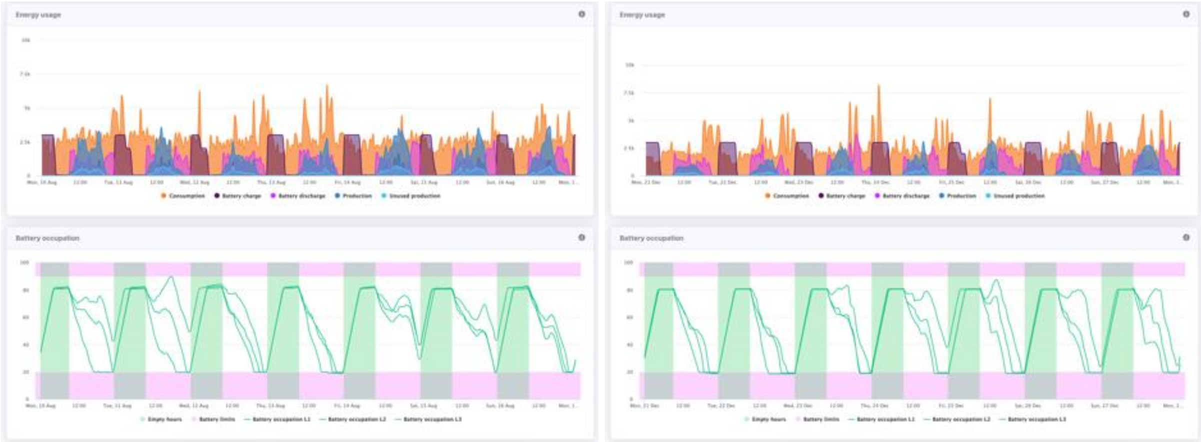


Figure 3.19: Energy flows and battery SOC for one week in August (left), and another in December (right) for UPAC 8.

The final observation concerns the very low savings obtained in phase 3, despite having similar SC rates. After further exploration, it was concluded that this happens due to the high instability of the load on this phase, that has very fast power fluctuations in that happen due to the fact that the the equipment installed for the commercial activity of the owner have some specific requirements. This effect can be observed in Figure 3.20, where L3.P represents the load on phase 3.
Ultimately, it was concluded that operating the battery every two minutes is not enough to cope with such power fluctuations. Instead, in order for this phase to work properly, the storage control would have to be performed close to real-time.

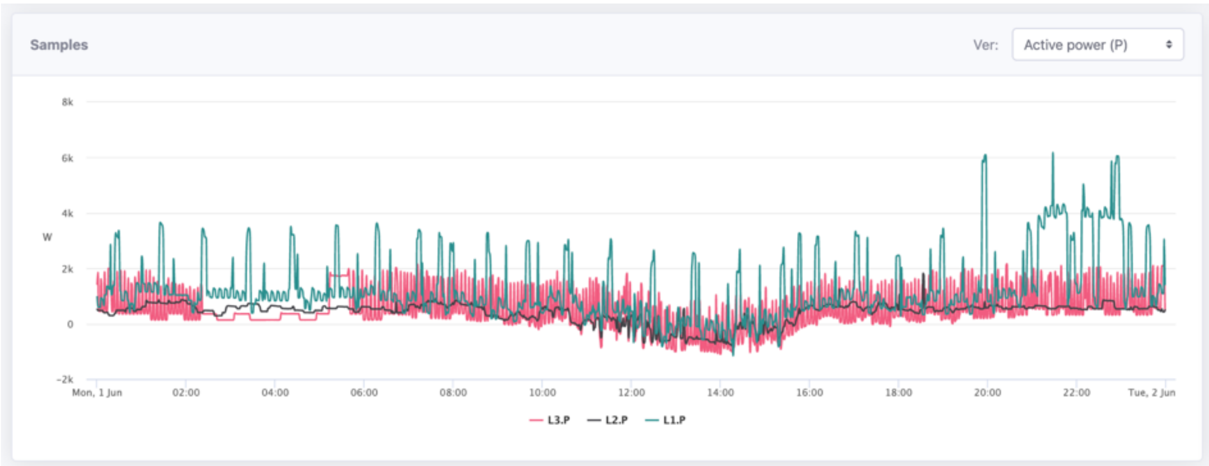


Figure 3.20: One days of minutely averages of active power for the three phases in UPAC 8.

Simulations with Digital Twins

Again, to further explore the potential of BESS in UPAC 8, a simulation of the pre-charge control strategy was conducted for the same time period. The results are presented in Figure 3.21, Figure 3.22, and Figure 3.23.

Regarding the overall SC, the results are fairly similar to those obtained in the real-world case, with an average increase of 16%. The same holds for the savings from the pre-charge operation, with 26% of the total demand being fulfilled with energy acquired in the off-peak periods.

Regarding phase 3, the results confirm the expectation that a more granular control of the storage (in this case every minute), would be beneficial. This effect can be seen in the savings column, that went from 27.2 Euros in the real-world to 195 in the simulation. In other words, by updating the inverter setpoints more often it is possible to avoid injecting from the battery to the grid due to fast up-down fluctuation in the demand of this phase.

Year	Season	Month	PV (kWh)	Load (kWh)	PV Only					PV + BESS								
					SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	OPE (kWh)	OPE (%)	Estimated Cycles	Savings (€) BESS	Savings (€) Total
2020	Spring	Mar	181.16	1006.75	158.96	22.21	87.7%	15.8%	36.02	181.16	0.00	100.0%	18.0%	159.96	15.9%	30.4	18.13	54.16
		Apr	182.91	684.18	127.53	55.39	69.7%	18.6%	28.99	158.15	24.76	86.5%	23.1%	154.80	22.6%	27.1	15.92	44.90
		May	227.62	623.17	170.85	56.78	75.1%	27.4%	38.77	204.00	23.63	89.6%	32.7%	159.96	25.7%	25.6	15.82	54.59
			591.7	**2314.1**	**457.3**	**134.4**	**77.5%**	**20.6%**	**103.8**	**543.3**	**48.4**	**92.0%**	**24.6%**	**474.72**	**21.4%**	**83.1**	**49.9**	**153.7**
	Summer	Jun	199.61	924.69	183.67	15.94	92.0%	19.9%	41.66	199.61	0.00	100.0%	21.6%	154.80	16.7%	27.9	15.95	57.62
		Jul	264.45	959.19	245.59	18.87	92.9%	25.6%	55.87	264.45	0.00	100.0%	27.6%	159.96	16.7%	29.3	16.76	72.63
		Aug	218.96	850.99	189.77	29.19	86.7%	22.3%	43.21	218.95	0.01	100.0%	25.7%	159.96	18.8%	31.0	19.05	62.25
			683.0	**2734.9**	**619.0**	**64.0**	**90.5%**	**22.6%**	**140.7**	**683.0**	**0.0**	**100.0%**	**25.0%**	**474.72**	**17.4%**	**88.2**	**51.8**	**192.5**
	Autum	Sep	170.82	674.85	136.10	34.72	79.7%	20.2%	30.97	170.11	0.71	99.6%	25.2%	154.80	22.9%	30.6	19.24	50.22
		Oct	155.92	749.69	123.93	31.98	79.5%	16.5%	28.18	155.38	0.54	99.7%	20.7%	159.96	21.3%	30.7	18.83	47.01
		Nov	124.84	763.91	97.38	27.45	78.0%	12.7%	22.06	124.84	0.00	100.0%	16.3%	154.80	20.3%	29.1	17.88	39.93
			451.6	**2188.5**	**357.4**	**94.2**	**79.1%**	**16.5%**	**81.2**	**450.3**	**1.3**	**99.8%**	**20.7%**	**469.56**	**21.5%**	**90.4**	**56.0**	**137.2**
	Winter	Dec	119.98	786.07	90.90	29.60	75.8%	11.6%	20.75	117.48	2.50	97.9%	14.9%	159.96	20.3%	29.4	17.83	38.57
2021		Jan	110.22	854.50	94.89	15.34	86.1%	11.1%	20.77	110.22	0.01	100.0%	12.9%	159.96	18.7%	27.3	15.86	36.63
		Feb	162.93	688.80	125.20	37.73	76.8%	18.2%	27.37	162.48	0.45	99.7%	23.6%	144.48	21.0%	28.4	18.89	46.27
			393.1	**2329.4**	**311.0**	**82.7**	**79.6%**	**13.6%**	**68.9**	**390.2**	**3.0**	**99.2%**	**17.1%**	**464.40**	**20.0%**	**85.1**	**52.6**	**121.5**
Grand Total			**2119.4**	**9566.8**	**1744.8**	**375.2**	**81.7%**	**18.3%**	**394.6**	**2066.8**	**52.6**	**97.8%**	**21.9%**	1883.40	20.1%	**346.8**	**210.2**	**604.8**

Figure 3.21: Year-long simulation results for UPAC 8 (Phase 1) considering the pre-charge strategy.

Year	Season	Month	PV (kWh)	Load (kWh)	PV Only					PV + BESS								
					SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	OPE (kWh)	OPE (%)	Estimated Cycles	Savings (€) BESS	Savings (€) Total
2020	Spring	Mar	175.32	631.26	142.09	33.22	81.1%	22.5%	32.29	173.80	1.52	99.1%	27.5%	159.96	25.3%	31.9	19.86	52.15
		Apr	177.68	556.72	129.72	47.96	73.0%	23.3%	29.61	158.66	19.02	89.3%	28.5%	154.80	27.8%	27.7	16.26	45.87
		May	221.91	455.93	155.10	66.81	69.9%	34.0%	35.30	194.52	27.38	87.7%	42.7%	159.96	35.1%	24.7	15.61	50.90
			574.9	**1643.9**	**426.9**	**148.0**	**74.7%**	**26.6%**	**97.2**	**527.0**	**47.9**	**92.0%**	**32.9%**	**474.72**	**29.4%**	**84.3**	**51.7**	**148.9**
	Summer	Jun	193.48	498.42	153.63	39.85	79.4%	30.8%	34.92	185.49	7.99	95.9%	37.2%	154.80	31.1%	26.9	15.73	50.65
		Jul	258.00	543.06	199.49	58.51	77.3%	36.7%	45.46	238.14	19.85	92.3%	43.9%	159.96	29.5%	25.6	14.98	60.45
		Aug	213.56	569.88	172.89	40.67	81.0%	30.3%	39.47	201.43	12.13	94.3%	35.3%	159.96	28.1%	27.6	15.99	55.46
			665.0	**1611.4**	**526.0**	**139.0**	**79.2%**	**32.6%**	**119.9**	**625.1**	**40.0**	**94.2%**	**38.8%**	**474.72**	**29.5%**	**80.1**	**46.7**	**166.6**
	Autum	Sep	164.67	539.52	133.33	31.34	81.0%	24.7%	30.46	159.17	5.50	96.7%	29.5%	154.80	28.7%	27.9	15.94	46.40
		Oct	149.90	525.35	117.10	32.79	78.1%	22.3%	26.74	143.42	6.48	95.7%	27.3%	159.96	30.4%	28.7	16.84	43.58
		Nov	119.04	473.63	91.50	27.53	76.9%	19.3%	20.83	115.19	3.85	96.8%	24.3%	154.80	32.7%	27.1	16.11	36.94
			433.6	**1538.5**	**341.9**	**91.7**	**78.7%**	**22.1%**	**78.0**	**417.8**	**15.8**	**96.4%**	**27.0%**	**469.56**	**30.6%**	**83.7**	**48.9**	**126.9**
	Winter	Dec	114.55	451.72	76.27	39.11	66.6%	16.9%	17.59	106.30	8.26	92.8%	23.5%	159.96	35.4%	27.7	17.04	34.63
2021		Jan	105.08	435.36	77.79	27.43	74.0%	17.9%	17.15	102.76	2.32	97.8%	23.6%	159.96	36.7%	27.9	16.52	33.67
		Feb	157.15	421.40	101.25	56.33	64.4%	24.0%	22.24	143.08	14.08	91.0%	34.0%	144.48	34.3%	25.0	17.47	39.70
			376.8	**1308.5**	**255.3**	**122.9**	**68.3%**	**19.6%**	**57.0**	**352.1**	**24.7**	**93.9%**	**27.0%**	**464.40**	**35.5%**	**80.6**	**51.0**	**108.0**
Grand Total			**2050.3**	**6102.3**	**1550.2**	**501.6**	**75.2%**	**25.2%**	**352.1**	**1922.0**	**128.4**	**94.1%**	**31.4%**	1883.40	31.3%	**328.7**	**198.4**	**550.4**

Figure 3.22: Year-long simulation results for UPAC 8 (Phase 2) considering the pre-charge strategy.

Year	Season	Month	PV (kWh)	Load (kWh)	PV Only					PV + BESS								
					SC (kWh)	To Grid (kWh)	SC	SS	Savings (€)	SC (kWh)	To Grid (kWh)	SC	SS	OPE (kWh)	OPE (%)	Estimated Cycles	Savings (€)	
																	BESS	Total
2020	Spring	Mar	176.82	599.86	149.95	26.87	84.8%	25.0%	34.05	176.19	0.62	99.6%	29.4%	159.96	26.7%	30.3	18.30	52.35
		Apr	178.83	466.81	142.74	36.10	79.8%	30.6%	32.53	169.50	9.33	94.8%	36.3%	154.80	33.2%	26.7	16.11	48.64
		May	224.11	572.17	186.09	38.02	83.0%	32.5%	42.33	220.69	3.42	98.5%	38.6%	159.96	28.0%	30.1	18.47	60.80
			579.8	**1638.8**	**478.8**	**101.0**	**82.5%**	**29.4%**	**108.9**	**566.4**	**13.4**	**97.6%**	**34.8%**	**474.72**	**29.3%**	**87.1**	**52.9**	**161.8**
	Summer	Jun	195.41	630.24	172.26	23.16	88.2%	27.3%	39.14	194.33	1.08	99.4%	30.8%	154.80	24.6%	28.4	16.13	55.28
		Jul	260.32	647.90	219.99	40.33	84.5%	34.0%	50.11	257.70	2.62	99.0%	39.8%	159.96	24.7%	31.1	18.60	68.71
		Aug	214.94	661.36	185.40	29.54	86.3%	28.0%	42.29	213.98	0.96	99.6%	32.4%	159.96	24.2%	30.4	17.81	60.10
			670.7	**1939.5**	**577.7**	**93.0**	**86.3%**	**29.8%**	**131.5**	**666.0**	**4.7**	**99.3%**	**34.3%**	**474.72**	**24.5%**	**89.9**	**52.5**	**184.1**
	Autum	Sep	166.47	653.49	147.84	18.62	88.8%	22.6%	33.73	166.47	0.00	100.0%	25.5%	154.80	23.7%	27.9	16.12	49.84
		Oct	150.66	683.01	136.04	14.63	90.3%	19.9%	31.01	150.16	0.50	99.7%	22.0%	159.96	23.4%	27.7	15.05	46.07
		Nov	120.36	658.30	112.61	7.75	93.6%	17.1%	25.61	120.31	0.05	100.0%	18.3%	154.80	23.5%	25.7	13.68	39.29
			437.5	**1994.8**	**396.5**	**41.0**	**90.9%**	**19.9%**	**90.4**	**436.9**	**0.6**	**99.9%**	**21.9%**	**469.56**	**23.5%**	**81.3**	**44.9**	**135.2**
	Winter	Dec	116.12	686.18	102.33	14.22	88.1%	14.9%	23.41	115.27	0.84	99.3%	16.8%	159.96	23.3%	27.0	15.13	38.54
2021		Jan	106.69	633.66	99.97	6.72	93.7%	15.8%	21.96	106.55	0.14	99.9%	16.8%	159.96	25.2%	26.0	14.26	36.21
		Feb	159.84	572.83	138.51	21.34	86.7%	24.2%	30.37	159.74	0.11	99.9%	27.9%	144.48	25.2%	25.4	15.56	45.93
			382.7	**1892.7**	**340.8**	**42.3**	**89.5%**	**18.3%**	**75.7**	**381.6**	**1.1**	**99.7%**	**20.5%**	**464.40**	**24.6%**	**78.4**	**45.0**	**120.7**
Grand Total			**2070.6**	**7465.8**	**1793.7**	**277.3**	**87.3%**	**24.3%**	**406.5**	**2050.9**	**19.7**	**99.1%**	**27.9%**	1883.40	25.5%	**336.7**	**195.2**	**601.8**

Figure 3.23: Year-long simulation results for UPAC 8 (Phase 3) considering the pre-charge strategy.

4 Pilot Assessment: BESS Substation

This chapter presents the technical assessment of the pilot conducted at the distribution substation, namely pilot 5. The chapter is organized in four main sections. Section 4.1 provides the content and background information necessary to understand the remaining sections of the chapter. Section 4.2 presents and describes the storage control algorithms that were tested in the context of the pilot. Section 4.3 describes the assessment methodology, including the considered performance indicators. Finally, the assessment results are presented and discussed in section 4.4.

4.1 Context and Background Information

4.1.1 Fazendinha Substation

Fazendinha's low voltage distribution substation is located in one of the most western villages of Madeira Island, Estreito da Calheta. This substation has a transformer with an apparent power of 250 kVA, connected in delta-wye, which transforms the voltage from the transmission grid (6600 V) to the distribution grid (400 V).

As shown in Table 4.1, *Fazendinha* has a daily average load of 31 kW, an Off-Peak power of 10 kW, and a Peak power of 74 kW. At the moment the capacity of the transformer is relatively high when compared with the power requested by the grid, mostly due to the expectation of growth in farming activities and local accommodation businesses in this rural area.

Table 4.1 – Average Power values at the *Fazendinha* substation between 2019 and 2020

Daily Period	Power (kW)
Average load	31
Off-Peak	10
Peak	74

The transformer feeds a low voltage distribution board (QGBT) with five outputs that distributes the electricity throughout the public grid, supplying around 100 customers consisting mostly of domestic, small businesses and agricultural facilities. This is one of Madeira's low voltage grids with higher micro photovoltaic generation, with a total installed capacity of 36 kWp, distributed over 9 UPPs.

4.1.2 Load Levelling

With the high generation of energy from photovoltaic in micro-grids new problems start to arise to the DSO management system. One of the major challenges with photovoltaic generation is the lack of load in the grid when the production reaches high values.

This outcome was first verified in California, where the installation of photovoltaic power plants with high power peak capacity installed caused a sudden decrease/increase in the load when the sun starts rises/sets respectively [7]. Consequently, in order to account for such an effect, the TSO/DSO must have higher reserves (normally on the form of conventional thermal power plants) ready to respond when such load events may occur.

With a total installed PV capacity of 36 kWp and such a small number of consumers, such an effect is very likely to happen at the *Fazendinha* substation. In fact, this effect can be easily recognized in Figure

4.1 that represents the hourly trends and seasonality for the net-load (left), and solar radiation (right) for the years of 2019 and 2020.

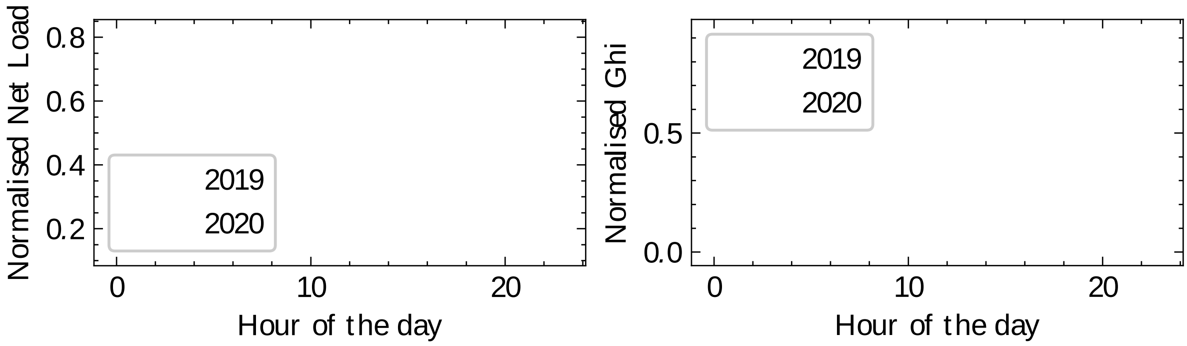


Figure 4.1: Seasonality in the trends for the net-load (left) and solar irradiation (right) during 2019 and 2020.

In line with what is being done around the world, the SMILE project presented the perfect opportunity to study how this effect can be mitigated using storage devices. To this end, two control strategies where developed and deployed through the EMS, one in real-world settings, and the other using Digital Twins.

4.2 Battery Control Algorithms

As just mentioned, two control strategies where developed and deployed through the EMS. The first algorithm is an Expert Heuristic (EH), and was deployed in real-world settings (i.e., with real-time storage control). The second algorithm is a Hybrid Expert Heuristic (HEH) that was optimized using a receding horizon strategy, as was deployed using the Digital Twins. Details of the two algorithms are provided in the following sub-sections.

4.2.1 Expert Heuristic

An expert heuristic (EH) algorithm was designed taking into consideration the tariffs currently in place, and the sun maps in Madeira Island. The objective of this EH is to increase the net-load demand during the sun periods and lower it in the early morning and early evening periods. Finally, the setpoints for inverter power were defined such that the battery would perform one full-cycle per day, i.e., charge and discharge the available 56 kWh, which corresponds to 70% of the nominal battery capacity (SOC_{min}=20%, SOC_{max}=90%).

The developed heuristic is summarized in Figure 4.2. Note that the heuristic varies slightly according to the established billing periods, i.e., Summer (from June to October), and Winter (from November to May) to account for seasonality effects.

WINTER (NOV - MAY)					
Tariff EEM	Sun Map	Time EH	Setpoint	Hours	kWh
00:00 - 09:00	00:00 - 07:30	00:00 - 01:00	-2.5	1	-2.5
09:00 - 10:30	07:30 - 10:00	01:00 : 07:30	-1	6.5	-6.5
10:30 - 12:00	10:00 - 12:00	07:30 - 09.00	1	1.5	1.5
12:00 - 18:30	12:00 - 14:00	09:00 - 10:00	2	1	2
18:30 - 21:00	14:00 - 16:00	10:00 - 12:00	5	2	10
21:00 - 23:00	16:00 - 18:30	12:00 - 14:00	11.5	2	23
23:00 - 00:00	18:30 - 00:00	14:00 - 16:00	6.5	2	13
		16:00 - 17:00	3.5	1	3.5
		17:00 - 18:30	2	1.5	3
		18:30 - 21:00	-10	2.5	-25
		21:00 - 23:00	-8	2	-16
		23:00 - 00:00	-6	1	-6
				24	56
					-56

Peak Period
Full Period
Off-peak Period
Peak Sun
High Sum
Sun Rise/Down

SUMMER (JUN - OCT)					
Tariff EEM	Sun Map	Time EH	Setpoint	Hours	kWh
00:00 - 09:00	00:00 - 07:00	00:00 - 01:00	-2.5	1	-2.5
09:00 - 10:30	07:00 - 11:00	01:00 - 07:00	-1	6	-6
10:30 - 13:00	11:00 - 13:00	07:00 - 09:00	1	2	2
13:00 - 20:30	13:00 - 15:00	09:00 - 11:00	2	2	4
20:30 - 22:00	15:00 - 17:00	11:30 - 13:00	5	2	10
22:00 - 23:00	17:00 - 21:00	13:00 - 15:00	11.5	2	23
23:00 - 00:00	21:00 - 00:00	15:00 - 17:00	6.5	2	13
		17:00 - 19:00	2	2	4
		19:00 - 20:00	-1	1	-1
		20:00- 22:00	-15	2	-30
		22:00 - 23:00	-10.5	1	-10.5
		23:00 : 00:00	-6	1	-6
				24	56
					-56

Peak Period
Full Period
Off-peak Period
Peak Sun
High Sum
Sun Rise/Down

Figure 4.2: Expert Heurists for winter and summer periods and their relation to power tariffs and sun maps (Setpoints are inverter power setpoint in kW; positive for charge).

4.2.2 Hybrid Expert Heuristic

In the hybrid exported heuristic the previously defined heuristic is optimized using receding horizon optimization procedure. More precisely, at each half-hour (h), the setpoint is set such as it minimizes a loss function for the receding period T – h, where T is the optimization horizon, in this case, 24 hours. An illustration of the procedure is provided in Figure 4.3. In the first step, at 00:00, the invert setpoint is optimized with a forecasting horizon from 00:30 to 23:30. On the 12th step, the optimization occurs at 12:00, with a forecasting horizon from 12:30 to 23:30. On the 46th step, the optimization occurs at 23:00, with a forecasting horizon from 23:30 to 00:00. Finally, on the 47th and last step of the day (not illustrated), the optimization occurs at 23:30, with a single point forecast at 00:00.

At this stage it is important to remark that the optimization interval of half-hour was selected due to restrictions in the availability of real-time solar irradiation forecasts, which is only available at 30-minute intervals, as will be explained next.

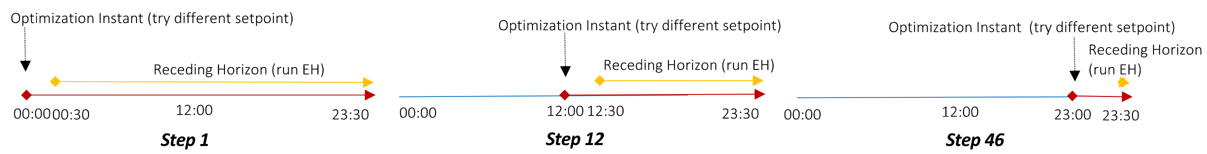


Figure 4.3: Illustration of the receding horizon optimization procedure.

To this end, it was necessary to define a net-load forecasting procedure and an objective function for the optimization step.

4.2.2.1 Net-load Forecasting

For net-load forecasting a Sequence to Sequence (Seq2Seq) architecture based on Recursive Neural Networks has been implemented. The neural network takes inputs such as historical net-load and solar radiation measurements as well as exogenous variables that were derived from the calendar, e.g., time of day and day of week. The output is a sequence of net-load predictions. An illustration of the net-load forecasting procedure is given in Figure 4.4.

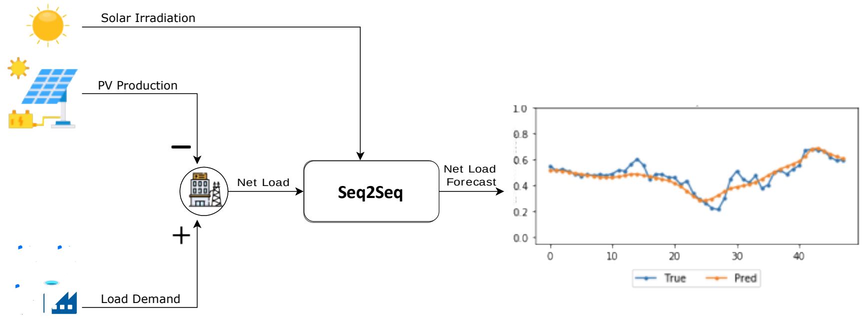


Figure 4.4: Illustration of the developed net-load forecasting procedure.

At the time of development, historical net-load demand measurements were available at the EMS at 1-minute intervals for each phase. This dataset spans from March 2019 to December 2020. During this period, and also until this writing, the installed PV generation remained the same (36 kWp). Still, the demand showed a slight increase due to more extended periods at home as a result of the Covid-19 contingency measures that were in place during part of 2020. This increase is easily observable in Figure 4.1 (left). Real-time net-load measurements, needed for the real-world deployment, are also available from the EMS, at the same resolution of one sample per minute.

Historical solar irradiation data was downloaded from Solcast [8] using the geographical coordinates of the substation. The downloaded data spans from March 2019 to December 2020 and are available at 5, 10, 15, 30, and 60-minute resolutions. Real-time solar irradiation forecasts are also available for the next seven days at 30-minute resolution through a Solcast webservice that was integrated in the EMS.

For the purpose of this project, the algorithm was configured such that it takes two days of historical data as inputs, using 30 minutes time steps (96 samples), and returns the net-load predictions for the next 24 hours (48 samples). The following features were used:

- Scaled net-load for the previous 48 hours (Load)
- Scaled Historical Global Horizon Irradiance for the last 24 hours (Ghi)
- Scaled Forecasted Global Horizon Irradiance for the next 24 hours (GhiD)
- Point-wise subtraction of Ghi and GhiD from Load (Load - Ghi)
- Exogenous features from the date and time (Day of Week and Hour)

The input features are illustrated in Figure 4.5.

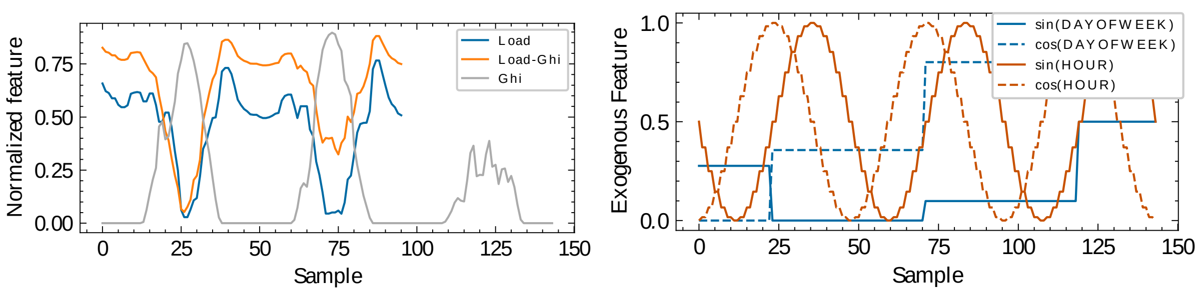


Figure 4.5: Illustration of domain (left), and exogenous (right) features used for net load forecasting.

4.2.2.2 Objective Function

In very high-level terms, the objective of load leveling through BESS is to minimize the amount of load that is above or below an upper and lower threshold, respectively, by setting different charging and discharging setpoints in the BESS. To this end, the objective function presented in Equation (4.1) was defined:

$$Minimize\ O(h)_{inv} = \left(\sum_{h}^{T} NL_{>uthr} + \sum_{h}^{T} NL_{<lthr} + \sum_{h}^{T} NL_{<0} \right) \quad (4.1)$$

$$subject\ to:$$
$$-40\ kW \leq inv \leq 40\ kW$$
$$20\% \ \leq SOC \leq 90\%$$

where $NL_{>uthr}$ represents the net-load that is above the upper threshold (*uthr*), $NL_{<lthr}$ is the net-load that is below a lower threshold (*lthr*), and $NL_{<0}$ represents negative net-load, i.e., when the load is flowing from the Low Voltage (LV) to the Medium Voltage (MV) network. The first constraint refers to the inverter nominal power that needs to be equal or less than 40 kW in absolute value (see Table 2.5). The second constraint refers to the minimum and maximum levels of SOC that were set to 20% and 90%, respectively.

Regarding the upper (*uthr*), and lower (*lthr*) net-load thresholds, they were set to 75% and 25% quartiles of the historical net-load, respectively. In other words, the net-load is considered levelled if it lies within the Inter-Quantile Range, which is a measure of where the bulk of the values lie and how they are clustered around the mean.

Implementation notes

Concerning the implementation, it is important to note that since the objective is to optimize the expert heuristic, when calculating the objective function the different inverter setpoints (*inv*) are only tested in the optimization timestep *h*. In all the remaining timesteps (*h+1, …, T*), the inverter setpoint is given by the expert heuristic. In other words, at each optimization timestep *h*, there are $S = I \times (T - h)$ possible solutions to be evaluated, where I is the set of all possible inverter setpoints.
In this concreate case, it was established that the set of possible setpoints is discrete, with a step size of 5 kW, i.e., the size of I is 17. Hence, at 00:00, $S = 17 \times (48 - 1) = 799$.

This algorithm was implemented using a top-down dynamic programming with memorization approach. More precisely, at each optimization step the different values of the objective function are stored (in volatile memory), such that whenever a new optimization step is performed, it is first checked in the memory to see if it was already calculated. If a solution exists it can be directly used, otherwise the new problem is solved and its solution is added to the memory.

4.3 Assessment Methodology

The assessment is performed in two steps: 1) the performance of the net-load forecasting, and 2) the performance and benchmark of the two load levelling approaches.

Net-load forecasting

With respect to the net-load forecasting algorithm, the training and test procedures are described and the forecasting results are discussed. The performance metric used for this case is the Normalized Root Mean Squared Error (RMSE), which is given by Equation (4.2):

$$RMSE = \sqrt{\frac{\sum_{t=1}^{T}(\hat{y}_t - y_t)^2}{T}} \quad (4.2)$$

where $\widehat{y_t}$ is the net-load forecast at step t, y_t is the actual net-load at step t, and T is the number of forecasted samples. The RMSE is always non-negative, and a value of 0 would indicate a perfect net-load forecast. Another important property of the RMSE is that the performance is reported in the same unit as input data, in this case Watts.

Load levelling

Concerning the load levelling ability, this is assessed by measuring the total energy above and below the upper and lower thresholds, respectively, and comparing the improvements with respect to the case where load levelling is not performed. In this way, the best performing algorithm is the one that is able to move more energy to the range defined by the IQR of the historical net-load, as presented above. To enable a direct comparison between seasons of the year, the results are presented per month, supplemented with seasonal and yearly totals.

To this end, the net-load measurements (original and levelled) were first averaged from the original 1-minute resolution to 60-minutes. The upper and lower thresholds were calculated from the original net load of each month and were then used to calculate the monthly net energy that is not within the thresholds. To enable an individual assessment of the ability to level peak and off-peak net-load, one net-energy value was calculated for each threshold.

4.4 Results and Discussion

4.4.1 Net-load Forecasting Performance

The net-load forecasting algorithm was trained using historical data from March 1st, 2019, to August 31st, 2020, i.e., a total of 17 months. The one-minute data was first cleaned by dropping null entries and then averaged to 30 minutes. The maximum number of training epochs was set to 1000, with patience of 100. In other words, if during 100 consecutive training epochs there is no improvement in the validation loss (i.e., the algorithm is no longer learning any new information), the training stops, and the model with the lowest validation loss is selected.

The testing was performed using data from September 1st and September 27th, following a sliding window approach with a step size of 30 minutes. This was done to simulate the real-world environment, where a new net-load forecast will be required every 30 minutes. To this end, and to avoid having inconsistent sequences, the one-minute data are cleaned by applying forward and backwards filling. The one-minute data are then averaged to 30-minute intervals.

To illustrate the net-load forecasting results, Figure 4.6 and Figure 4.7 display the performance of the 27 days in the test set, i.e., between 00:00 and 23:30. More precisely, Figure 4.6 presents the 24H average RMSE, whereas Figure 4.7 plots the predictions against the actual net-load values for the first 20 days (the other seven days are omitted to reduce the size of the figure).

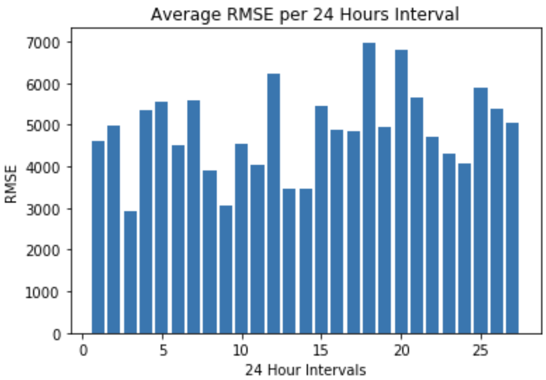


Figure 4.6: Average RMSE obtained on the 27 full days of the test set.

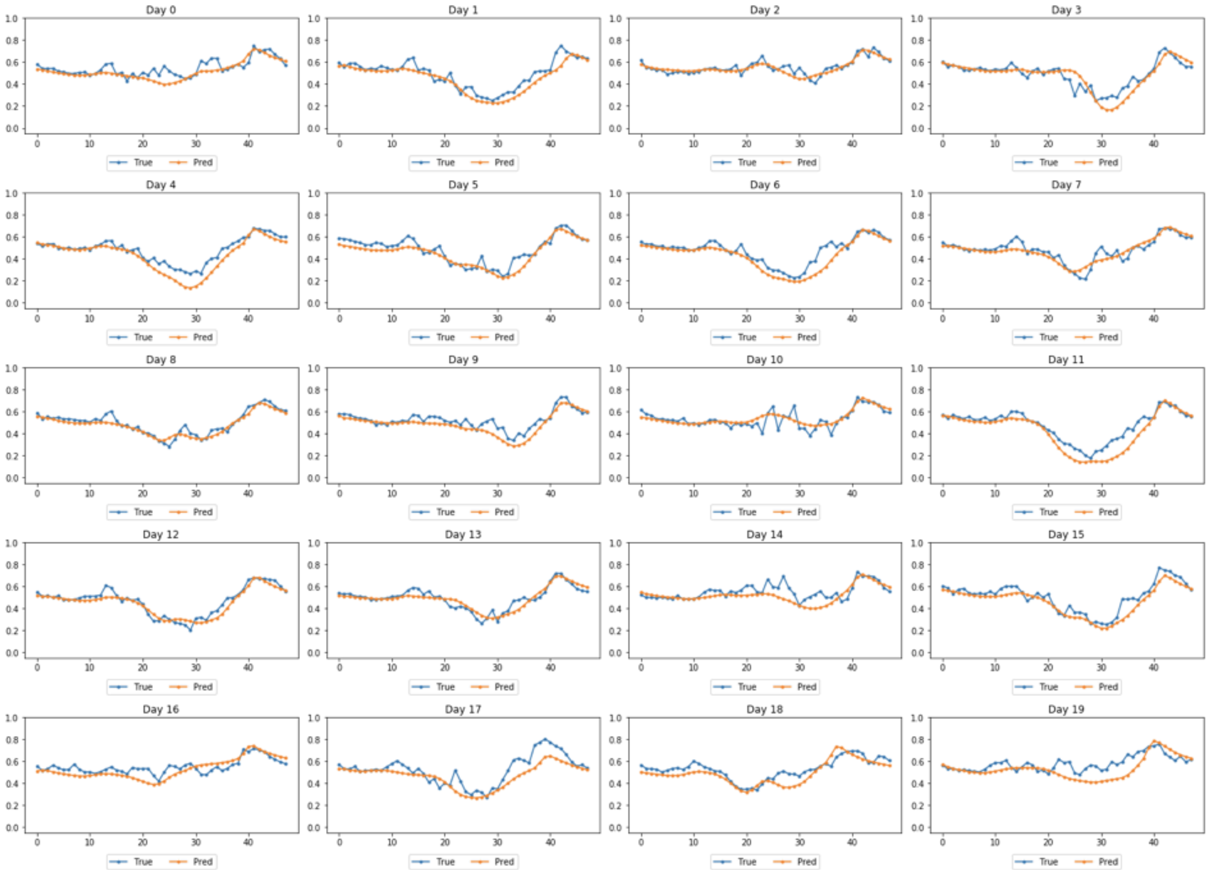


Figure 4.7: Forecasted net-load values vs the measure net-load for the first 20 full days of the test set.

As it can be observed, the RMSE ranges between 3kW and 7kW, with an average of around 4.5kW. Considering that the average net-load varies between 10kW and 74kW (see Table 4.1), it is expected that the average error will be around 7%. However, when it comes to an actual application of net-load forecasts (and any kind of forecast), the errors are not all equal. Hence, it is of crucial importance to reflect on the different aspects of the obtained results. In this concrete case, there are three aspects that should be highlighted as they can have profound effects on the load-levelling results.

First, the net-load forecasts tend to be accurate with respect to the peak demand, which usually happens around 8:00 - 8:30 PM. In the context of load levelling, this aspect is particularly important since the objective is to reduce peak demand by discharging the storage device during those periods.

Therefore, if the peaks are underestimated, the algorithm may set lower inverter setpoints that may not be enough to shave the most prominent peaks in consumption. In contrast, if the peaks are overestimated, the algorithm will set larger setpoints that will drain the battery faster, hence not accommodating the entire period when the peak demand is actually happening.

Another important observation is that when the net-load tends to be stable, which is an indicator of lower PV production, the forecasts are also very stable. In the context of load levelling, this means that in days of lower PV production, the inverter setpoints will tend to be set to lower values but for longer periods. Ultimately, this will avoid the unnecessary increase of the net-load during the afternoon, which in extreme cases can lead to net-load demand above the upper threshold.

On the other hand, it can be observed that on some days where PV production is higher, the algorithm tends to underestimate the net-load during the afternoon (e.g., days 4 and 11). In terms of load levelling, this can result in unnecessarily high charging setpoints for short periods of time. On such occasions, the battery capacity will be reached faster, meaning that it will not be possible to level most of the future net-load below the lower threshold.

4.4.2 Load Levelling Performance

The load levelling algorithms were deployed in December 2020 and January 2021. More precisely, the expert heuristic was deployed in the real-world system, whereas the hybrid expert heuristic was deployed with the help of the Digital Twins platform.

Still, due to some issues with the initial deployments, the earlier results were not consistent. For example, due to an issue with the radiation forecasts, the system was idled for two consecutive weeks in April. Therefore, the analysis was performed only on the data between May and October 2021, which was when the system reached the desired levels of stability. The monthly and seasonal results are presented in Figure 4.8.

Year	Season	Month	Net-Load (MWh)	uthr (kW)	lthr (kW)	Original		EH				HEH			
						>thr (kWh)	<thr (kWh)	>thr (kWh)	Impr. (%)	<thr (kWh)	Impr. (%)	>thr (kWh)	Impr. (%)	<thr (kWh)	Impr. (%)
2021	Spring	May	25.69	40.48	28.03	1449.32	3631.68	1036.52	28.48%	3774.79	-3.94%	727.78	49.8%	2441.19	32.8%
			25.69	**40.5**	**28.03**	**1449.32**	**3631.68**	**1036.5**	**28.48%**	**3774.79**	**-3.94%**	**727.78**	**49.8%**	**2441.19**	**32.8%**
	Summer	Jun	24.32	39.53	28.60	1090.54	3710.13	754.97	30.77%	3747.25	-1.00%	776.57	28.8%	3130.17	15.6%
		Jul	25.35	39.74	27.91	1375.30	3732.33	428.95	68.81%	3349.17	10.27%	396.82	71.1%	2005.89	46.3%
		Aug	25.41	40.70	27.47	1396.29	3392.32	364.01	73.93%	3278.51	3.35%	365.33	73.8%	1913.30	43.6%
			75.08	**39.99**	**28.0**	**3862.13**	**10834.78**	**1547.9**	**59.92%**	**10374.93**	**4.24%**	**1538.7**	**60.16%**	**7049.36**	**34.94%**
	Autum	Sep	24.35	40.61	28.23	1354.48	3265.69	340.71	74.85%	3025.93	7.34%	291.85	78.5%	1880.32	42.4%
		Oct	26.11	42.30	29.99	1298.54	3641.61	500.60	61.45%	3159.60	13.24%	418.65	67.8%	2289.23	37.1%
			50.46	**41.46**	**29.11**	**2653.02**	**6907.30**	**841.3**	**68.29%**	**6185.53**	**10.45%**	**710.50**	**73.22%**	**4169.55**	**39.6%**
Grant Total			**151.23**	**40.64**	**28.4**	**7964.47**	**21373.8**	**3425.8**	**56.99%**	**20335.3**	**4.86%**	**2977.00**	**62.62%**	**13660.10**	**36.09%**

Figure 4.8: Results of the two load levelling algorithms at the Fazendinha substation.

By looking at the *uthr* and *lthr* columns, it can be seen that the load would be considered levelled when following in the interval between around 28 and 40 kWh. Likewise, looking at the original values, i.e., without load levelling, it is concluded that the amount of load below the *lthr* is much higher than the load above the *uthr*, which can be considered natural due to the high penetration of PV power in this substation.

Regarding the performance of the two deployed algorithms, the results show that with respect to the levelling of peak demand (i.e., net-load above the *uthr*), the two approaches have similar performances, with a natural advantage to the HEH. Ultimately, the EH is capable of levelling in average

57% of the net-load above the upper threshold, whereas the HEH can level in average 63%. In contrast, when it comes to the lower threshold, the HEH is able to level up to 36% of the net-load below that 25% quantile, in contrast to the less than 5% achieved by the EH.

To better understand these results, Figure 4.9 depicts the results obtained by each algorithm during two days in July (left) and October (right). The top plot depicts the net-load time-series before and after the load levelling operations, the centre plot depicts the inverter setpoints defined by EH, whereas the last plot shows the inverter setpoints considered optimal by the HEH. Furthermore, Table 4.2 summarizes the load levelling results in these two particular periods.

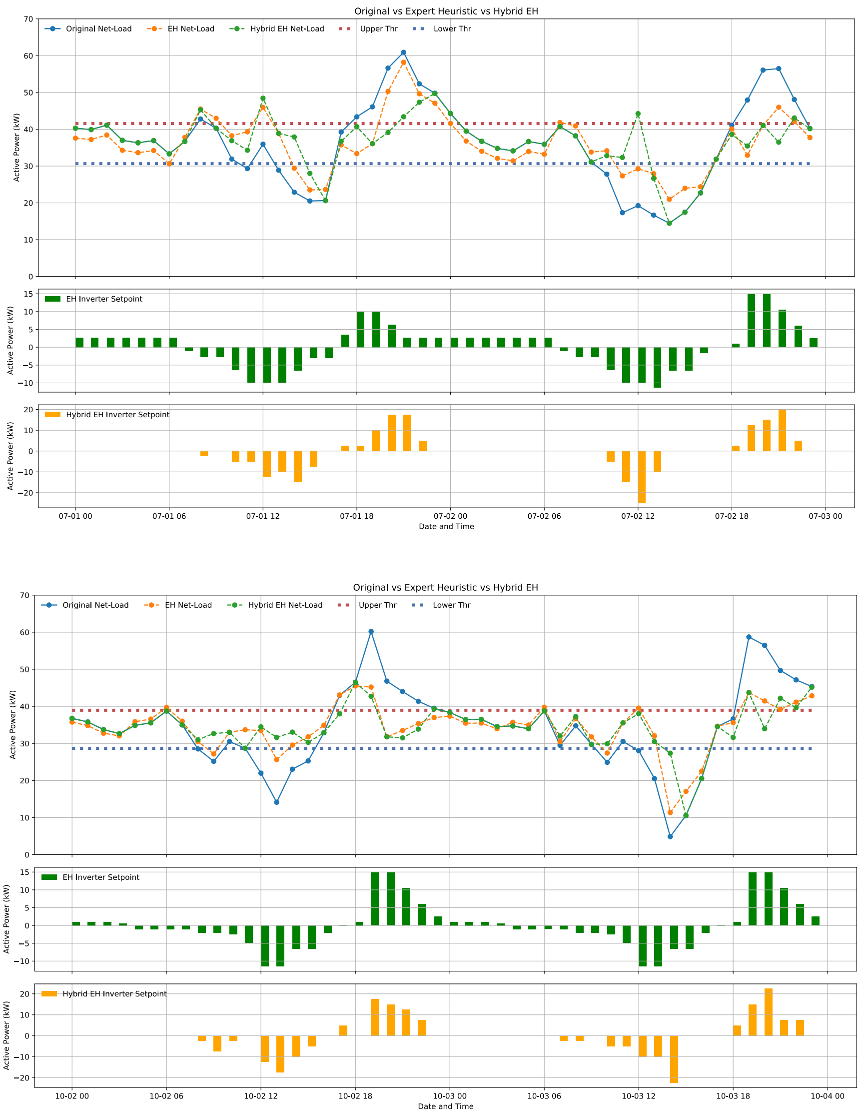


Figure 4.9: Results of the load levelling algorithms during two days in July, and in October 2021.

From the top plots it is possible to observe that originally, the net-load is above the upper limited for at least seven hours a day, normally between 6PM and 23:59PM, with some periods that easily reach 20 kW. Considering that with a SOC of 90%, the full capacity of the battery is around 56 kWh, an inverter setpoint of 15 kW, would drain the battery in less than four hours which is just above half of the period that the net-load is above the upper threshold. Consequently, while the HEH can reach setpoints up to 40 kW, anything above 20 kW is unfeasible. This is why the highest setpoint of the HEH is 20 kW, and therefore around the same range of the setpoints defined in the EH. It is also observable that the setpoints of the HEH are set to zero during the night, leaving more energy available for the load levelling operation, hence the slight upper hand when compared to the EH.

Conversely, when considering the lower threshold, it is possible to observe that due the high penetration of PV power, there is a considerable amount of net-load below the lower threshold. This effect is especially visible around 12PM, when the minimum threshold is infringed between 10 kW and 25 kW. Consequently, since the EH was designed with a maximum charging threshold of 11.5 kW (see Figure 4.2), it is not possible to meet the minimum threshold most of the time. Hence the poor performance, particularly in May and during the Summer, as shown in Figure 4.8. On the other hand, the HEH does not have such a limitation. However, following the same exercise as above, setting the inverter setpoint to values around 25 kW, the BESS would reach the maximum SOC (90%), in just about 2 hours from a SOC of 20%. Hence, the maximum charging setpoint only in rare occasions reaches such values, as seen on the bottom chart of Figure 4.9. Still, as per the obtained results, being able to defined setpoints above 11.5 kW considerably improves the ability to level the load during peak PV production time. This effect is easily observable in Table 4.2, that shows a difference in performance of 39 percentage points, when it comes to levelling net-load under the lower threshold.

Table 4.2: Results of the load levelling for the time period used in Figure 4.9.

Time Period (YYYY-MM-DD)	uthr & lthr (kW)	Energy (kWh)		
		Original	EH (Impr. %)	HEH (Impr. %)
2021-07-01 to 2021-07-02	41.5	106	54 (49)	33 (69)
	30.7	257	230 (11)	129 (50)
2021-10-02 to 2021-10-03	38.9	128	73 (43)	50 (61)
	28.6	257	230 (11)	129 (50)

5 Conclusions

This report presented the results of three pilots aimed at demonstrating the real-world applicability of a cloud-to-cloud solution for deploying energy monitoring and BESS control in different micro-production contexts where the main source of renewable energy is solar PV. In pilot number one the cloud-to-cloud solution was demonstrated in the scope of domestic micro-producers, whereas in the second pilot the demonstration focused on commercial micro-producers. Overall, in these two pilots the main goal was to demonstrate and assess the effectiveness of using BESS for increasing the self-consumption and self-sufficiency rates. Finally, in the third pilot the cloud-to-cloud system was used the demonstrate the potential of BESS to provide load levelling capabilities at the substation level.

In total, seven residential BESS systems have been tested, four in domestic UPACs, and three in a commercial UPAC with a three-phase power system. In each of the cases, the benefits of introducing BESS were demonstrated, with clear impacts on the potential savings as a result of increased self-consumption.

For the residential systems with higher PV capacity (UPACs 6, 9 and 13) the addition of a BESS has almost doubled the self-consumption from PV power production. Leading to savings of 30-60% based on the Greedy Algorithm. Interestingly, all the UPACs have presented their own challenges and consequently different levels of benefit. For example, for UPAC 6, it was shown that it was possible to achieve a degree of self-sufficiency of around 90%, even with a smaller battery. Still, it should be stressed that this happens due the a consistently low demand throughout the day. On the other hand, for UPAC 2, it was shown that pre-charge can be an option when the levels of consumption are much higher than the available PV capacity.

A seasonal analysis has revealed that during Autumn and Winter, the rates of self-sufficiency drop in all the domestic UPACs as the result of the lower availability of PV power. Furthermore, December has shown to be the worst month in this regard, since to the lower PV availability it is also added an increase in the demand due to the holiday season. Again, this presents an opportunity for pre-charging the battery in autumn and winter. Still, pre-charging needs to be handled with care, since excessive levels of pre-charge can lead to decreases in the SC rates, especially in the morning periods. Furthermore, the profitability of pre-charge operations is highly dependent on the pricing mechanisms in place. In the concrete case of Madeira Island, a time-of-use tariff with two billing periods (peak and off-peak), revealed to be effective.

For the commercial UPACs, three battery systems were deployed, one in each consumption and production phase. In this UPAC, due to the small size of the PV installation, the SC rates were considerably high even before installing the BESS, ranging between 61% and 70% across the three phases. Therefore, overnight pre-charge was the only viable option in this UPAC. Overall, the demonstration has shown a smaller effect of the BESS in increasing the SC rates, with an average increase of 18%. However, the overnight charging strategy has moved power demand to off-peak hours, which as leads to significant saving in the energy bill. In the concreate case of UPAC, this operation enabled to cover in average 26% of the total demand with energy acquired during the off-peak period.

In the case of the commercial UPAC, the seasonal analysis revealed that the consumption remains stable throughout the year, despite the evident effects of the Covid-19 measures in April and May of 2020 that lead to a significant decrease in the electricity demand due to the lockdowns measures that were in place during that time.

The large-scale BESS deployed in the substation has allowed demonstration of how such devices can also be used to stabilize the net-load demand at the substation level through load-levelling strategies. Using a Hybrid Expert Heuristic, with 30-minute updates, revealed that it was possible to level down an average of 57% of the top 25% of the peak net-load demand by charging the BESS during the periods of higher PV production. Furthermore, by charging the storage device during the periods of peak PV production, it was also possible to level up up-to 36% of the lower 25% of the net-load demand.

A seasonal analysis of results as also revealed that the highest rates of load levelling are achieved during the summer months, taking full advantage of the increase in the PV production that is naturally observed during the summer season.

Overall, the three real-world pilots served to demonstrate the feasibility of cloud-based storage control. However, on some occasions, it became evident that the latency introduced by the cloud-to-cloud communications may hurt the overall performance of the system. This was the case of UPAC 8, where it was shown that updating the inverter setpoints every two minutes was not enough to cope with the fast variations in the demand of phase 3. Therefore, in certain situations, it is necessary to bring computation closer to the storage device. A typical solution for this would be to put the storage control logic on an edge device that has direct access to the battery management system. In this situation, commonly known as cloud-to-edge computing, the storage control algorithm would still be executed on the cloud, but the interactions with the battery would be direct, hence reducing the latency between data acquisition, control logic, and actuation.

To conclude, it is important to remark that since the beginning of the SMILE project, there have been some important changes in the renewable energy landscape in Madeira Island. Among them is the possibility of selling excess production at a feed-in tariff, and with that, the opening of the grid to the establishment of renewable energy communities. While the latter is still in its infancy, the former is already in practice with a feed-in tariff that, as of this writing, is around 7 cents per kWh. Therefore, it is expected that the number of PV installations will increase in the near future, not only in the number of micro-producers but also in installed capacity. In fact, as it was discussed in deliverable D4.3 [9], [10], the installed capacity of the majority of the existing UPACs in Madeira Island is considerably small due to the inability to sell the excess PV production to the grid.

Still, while this brings added benefits to the micro-producers, that will be rewarded for feeding back excess PV production to the grid, it will bring added challenges to the grid operators that have to find new ways to deal with the effects of having higher shares of energy from behind-the-meter PV installations. Simply put, in such a scenario, storage will play an even higher role, independently of being distributed (i.e., at the premises of the micro-producer) or centralized (e.g., at the premises of the grid operator, or renewable energy community manager).

With this regard, the main takeaway of these three pilots, as well as of other related pilots in the SMILE project, is that the required technologies are available and ready to be deployed in production environments. Naturally, there is still some ground to cover, especially when it comes to the practicalities inherent to making any new technology widely available and accepted. These include public policy, business models, user acceptance, and cyber-security, all of which have been to some extent addressed in the SMILE project.

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