REGULATORY-FRAMEWORK-EMBEDDED ENERGY MANAGEMENT SYSTEM FOR MICROGRIDS: THE CASE STUDY OF THE SPANISH SELF-CONSUMPTION SCHEME

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Abstract

This paper proposes for the first time to analyse the impact of embedding the regulatory framework constraints inside a model for the energy management optimization of a microgrid. As a case study, a low voltage microgrid using solar energy under the Spanish self-consumption scheme has been selected. The proposed model is based on a previous one elaborated by the authors, which did not include the regulatory framework. The results provided by the former and the new model have been compared, corroborating the importance of taking into account the economic aspects of the regulatory constraints when managing the facility. Furthermore, the results also highlight the urgency to extrapolate this approach to other countries, in order to enhance the economic feasibility of these facilities and aid to their deployment. In addition, the performance of the model has been experimentally validated at the Microgrid Research Laboratory of Aalborg University.

Keywords

Self-Consumption, microgrid, energy management, regulatory framework

1. Introduction

The European Union's (EU) energy policy has made it a world leader in the promotion of renewable energy [1]. The consumer rights and protection are a crucial part of this policy. In this regard, the EU is currently working to guarantee that the European consumers may have the right to produce, store, consume, and resell their self-generated electricity to the grid. In fact, self-consumption is nowadays a reality in a significant part of the EU countries and around the world [1]. It is expected to be a promising tool to promote renewable energy in the tertiary and domestic sectors, with microgrids being an intrinsic part of the self-consumption facilities.

Hereof, research on microgrids has deserved special attention in these last decades, and some recent studies have focused on reviewing their evolution. Some of these reviews provide a holistic view of the microgrid concept and allow to see its intricacies [2], while others focus their attention on specific parts or processes, such as energy management systems (EMS) of microgrids [3, 4]. In this regard, an update on the state of the art of the EMS has been here conducted, elaborating on the studies [3, 4]. This update includes both new articles and some older ones not covered by the aforementioned reviews. The resulting upgraded state of the art is shown in Table 1.

Table 1. State of the art of microgrid research. Source: self-elaboration based on [3, 4].

The rows of Table 1 are grouped into two sections. Whereas the upper rows contain references using single objective optimisation (SOO), the lower rows collect those with a multi-objective optimisation (MOO) approach. Both the SOO and the MOO sections of Table 1 are further divided into new subsections containing the most relevant objective functions identified in [3]. Likewise, the columns of Table 1 are grouped into two sections. The columns on the left side include references considering a single energy vector (electricity), while the columns on the right side gather those using multiple energy vectors (electricity, heating/cooling and/or water). In turn, a second level of classification is established in each of the single/multiple energy vector sections, according to the implementation or not of a demand response system in the microgrid EMS. Finally, the references are sorted depending on whether additional features such as grid model, uncertainty, experimental validation, regulatory framework, etc., are considered.

As can be seen in Table 1, SOO prevails over the MOO approach. Regarding the objective function type, the minimisation of the system operating cost is the most spread, followed by the minimisation of the energy purchasing cost and the maximisation of the revenue of energy selling. At all events, economic considerations in the objective function predominate over the environmental issues. On the other hand, electricity is the only energy vector considered by over 65% of the references, and 78% of the studies do not contemplate the use of a demand response system when managing the energy system. Also, 58% of the references include some of the listed additional features in their models. In this regard, 38% of the studies opted for incorporating uncertainty in their analyses.

Nevertheless, to the authors' knowledge and according to the state of the art in Table 1, 97% of the analysed research don't incorporate in their algebraic models the regulatory constraints. This is at least surprising considering the deep impact of the regulatory frameworks in the economic performance of the energy assets [98, 99]. Even though the energy sector is highly regulated, only a few articles [88, 91, 97] contemplated the use of regulatory constraints in their models, but they did not analyse neither their impact nor their importance. As a result, the lack of studies elucidating the influence of regulatory constraints on energy management results may induce to think that there is no need to incorporate such limitations in the models. To overcome this gap, the article is aimed to give clear evidence that regulatory framework constraints alter the optimal energy management of a microgrid. To do so, a model used in previous works [59,60] has been modified in order to consider the regulatory framework applied

Table 1. State of the art of microgrid research. Source: self-elaboration based on [3, 4].

		Electricity												Electricity, Heat (cooling) and (or) Water											
		Type of management												Type of management											
		Energy management						Energy management and Demand Response System						Energy management						Energy management and Demand Response System					
		No additional features	Dealing With additional features					No additional features	Dealing With additional features					No additional features	Dealing With additional features					No additional features	Dealing With additional features				
			Power flow /Grid model	Uncertainty	Experimental validation	Regulatory framework	Others		Power flow /Grid model	Uncertainty	Experimental validation	Regulatory framework	Others		Power flow /Grid model	Uncertainty	Experimental validation	Regulatory framework	Others		Power flow /Grid model	Uncertainty	Experimental validation	Regulatory framework	Others
Type of Objective Functions / Single Objective Optimization (SOO) / Type of Objectives	Minimize the risk / Deviations		[73,74,81]	[70]	[70,74,81]					[69]				[8]											
	Minimize polluting gas emission	[36,54,58]		[40]										[56]											
	Maximize the revenue of MG	[36,58,63,80, 83]	[16,25,26,52]	[6,16,25,26, 55,59]	[15]			[33,25]						[8,18,34,56]		[17,23,51]		[88]		[7,29,32,50]	[11]	[11]	[11]	[97]	
	Maximize comfort /energy output DER		[66]	[70,84]	[70]																				
	Minimize the system operating cost	[22,30,36,54, 58,60,94]	[5,6,16,20,25, 26,52]	[6,16,21,25, 26,28,37,40, 41,42,45,46, 49,55,59,65,87]	[15,21,28]		[75]	[33,35,62]	[72]					[8,18,31,34, 38, 56,67]		[17,23,43,51, 89]	[82,93]	[91]		[7,29,32,50]	[11]	[11,90]	[11,76,77,79]		

Multi-Objective Optimization (MOO)								
Type of Objectives								
Minimize the total cost for purchasing electricity	Minimize the energy loss	Minimize the system operating cost	Maximize comfort /energy output DER	Maximize the revenue of MG	Minimize polluting gas emission	Minimize the risk / Deviations	Minimize the total cost for purchasing electricity	Minimize the energy loss
[19,48, 57]		[19,48,57,68, 71]	[48]	[19,48,57,64]	[57,68,71]	[19,64]	[22,36,58,60, 95,96]	
[24]	[24]	[24]		[24]			[5,6,16,25,26, 52]	[5]
[9,12,39]		[9,12,39,44, 47,78]		[9,12,39,47]	[9,44,78]		[6,16,25,26, ,55,59]	
[85]			[85]			[85]	[15]	
							[35]	
[27]		[13,27]		[27]	[13,27]			
[86]		[86]			[61]		[8,18,34, 56]	
[14]		[14]		[14]	[14]		[17,23,51]	
[10,53]			[10,53]	[10,53]	[53]		[7,29,32,50, 92]	
							[11]	
							[11]	
							[11]	

to a consumer owning a microgrid. In addition, the characterisation of the regulatory framework has been realised accurately, not just conceptually. Concerning this, the Spanish regulatory framework has been selected for this study as it is considered one of the most complex systems in the EU countries, either due to its energy contracts or to the self-consumption scheme applied to consumers.

To this end, the paper provides a description of the energy contracts and the self-consumption regulatory scheme applied to low voltage consumers in Spain (section 2). Next, the research methodology is introduced (section 3) and the model addressing the regulatory framework (section 4) is described. Then, a case study is undertaken, and the obtained results are experimentally validated at the Microgrid Research Laboratory of Aalborg University (section 5) [100]. Finally, all the factors deemed relevant are duly systematised, and conclusions are raised (section 6).

2. Setting the context

2.1. Energy bill structure for low voltage consumers

Low voltage consumers not exceeding 10kW are allowed to choose between two types of energy contracts, either those under the Royal Decree (RD) 216/2014 [101] (a sort of energy contract with regulated energy prices) or those under the rules of the liberalised energy market. The rest of low voltage and all the high voltage consumers are forced to hire energy in the liberalised energy market. In all cases, the resulting cost for a consumer is a function of the energy cost and the access tariff cost. In this article, the attention will be focused on the energy contracts in the liberalised energy market, as they are the common case of energy contracts applicable to all type of energy consumers.

In Spain, the energy cost is the result of three processes, i.e., the cost of producing energy in the Iberian Electricity Market (IEM) (subjected to the RD 2019/1997 [102] and the Day-Ahead and Intraday Electricity Market Operating Rules of May 2018 [103]), the energy transport and distribution losses and the economic margin of the retailer.

Regarding the cost of producing energy in the IEM, sale and purchase bids are made one day ahead, considering between 1 and 25 energy blocks with their respective power and energy prices offers for each hour of the day. For purchase bids, preference is given to those bids that have the highest energy prices. For sale bids, it is quite the opposite. As a result, a marginal price is determined for each hour of the following day, called the daily market price (Pm_h). Nevertheless, this price is increased due to the cost of all the required services addressed to guarantee the energy supply (technical constraints, ancillary services, capacity payments, etc.), resulting in a final price called average hourly final price.

Due to the energy losses of the grid, a loss coefficient increasing the energy price is applied to the energy consumption according to the voltage level and the rated power of the consumers. Additionally, the commercial margin of the retailer is charged to the consumers, giving as a result, the final energy purchased price ($fepp_h$) [1]. In this regard, the hourly demand of the consumer (DH_h) is calculated according to this final energy purchased price, resulting in the energy cost (see Figure 1).

The other significant term in the energy bill is the access tariff cost to the grid. In this regard, (article 16 of the Law 24/2013 [104] of the Spanish Electricity Sector (LSES)) the access tariffs are applied to energy consumers to guarantee the incomes of the Spanish Electricity Sector (SES) and the retribution of the regulated activities (mainly, transport and distribution and the specific retribution of renewable energy). According to the RD 1164/2001 [105] and its subsequent amendments, all the consumers of the SES are classified according to their voltage level and rated power. Each group has its corresponding type of access tariff, which, at the

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[1] Depending on the type of contract, this energy price might be charged to the consumer either in form of fixed rate (i.e., the energy price remains stable throughout all the hours of the day and month) or variable rate (the energy price may change depending on the period of the day, or from month to month, etc.) or indexed to the IEM (pass-through). In this study, it was assumed that the consumer's facility had an indexed contract as it is the type of contract where the variation of the energy prices in the IEM might be easily translated into economic decisions for the consumer.

same time, is composed by two terms, i.e., the energy term and the power term. The consumer will be charged for the energy consumption and the rated power according to the energy term (AE_Grid) and to the power term (AP_Grid), respectively (see Figure 1).

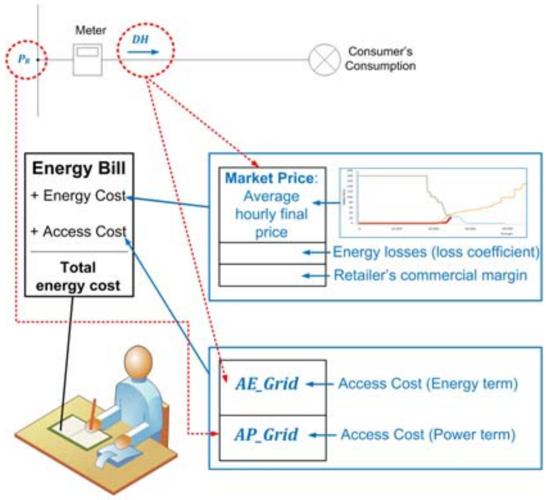

Figure 1. Conceptual definition of the consumer's total energy cost. Source: Self-elaboration.

2.2. Describing 2015-2018 RD 900/2015 self-consumption regulatory framework applied to low voltage premises

Article 9 of the LSES enabled consumers to produce and consume their own generated electricity. Nevertheless, it was not until 2015 when the economic scheme applied to self-consumption became a reality by virtue of the RD 900/2015 [106].

The RD 900/2015 defines two types of self-consumption economic schemes, i.e., Type I and Type II schemes. While the Type II scheme allows the consumer to sell the produced energy to the market, for Type I any excess generated energy injected into the grid will not be rewarded anyhow.

Only consumers' facilities with rated power (P_R) equal or less than 100kW are authorised to opt for Type I scheme. Conversely, all the consumers (regardless their P_R) may opt for the Type II scheme. Nevertheless, for both schemes the rated power of the generation facility (PVG_N) cannot exceed the P_R of the consumer's facility:

$$PVG_N \leq P_R \tag{1}$$

When the consumer's P_R is less than 100 kW, the electric scheme will be the same for either Type I or Type II economic schemes (see Figure 2). As can be seen, the only smart meter that is shown in Figure 1 remains connected in Figure 2, after the point of common coupling of the facility. Besides, according to RD 900/2015 (article 11 and tenth transitory disposition) the energy storage system (ESS), if any, is forced to share the meters and protections of the generation facility. As a result, there are two differentiated power lines in a self-consumption facility, one related to consumption and the other related to power generation.

When comparing Figure 1 and Figure 2 it is easy to realise that the self-consumption regulatory framework has introduced an amendment in the consumer's bill due to the existence of the so-called self-consumption charges. These charges were first introduced by article 16 of the LSES[2] to mitigate the economic impact regarding income reduction for the SES that self-consumption might produce. In particular, self-consumption in Spain is taxed by means of two types of charges[3], namely, the charges related to the cost of the SES (fixed charges and variable charges) and the charges related to other system services.

In brief, some of the intricacies and complexity between the measures and the charges are depicted in Figure 2. As it can be seen, all charges are related somehow to the measurements of meters 1 and 2, either regarding power or energy.

[2] As well as RD 900/2015, articles 17 and 18.

[3] RD 900/2015, articles 17 and 18.

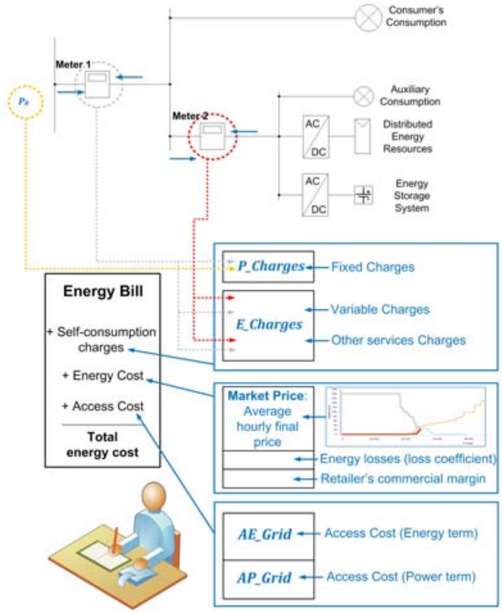

Figure 2. Electric scheme and conceptual definition of the energy cost for a generalised low voltage consumer with a Type I self-consumption facility. Source: Self-elaboration based on [106].

3. Applied methodology

A representation of the different stages followed in this study is made in Figure 3. After the analysis of the Spanish self-consumption regulatory framework, a new EMS model able to consider the regulatory restrictions introduced by the RD 900/2015 was developed. In this model, the formulation of the physical elements of the facility was based on a former model used by the authors in a previous study [60]. To compare how the constraints related to the self-consumption regulatory framework might alter the energy management of a microgrid, a case study of a low voltage facility with a rated power less than 10kW[4] was undertaken. In the case study, the optimal energy management of the energy asset was determined by using both the

[4] According to the First Transitory Disposition of RD 900/2015, facilities under the Type I self-consumption scheme with P_R not exceeding 10kW are exempt to pay the variable charges. Despite this fact, as a worst-case scenario, most companies promoting and installing facilities under the self-consumption scheme do not consider this exemption when analysing the economic results of the energy asset (due to the "transitory" characteristics of this Disposition). In the same way, the study here conducted does not contemplate this exemption in the new model formulation.

former and the new energy management models. The results of the two models were compared to determine the effects of the self-consumption regulatory framework on the energy management of the microgrid. Next, an experimental validation was conducted to corroborate the theoretical results, and finally, a set of conclusions regarding the research study were drawn.

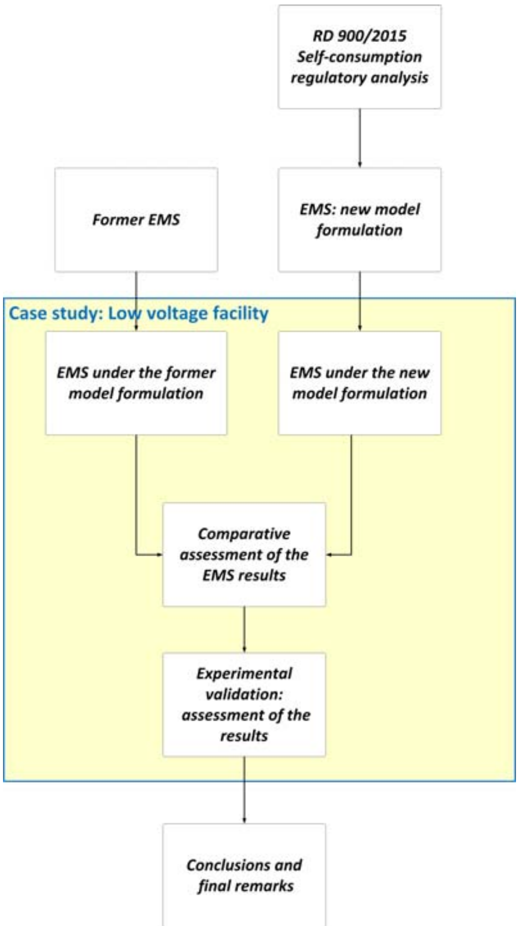

Figure 3. Methodology applied in the research study. Source: Self-elaboration.

4. New model description

4.1. New model with self-consumption regulatory restrictions

The new model is based on a previous authors' work [60] and it is defined in time discrete values, with h being the elementary unit of time within the range of twenty-four hours h=1, 2, ..., 24 and $24 \cdot \Delta h$ its time horizon. The main variables of the model are depicted in Figure 4, and its central intrinsic relations are stated in the following.

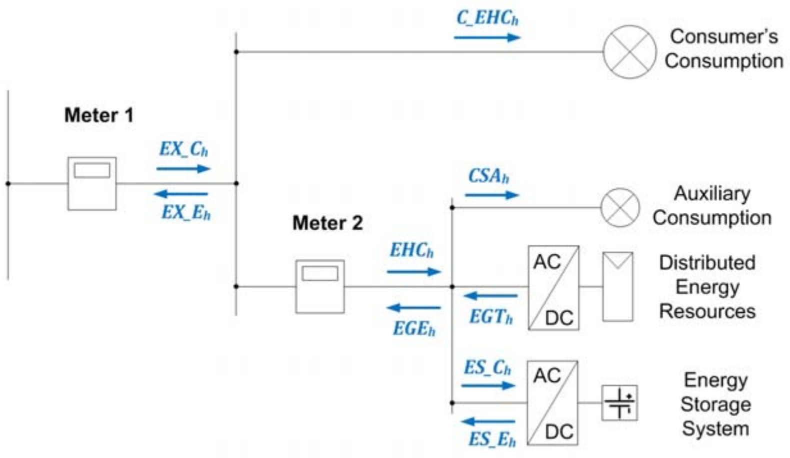

Figure 4. Electrical scheme according to RD 900/2015 for a low voltage consumer with rated power equal or less than 100kW. Source: Self-elaboration based on [106].

a) Energy balance

The formulation of the energy balance is consistent with the definitions and the electrical scheme stated by the RD 900/2015. As can be seen in Figure 4, two complementary energy balances can be formulated at the nodes after the meters 1 and 2:

$$EX\_C_h + EGE_h = C\_EHC_h + EHC_h + EX\_E_h,\ \ EX\_C_h, EGE_h, C\_EHC_h, EHC_h, EX\_E_h \geq 0,\ \forall\, h \quad (2)$$

$$EHC_h + ES\_E_h + EGT_h = EGE_h + ES\_C_h + CSA_h,\ \ ES\_E_h, EGT_h, ES\_C_h, CSA_h \geq 0,\ \forall\, h \quad (3)$$

with EX_C_h being the aggregated hourly consumption of the overall facility, EX_E_h the aggregated hourly injected energy into the grid, C_EHC_h the aggregated hourly consumption of the consumer, EHC_h and EGE_h the aggregated hourly consumption and the aggregated net hourly generation related to the power generation line of the facility, CSA_h the aggregated hourly auxiliary consumption related to the RES and the ESS, EGT_h the aggregated net hourly generation related to the RES, and ES_C_h and ES_E_h the aggregated hourly charged and discharged energy in the entire set of the ESS, respectively.

b) Generation

EGT_h in eq. (4) is calculated as:

$$EGT_h = \sum_t EGT_{t,h}\,,\ EGT_h \geq 0,\ \forall\ h \tag{4}$$

The new model contemplates a set of renewable energy sources (RES) present in the microgrid, with index t. The energy supplied by the RES t at a particular hour h ($EGT_{t,h}$) is defined according to the following equations:

$$EGT_{t,h} = PGT_{t,h} \cdot \Delta h,\ \ EGT_{t,h}, PGT_{t,h} \geq 0,\ \ \forall\ t, h \tag{5}$$

$$PGT\_Max_t \geq PGT_{t,h},\ \forall\ t, h \tag{6}$$

$$PGT\_curt_{t,h} = PGT\_Max_t - PGT_{t,h},\ PGT_{curt_{t,h}} \geq 0,\ \forall\ t, h \tag{7}$$

Where $PGT_{t,h}$ is the power provided by the RES t within the hour h, $PGT\_Max_{t,h}$ is the maximum value of $PGT_{t,h}$, and $PGT\_curt_{t,h}$ is the power curtailed from $PGT\_Max_{t,h}$ for the RES t within the hour h.

c) Storage

Concerning the storage system, there is a set of different types of ESS present in the microgrid, with index ts. Nevertheless, the storage formulation in the new modelchanged compared to the previous model in [60]. The expression of the state of charge ($SoC_{ts,h}$) for the

ESS ts within the hour h was modified by adding two new variables $PS\_C_{ts,h}$ and $PS\_E_{ts,h}$, which are, respectively, the power charge and discharge of the ESS ts within the hour h. According to this $SoC_{ts,h}$ is defined as:

$$SoC_{ts,h} = SoC_{ts,h-1} + \frac{PS\_C_{ts,h} - PS\_E_{ts,h}}{PST\_N_{ts}}, \quad SoC_{ts,h}, PS\_C_{ts,h}, PS\_E_{ts,h} \geq 0, \ \forall ts, h \tag{8}$$

Where PST_N_{ts} is the nominal power of the ESS ts, In this regard, the SoC is forced at the end of the time horizon to be equal to or greater than its initial value:

$$\sum_{h=1}^{23} \left(SoC_{ts,h+1} - SoC_{ts,h} \right) \geq 0, \forall ts, h \leq 23 \tag{9}$$

ES_C_h and ES_E_h are calculated as:

$$ES\_C_h = \sum_{ts} ES\_C_{ts,h}, \ ES\_C_h \geq 0, \ \forall h \tag{10}$$

$$ES\_E_h = \sum_{ts} ES\_E_{ts,h}, \ ES\_E_h \geq 0, \ \forall h \tag{11}$$

with $ES\_C_{ts,h}$ and $ES\_E_{ts,h}$ being the energy charged and discharged, respectively, to the ESS ts within the hour h, which are calculated as:

$$ES\_C_{ts,h} = PS\_C_{ts,h} \cdot \Delta h, \ \ ES\_C_{ts,h} \geq 0, \ \forall ts, h \tag{12}$$

$$ES\_E_{ts,h} = PS\_E_{ts,h} \cdot \Delta h, \ \ ES\_E_{ts,h} \geq 0, \ \ \forall ts, h \tag{13}$$

$$EST_h = ES\_C_h - ES\_E_h, \ EST_h \geq 0, \ \forall h \tag{14}$$

Another constraint on the SoC has the purpose of avoiding any chance of overcoming its cap value (SoC_Max_{ts}) and its floor value (SoC_Min_{ts}). Consequently, for a better performance of the energy management of the ESS, a threshold SoC (SoC_th_{ts}) is introduced for each ESS to limit the values of $PST_{ts,h}$. By using the binary variable $Status_{ts,h}$, the model can determine whether the SoC is above SoC_th_{ts}. In this case, $Status_{ts,h}$ turns to 1 and limits the value of $PS\_C_{ts,h}$ and $PS\_E_{ts,h}$, between more restrictive discharge ($PS\_E\_th_{ts}$) and charge ($PS\_C\_th_{ts}$) threshold limits. Otherwise, the charge and discharge limits are widened to $PS\_C\_Max_{ts}$ and $PS\_E\_Max_{ts}$, respectively.

$$SoC_{ts,h} \leq SoC\_th_{ts} + Status_{ts,h} \cdot (\, SoC\_Max_{ts} - SoC\_th_{ts}) \tag{15}$$

$$SoC_{ts,h} \geq SoC\_Min_{ts} + Status_{ts,h} \cdot (\, SoC\_th_{ts} - SoC\_Min_{ts}) \tag{16}$$

$$PS\_C_{ts,h} \leq PS\_C\_th_{ts} + \left(1 - Status_{ts,h}\right) \cdot (\, PS\_C\_Max_{ts} - PS\_C\_th_{ts}) \tag{17}$$

$$PS\_E_{ts,h} \leq PS\_E\_th_{ts} + \left(1 - Status_{ts,h}\right) \cdot (\, PS\_E\_Max_{ts} - PS\_E\_th_{ts}) \tag{18}$$

d) Energy incomes and costs

The equations related to the grid energy cost (with and without self-consumption) are described according to the conceptual model proposed in [107] to simplify the model formulation:

a. Energy cost without self-consumption

$$Total\_Energy\_Cost = AE\_Grid \cdot Energy\_M1 + AP\_Grid \cdot Power\_M1 + Energy\_Cost \tag{19}$$

$$Energy\_M1 = \sum_h Energy\_M1_h \tag{20}$$

$$Energy\_Cost = \sum_h Energy\_M1_h \cdot fepp_h \tag{21}$$

with $Energy\_M1$, $Energy\_M1_h$ and $Power\_M1$ being the daily and hourly energy and the power related to the meter 1 in Fig. 4.

b. Energy cost with Type 1 self-consumption

$$Total\_Energy\_Cost\_Self = (AE\_Grid + E\_Charges) \cdot Energy\_M1 \quad + E\_Charges \cdot Energy\_M2 \quad + (AP\_Grid + P\_Charges) \cdot Power\_M1 \ + P\_Charges \cdot Power\_M2 + Energy\_Cost \tag{22}$$

with $E\_Charges$ and $P\_Charges$ being the energy and power charges defined by the RD 900/2015 according to the voltage level and type of self-consumption, and $Energy\_M2$ and $Power\_M2$ the daily energy and power related to the meter 2 in Fig. 4.

c. Income and cost with Type II self-consumption

In case of being under the Type II scheme, the owner of the facility would not only be considered a consumer but also a producer. As a producer, the owner would perceive an emolument (INC_Self) for the energy injected into the grid (eq. (23)), but at the same time, would undergo the costs (IMP_INC, IMP_EGE) arising from the charges and taxes applied to the producers by the Royal Decree-Law (RDL) 14/2010 [108] and the Law 15/2012 [109], respectively (eq. (24)):

$$INC\_Self = \sum_h INC\_Self_h = \sum_h Energy\_M1_h \cdot Pm_h \tag{23}$$

$$IMP\_EX\_E = IMP\_INC + IMP\_EGE \tag{24}$$

e) Generation and storage cost

The daily generation (CT_EGT) and storage (CT_St) total costs are the sums of their fixed (CF_G, CF_St) and variable (CV_G, CV_St) costs (Eqs. (25), (26)). In this regard, fixed costs are the product of the power rating of each RES and ESS of the facility and the values of the fixed cost parameters for each technology (CF_G_t and CF_St_{ts}) (Eqs. (27), (28)). In the same way, the variable costs of each RES and ESS of the facility are a function of the energy delivered or consumed (Eqs. (29), (30)).

$$CT\_EGT = CF\_G + CV\_G \tag{25}$$

$$CT\_St = CF\_St + CV\_St \tag{26}$$

$$CF\_G = \sum_t CF\_G_t \cdot PGT_t \tag{27}$$

$$CF\_St = \sum_{ts} CF\_St_{ts} \cdot PST\_N_{ts} \tag{28}$$

$$CV\_G = \sum_t \sum_h EGT_{t,h} \cdot CV\_G_t \quad (29)$$

$$CV\_St = \sum_{ts} \sum_h \{ (ES\_C_{ts,h} + ES\_E_{ts,h}) \cdot CV\_St_{ts} \} \quad (30)$$

f) Objective function

A new objective function is introduced, based on the Earnings Before Interest Taxes Depreciation and Amortization (EBITDA). It is addressed to optimise the savings of the system by minimising the difference between the EBITDA of the former model and the new EBITDA ($EBITDA\_Self$) under the self-consumption scheme. This function is defined as follows:

$$O\_function = EBITDA - EBITDA\_Self \quad (31)$$

Which for a Type I self-consumption scheme amounts to:

$$O\_function = Total\_Energy\_Cost\_Self - Total\_Energy\_Cost \quad (32)$$

And for a Type II self-consumption scheme:

$$O\_function = Total\_Energy\_Cost\_Self + IMP\_EX\_E - INC\_Self - Total\_Energy\_Cost \quad (33)$$

4.2. Regarding the meters and the need of using a disjunctive program

Both the energy cost and income present a disjunctive nature. That is, either the facility is consuming energy from the grid (in which case there will be an energy cost for the system and, consequently, no energy income at all) or it is injecting the surplus energy into the grid (in which case there will be an energy income but no energy cost). The same considerations apply to Meter 2.

In this regard, the disjunctive nature between energy cost and incomes equations and the measurements of the meters was solved by using a disjunctive program. A disjunctive program can be formulated as a special type of MINLP whose constraints can be defined using the logical “exclusive or” operator [110]. Concerning this, the big-M (BM) method was used to formulate the problem [111].

5. Case study: analysis of the impact of the RD 900/2015 Spanish self-consumption regulatory framework on the energy management of a low voltage microgrid

5.1. Problem definition

An actual consumer’s low voltage facility with P_R=5kW was used to analyse the impact of the Spanish self-consumption regulatory framework on the energy management of a microgrid (Figure 5). This microgrid is formed by a 2 kW PV system and an 8.9 kW ESS.

The operating costs of the PV system and the ESS are, 36.1€/kW/year [112] and 6.1€/kW/year and 0.49€/MWh [113], respectively. The other parameters related to the ESS, including the initial conditions of the ESS ts ($SoC_{ts,0}$) can be found in Table 2.

$PS\_C\_Max_{ts}$ [W]	$PS\_E\_Max_{ts}$ [W]	$PS\_C\_th_{ts}$ [W]	$PS\_E\_th_{ts}$ [W]	SoC_Max_{ts}	SoC_Min_{ts}	SoC_th_{ts}	$SoC_{ts,0}$
1000	1000	100	100	1	0.4	0.96	0.6

Table 2. Parameters related to the ESS model.

The values of the access tariff cost and the self-consumption charges were provided by the several Spanish Ministerial Orders such as IET 107/2014 [114] and ETU 1976/2016 [115]. In Figure 5, the consumption of the system, the maximum capacity of generation and the energy prices are also depicted.

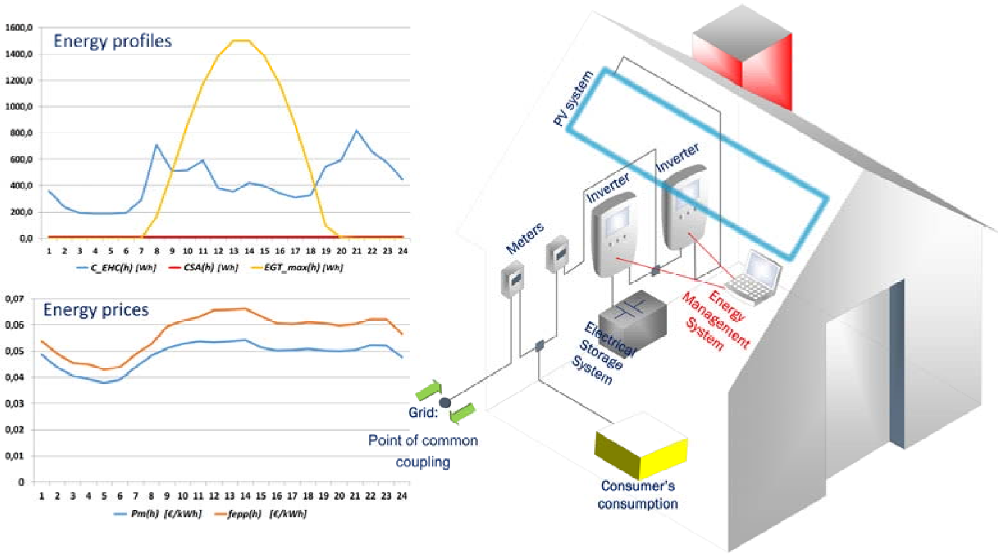

Figure 5. Conceptual approach to the problem description. Source: Self-elaboration.

The facility has an EMS that optimises the consumer’s energy cost, which includes the required communication equipment for applying the set points to the DC/AC converters of the energy system. The employed model only states the optimal scheduling for one day and does not contemplate the optimal sizing of the power ratings of the facility components. The EMS is aimed to determine the energy plan of the microgrid, including production, storage and the energy exchange with the grid. This EMS has been operated considering the former model with self-consumption and the new model (Section 4) for both Types 1 and 2 of self-consumption.

This facility was emulated at the Microgrid Research Laboratory of Aalborg University [100] using hardware in the loop (HiL) architecture. As can be seen in Figure 6, this architecture has three levels: the software level, the real-time simulator level and the physical level.

The software level was developed in the microgrid computer. There, using the developed models and the data storage, the EMS provided the scheduling to be applied to the system. The optimisation was achieved using the AIMMS Academic License [116] and its solver AIMMS Outer Approximation, as an Algebraic Modelling Language. In the same way, the software level was also in charge of the substation monitoring.

The real-time simulation level was performed on the platform dSPACE 1006, which includes the generation and consumption profiles, as well as a detailed model of a battery based energy storage system as proposed in [117]. This latter model allows reproducing the main dynamic and static characteristics of the battery variables such as voltage, current, and SoC. On top of that, the real-time level contains the controllers for the inverters implemented at the physical level, which are controlled as power sources or loads in accordance to generation or consumption profiles, presented in Figure 5, defined to emulate the behaviour of the renewable sources and the load, respectively. Meanwhile, the power references for the inverters that interconnect the energy resources are defined by the upper control levels to guarantee compliance with the energy plan provided by the EMS. The details of the control level can be read in [60]. Although the dSPACE platform was running in real time, the time slot of the energy profiles and the scheduling were scaled down to 60s. As a result, the whole simulation lasts 1440 s. Besides, the capacity of the ESS was also scaled in the same proportion [60].

Finally, the physical level is composed by the three inverters that emulate the PV system, the consumption, and the storage system which are interconnected to common AC bus through LCL filters, where a resistive load and the main grid are connected. The inverters are fed by a stiff regenerative DC source, which enables bidirectional power injections. The experimental setup was adapted to fit the electrical scheme imposed by the regulatory framework. The parameters of the microgrid are depicted in Table 3.

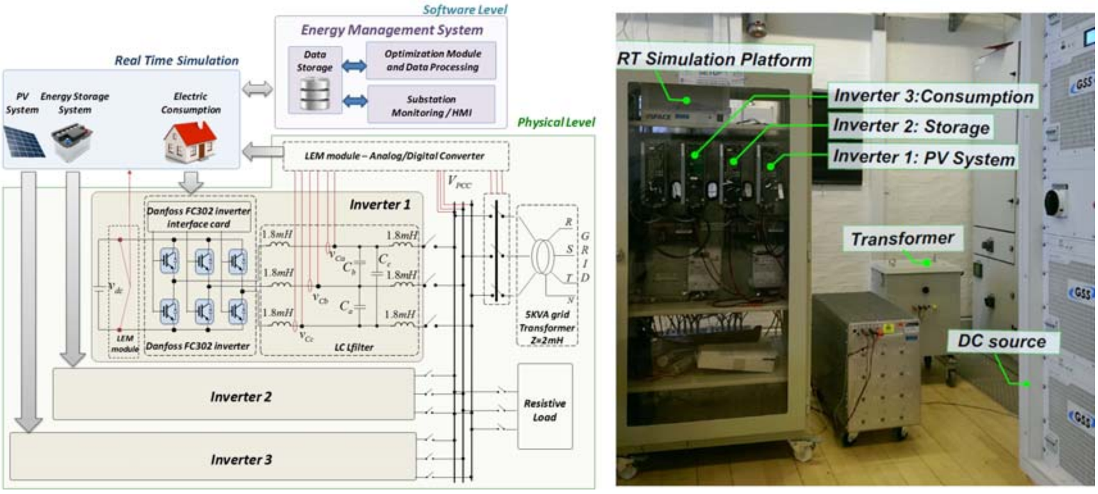

Figure 6. HiL implementation and experimental setup.

Parameters	**Symbol**	**Value**
	Power stage	
Nominal Voltage	E*	230·√2V
Nominal Frequency	ω*	2·π·50 rad/s
Inverter inductors	L	1.8mH
Filter Capacitor	C	27μF
Nominal Load	C_EHC_N	1000W
Maximum (RESs) and (ESSs) Power Rating	P_{max}	1600W
Reactive power Reference	Q*	0 VAR

	Battery Array	
Nominal Voltage	V_{bat}	672V
Regulation Voltage	V_r	756V
Nominal Battery Capacity	C_{bat}	16Ah

Table 3. Parameters of the microgrid

5.2. Assessment of the results

The results of both models applied to the facility under study are shown in Figures 7, 8 and 9. These figures are composed of six charts where different indicators of the facility are depicted. The charts belonging to the left side of the pictures illustrate the EMS scheduling results while those in the right side depict the experimental results of the EMS scheduling once applied on the setup. For each image, sections a, b and c represent, respectively, the inner relations between the consumption and generation line with the grid, the inner relationships in the generation power line and the performance of the ESS regarding its power and SoC.

Figure 7 shows the results of the EMS when the former model is applied. Specifically, Figure 7.a represents the aggregated consumption of the consumer, the energy provided or injected into the grid (meter 1) and the energy consumed or supplied by the generation power line (meter 2). There it can be seen that during the first hours of the day (3 am to 6 am) the EMS is focused on charging the ESS. In this regard, when looking at the charts 7.b and 7.c, it is possible to see that the energy consumption measured by meter 2 (positive value) is coincident with the ESS charge. At 7 am, once the ESS has been charged at a value close to SoC_th_{ts}, the energy provided by the grid to the facility becomes zero (see meter 1), and all the energy required by the consumer is provided either by the RES or by the ESS. Regarding the RES, from 7 am to 9 am it contributes along with the ESS to provide the necessary energy to guarantee the needs of the consumer. From 10 am to 18 pm, the RES performs a vital role in the system as it is responsible for charging the ESS near to its threshold limits and providing the necessary energy to the consumer. After that, it is the ESS the maximum energy contributor, discharging at the end of the day to its initial condition. As a result, the use of the former model by the EMS allowed the facility to reduce its energy consumption from the grid up to 56%.

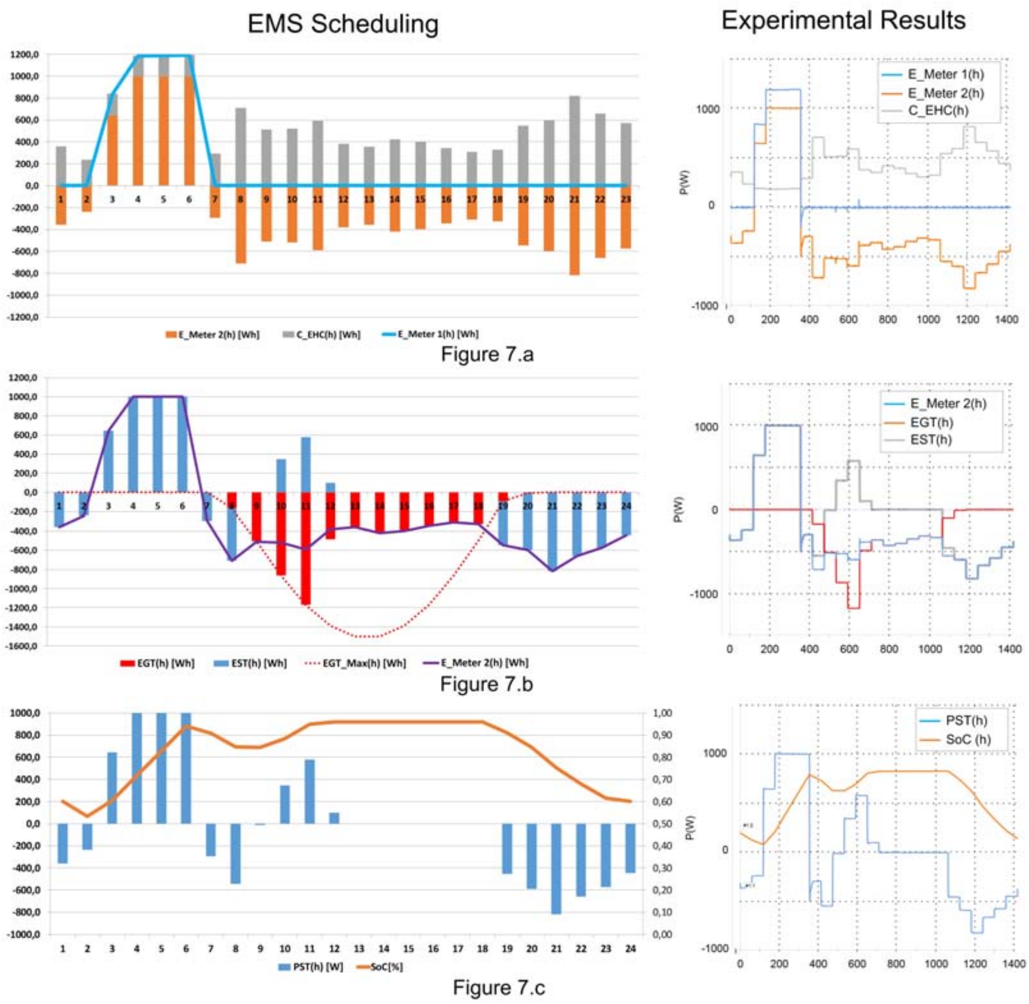

Figure 7. EMS solution applied to the facility under study according to

the former model and its experimental results. Source: Self-elaboration.

Next, Figures 8 and 9 provide the results of the EMS when the new model subjected to the Spanish self-consumption regulatory scheme is employed. In this regard, the regulatory constraints and the new objective function introduce a remarkable difference when managing the energy consumed or injected into the grid. As a result, for both Types I and II of self-consumption (see Figure 8.a and 9.a), just 5% of the energy consumption of the facility is provided by the grid, which is a non-despicable effect that highlights the importance to accurately define the regulatory constraints in models focused on managing this type of facilities.

The only slight difference between both types of self-consumption lies on the fact that, for self-consumption Type II, the total amount of energy injected into the grid during the day (2.2 kWh) is greater than the energy injected under the Type I scheme (1.6kWh). As the injection of the energy to the grid is rewarded in Type II scheme, this difference seems perfectly reasonable. In this regard, when comparing Figures 8.a and 9.a, it is easy to see that this incentive forces the EMS to increase the injection of the energy when the energy market price is higher to increase the value of the incomes.

Regarding the energy management response in the self-consumption scheme, a resulting consequence of using the new model is that the elements belonging to the generation power line are forced to increase their participation in the energy supply (see Figures 8.b and 9.b) when comparing with the results of the former model (see Figure 7.b). In the case of the ESS under Type I and II regulatory scheme, the increase of energy supplied by the ESS if compared with the former model was about 8.3% and 20.9%, respectively. Ergo, under both types of self-consumption schemes, the ESS was compelled to reach its SoC limits (minimum and threshold) (see Figure 8.c and 9.c). Regarding the RES, this increase was even higher. For both types of regulatory schemes, the RES was forced to supply its maximum production of energy.

Concerning the experimental results, the set of figures have also demonstrated the excellent performance of the local controllers of the setup, which proved to be able to follow the scheduling provided by the EMS.

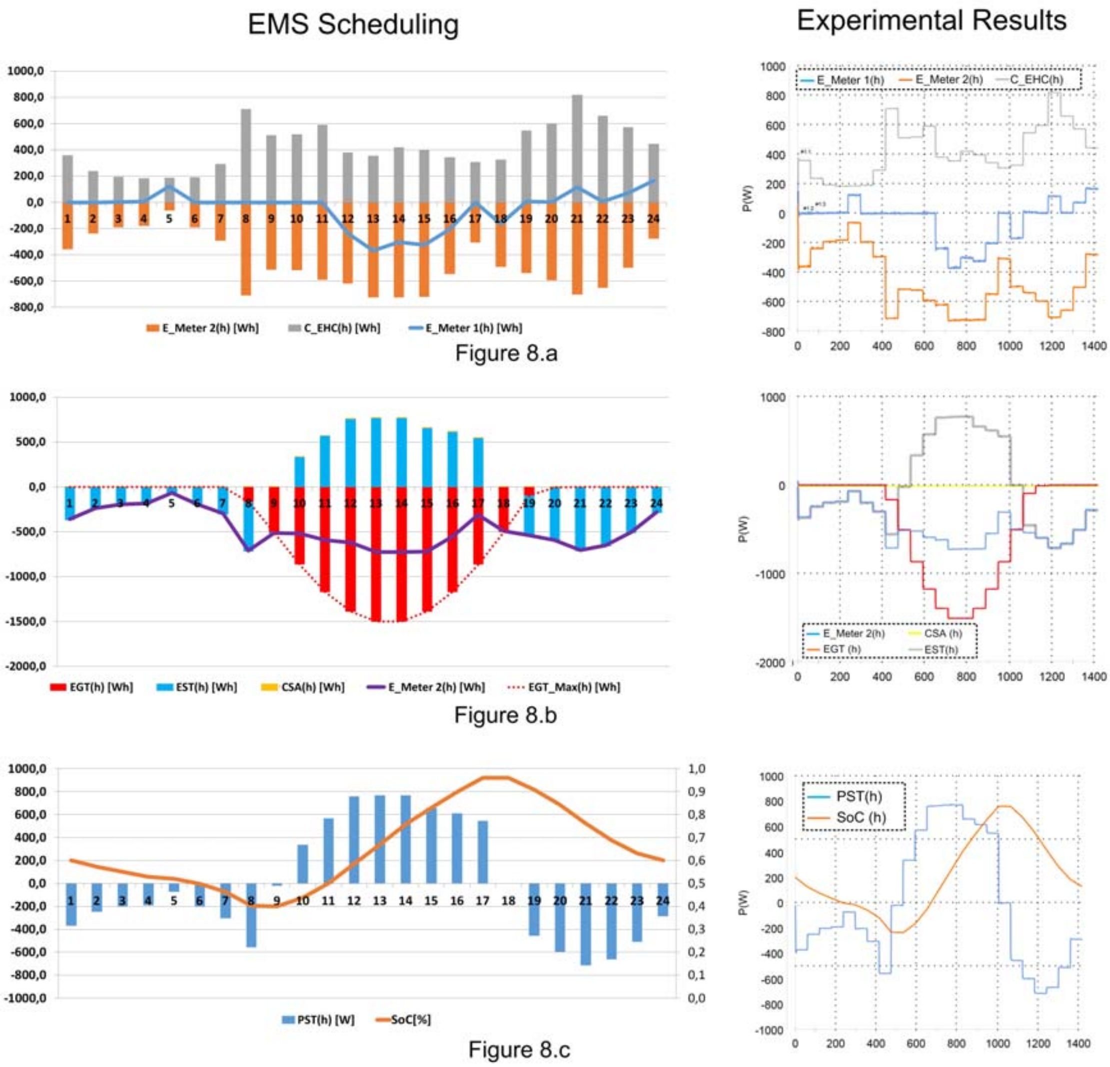

Figure 8. EMS solution applied to the facility under study according to the Type I self-consumption scheme and its experimental results. Source: Self-elaboration.

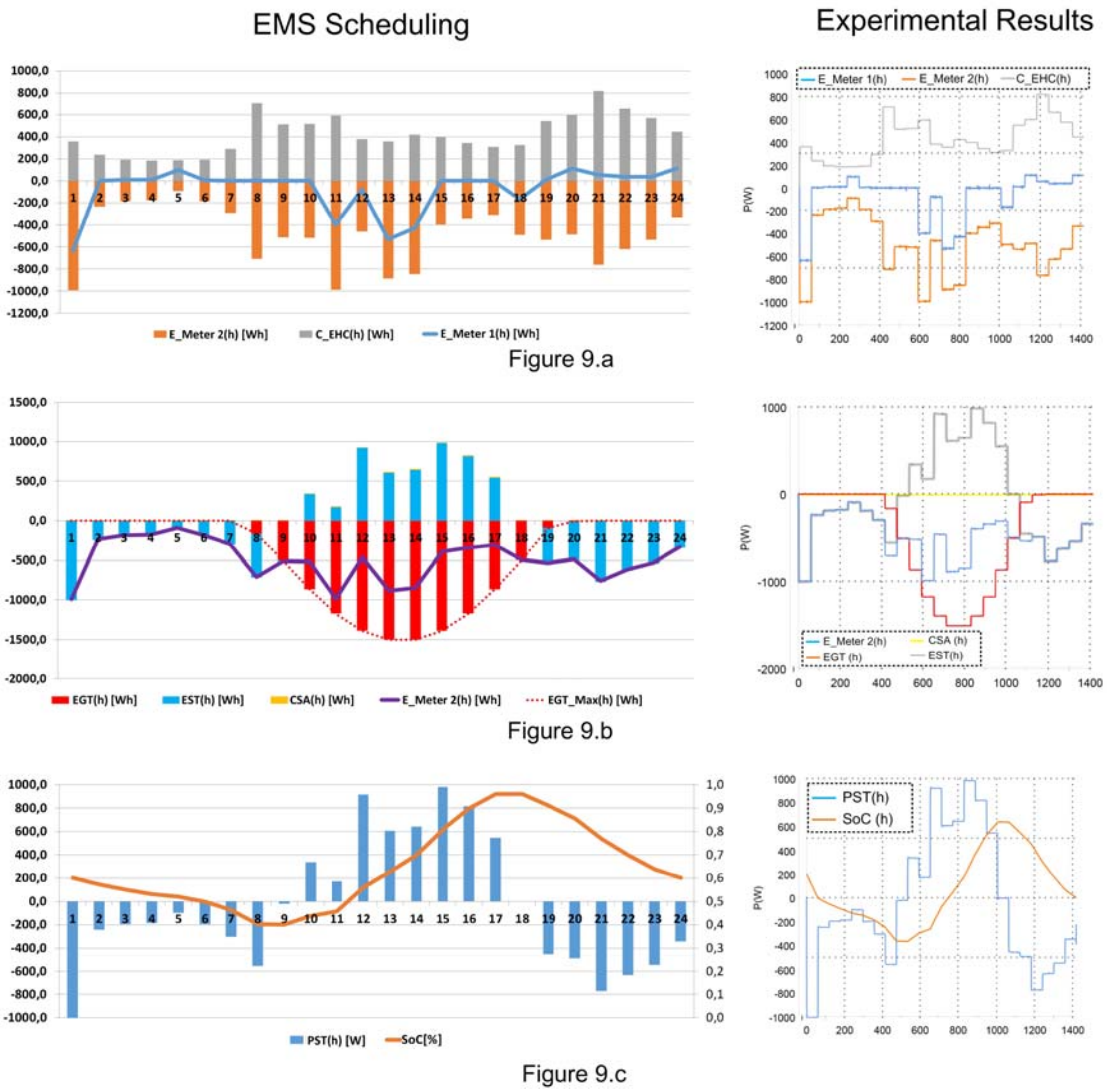

Figure 9. EMS solution applied to the facility under study according to the Type II self-consumption scheme and its experimental results. Source: Self-elaboration.

6. Conclusions

A new model addressed to optimise the energy management of a low voltage microgrid has been developed. While most of all the existing models do not consider the regulatory restrictions applied to the facilities when optimising the energy management, the proposed new model contemplates in detail this type of constraints.

A low voltage microgrid under the Spanish self-consumption scheme was selected as a case study and emulated at the Microgrid Research Laboratory of Aalborg University. The obtained results were analysed to determine whether the modelling of the regulatory scheme was relevant or not for the management of these types of facilities.

The results have corroborated the importance of considering the regulatory constraints when managing the facility, especially in relation to highly complex regulatory frameworks. Significant differences have appeared regarding the exchange of energy between the facility and the grid with and without taking into account the regulatory framework, such as a drastic reduction of the energy consumption provided by the grid and an increase of the use of the ESS and the RES of the system. These differences for the analysed case prove the weight that the regulatory constraints may have on the results of the optimisation process.

Microgrids are called to be handy tools for the deployment of renewable energy systems, especially on buildings and industry. In this regard, the results also corroborate that those microgrid manufacturers interested in differentiating themselves from competitors might see the energetic and economic performance of their products increased by embedding these regulatory constraints in their EMS. In this regard, the Regulatory-Framework-Embedded energy management system approach could be a useful tool to improve the optimal use of microgrids.

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Acronyms

DER: Distributed Energy Resources

EBITDA: Earnings Before Interest Taxes Depreciation and Amortization

EMS: Energy Management System

ESS: Energy Storage System

EU: European Union

HiL: hardware in the loop

IEM: the Iberian Electricity Market

LSES: Law of the Spanish Electricity Sector

MINLP: Mixed-Integer Nonlinear Problem

MOO: Multi-Objective Optimization Approach

RD: Royal Decree

RDL: Royal Decree-Law

RES: Renewable Energy Source

SES: Spanish Electricity Sector

SoC: State of Charge

SOO: Single Objective Optimization Approach

Indexes, parameters and variables

Indexes

h: time intervals within a day

t: RES generators in the microgrid

tl: electric appliances in the microgrid

ts: ESSs in the microgrid

Parameters

AE_Grid: daily energy term of the access tariff cost [€/Wh]

AP_Grid: daily power term of the access tariff cost [€/W]

CF_G_t: fixed generation cost per unit of rated power of an RES t [€/W]

CF_St_{ts}: fixed storage cost per unit of rated power of an ESS ts [€/W]

CV_G_t: variable generation cost per unit of energy of an RES t [€/Wh]

CV_St_{ts}: variable storage cost of an ESS ts [€/Wh]

$E\_Charges$, $P\_Charges$: daily energy and power charges defined by the RD 900/2015 according to the voltage level and type of self-consumption scheme [€/Wh] and [€/W]

Nts: total number of ESS in the microgrid

P_R: rated power of the consumer's facility [W]

PGT_Max_t: maximum power of an RES t [W]

PST_Max_{ts}, PST_Min_{ts}: maximum positive (charge) and minimum negative (discharge) values of $PST_{ts,h}$ when $SoC_{ts,d,h} \leq SoC\_th_{ts}$ [W]

PST_th1_{ts}, PST_th2_{ts}: positive (charge) and negative (discharge) limited values of $PST_{ts,h}$ when $SoC_{ts,d,h} > SoC\_th_{ts}$ [W]

PST_N_{ts}: nominal power of an ESS ts [W]

$PS\_C\_th_{ts}$, $PS\_E\_th_{ts}$: limited values of $PS\_C\_th_{ts,h}$ and $PS\_E\_th_{ts,h}$ when $SoC_{ts,d,h} > SoC\_th_{ts}$ [W]

$PS\_C\_Max_{ts}$, $PS\_E\_Max_{ts}$: maximum values of $PS\_C\_th_{ts,h}$ and $PS\_E\_th_{ts,h}$ when $SoC_{ts,d,h} \leq SoC\_th_{ts}$ [W]

SoC_Max_{ts}, SoC_Min_{ts}: cap and floor values of $SoC_{ts,h}$ for an ESS ts

SoC_th_{ts}: threshold value of $SoC_{ts,d,h}$ from which PST_Max_{ts} and PST_Min_{ts} are limited to PST_th1_{ts} and PST_th2_{ts}

$SoC_{ts,0}$: the initial conditions of the ESS ts

Δh: duration of the time intervals h [h]

φ_{ts}: parameter of the ESS ts

Variables

CF_G: daily fixed generation cost [€]

CF_St: daily fixed storage cost [€]

CSA_h: auxiliary consumption related to the RES generators and ESS within the hour h [Wh]

CT_EGT: daily total generation cost [€]

CT_St: daily total storage cost [€]

CV_G: daily variable generation cost [€]

CV_St: daily variable storage cost [€]

C_EG_h: cost of the energy supplied by the grid within the hour h [€/Wh]

C_EGT_{th}: cost of the energy supplied by a RES generator t within the hour h [€/Wh]

C_EHC_h: aggregated consumption of the consumer within the hour h [Wh]

DH_h: consumer's demand within the hour h [Wh]

EG_h: energy consumed from the grid within the hour h [Wh]

EGE_h: net generation related to the power generation line of the facility within the hour h [Wh]

EGT_h: energy supplied by the RES generators within the hour h [Wh]

$EGT_{t,h}$: energy supplied by a RES generator t within the hour h [Wh]

EHC_h: energy consumption related to the power generation line of the facility within the hour h [Wh]

$EL_{tl,h}$: energy consumption of the appliance l within the hour h [Wh]

$ELosses_h$: average energy loss in the microgrid within the hour h [Wh]

$Energy\_M1, Energy\_M2$: daily energy measured by meter 1 and by meter 2, respectively, under the self-consumption scheme [Wh]

$Energy\_M1_h$: energy measured by meter 1 under the self-consumption scheme within the hour h [Wh]

$EST_{ts,h}$: energy charged (positive) or discharged (negative) of the ESS ts within the hour h [Wh]

ES_C_h: energy charged to all the ESS within the hour h [Wh]

$ES\_C_{ts,h}$: energy charged to the ESS ts within the hour h [Wh]

ES_E_h: energy discharged from all the ESS within the hour h [Wh]

$ES\_E_{ts,h}$: energy discharged to the ESS ts within the hour h [Wh]

EX_C_h: consumption of the overall facility within the hour h [Wh]

EX_E_h: energy injected into the grid within the hour h [Wh]

$fepp_h$: purchased energy final price within the hour h [€/Wh]

IMP_EGE: daily cost of the tax set by the Law 15/2012 [€]

IMP_EX_E: sum of the costs of the charges and taxes applied to electricity producers under a Type II self-consumption scheme [€]

IMP_INC: daily cost from the charge set by the RDL 14/2010 [€]

INC_Self: daily income related to the energy injected into the grid [€]

Pm_h: daily market price within the hour h [€/Wh]

PG_h: power provided by the grid within the hour h [W]

$PGT_{t,h}$: power provided by the RES t within the hour h [W]

$PGT\_curt_{t,h}$: power of a RES t within the hour h curtailed from $PGT\_Max_{t,h}$ [W]

$Power\_M1$, $Power\_M2$: daily power measured by meter 1 and by meter 2, respectively, under the self-consumption scheme [W]

$PST_{ts,h}$: charged (positive) or discharged (negative) power of the ESS ts within the hour h [W]

$PS\_C_{ts,h}$: charged power in the ESS ts within the hour h [W]

$PS\_E_{ts,h}$: discharged power in the ESS ts within the hour h [W]

PVG_N: rated power of the generation facility [W]

$Status_{ts,h}$: binary variable activated when $SoC_{ts,h} \geq SoC\_th_{ts}$

$SoC_{ts,h}$: state of charge of the ESS ts within the hour h

Table list

Figure list