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A Genetic Algorithm Approach for Sizing Integrated PV-BESS Systems for Prosumers

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***Abstract*—A procedure for properly sizing integrated configurations of photovoltaic (PV) and battery energy storage systems (BESSs) is presented in this paper. Specifically, an energy management strategy oriented to maximise the electricity self-consumption has been used. In this regard, the energy management of Li-ion BESS is optimised by means of a specific tool based on a Genetic Algorithm (GA). In order to determine the best rated power and capacity of integrated PV-BESS system for residential and commercial users, the optimisation has been performed for different combination of PV and BESS rated powers and capacities, evaluating, for each of them, the annual self-consumption. The analysis of the results permits the proper choice of the PV-BESS system for a specific prosumer end for a given self-consumption target. Moreover, the proposed design approach highlights that the increase of BESS size for a defined electricity demand may lead to weak benefits in terms of increased self-consumption and, thus, to an unsuitable oversizing of the PV-BESS system.**

***Index terms* —** Self-consumption sizing optimisation, Energy management, Photovoltaic, Battery energy storage system

I. Introduction

In accordance with the Paris Agreement of 2015 for the mitigation of climate change, more than sixty countries have stated their intent to achieve net zero carbon dioxide emissions by 2050 [1]. For achieving this ambitious target, Renewable Energy Sources (RESs) play an important role because they contribute to reduce the carbon dioxide emissions by replacing the electricity produced by the traditional fossil-fed power plants. However, integration of RESs into electricity networks is still an open issue for energy service operators due to their intermittent nature and, thus, weak programmability.

In this context, RES self-consumption can play an important role in easing the integration of RESs into existing electricity networks [2]. Self-consumption offers several benefits, such as extenuating raised network costs due to the integration of photovoltaic power plants (PVs) [3], and peak shaving [4] but it is not widely implemented due to its uncertain profitability [5]. Although PVs are increasingly being installed in residential areas, the prosumers do not still consider self-consumption as a key target [6]–[8]: this goal can be achieved also by means of energy storage installed in electric vehicles, as extensively analysed in [9], [10].

The major challenge of PV self-consumption is the time shifting between electricity production and demand. Generally speaking, PV peak production happens when householders are not at home due to their daily activities. In this regards, two solutions are proposed to bring out more self-consumption: 1- Demand-Response programming approaches, which require the introduction of management algorithms for shifting the usage of controllable electrical devices when PV production occurs. 2- Use of Energy Storage Systems (ESSs), for properly matching PV production with electricity demand [7].

Many studies are carried out within companies and research bodies by analysing self-consumption advantages. In particular, the profitability of PV self-consumption for commercial users is analysed in [11], economic analysis of integrated PV-ESS system is reported in [8], while the benefit in term of power quality improvement is shown in [12]. Specifically, [12] shows the improvement of voltage profile on the distribution power system due to the implementation of a self-consumption control algorithm for ESSs installed into a PV-based micro-grid.

In this paper, a general approach for sizing PV-ESS systems for domestic or commercial prosumers is presented. At this purpose the annual time evolution of electricity demand with a proper resolution and accuracy is required. Therefore, one-year real data of electricity consumption of residential and commercial users have been used. Regarding the ESS technology, the proposed method has been developed referring to Li-ion batteries, but it can be extended to any kind of ESS.

The goal of this study is the definition of a tool able to find out the most suitable configurations of PV-BESS system for the conversion of end users (residential and/or commercial) in prosumers. At this scope, an energy management strategy based on genetic algorithm (GA) is implemented in order to maximise self-consumption.

The application of the proposed GA energy management system (GA-EMS) for different combination of PV and BESS size (rated power and/or capacity) allows the evaluation of the prosumer gross energy saving for each combination. . In particular, differently from many studies presented in the literature, the aim of the proposed procedure is not giving an optimal result, but determining a self-consumption map that supports the prosumer in choosing the PV-BESS system most suitable for him/her. In this regard, the result comparison allows the definition of the proper size of PV-BESS system in accordance with prosumers specific habits and desired self-consumption target. Moreover, the results highlights also unsuitable oversizing of PV-BESS system for a defined evolution of electricity demand.

The paper is organized as follows: Sections II and III introduces methods and the cases of study; Section IV describes and analyses the results; conclusion is given in Section V.

II. Proposed Methodology for PV-ESS Sizing

A. System Overview

Fig. 1 shows a schematic representation of the system under evaluation, by highlighting its main components contributing to self-consumption and the potential direction of power flow among them. In order to clarify the self-consumption concept implemented in the proposed methodology, Fig.2 reports an example of the power time evolutions of each component. In particular, when PV overproduction occurs, BESS charging is firstly carried out until the achievement of maximum State of Charge (SoC). Subsequently, when PV underproduction occurs, BESS supplies the residual power demand at the aim of maximizing the self-consumption of the PV daily production.

The proposed methodology thus aims at optimising the BESS SoC in presence of PV for obtaining the maximum self-consumption rate for a defined end user power demand. To take into account optimal usage of BESS, Multi Period Optimal Power Flow (MPOPF) strategies have been considered [13], [14]. Specifically, GA-based MPOPF methodology proposed in [15] has been used for optimisation of the SoC of BESS. Moreover, for any power demand evolution, various values of PV and BESS rated power and/or capacity have been considered; in this way, GA-MPOPF methodology is implemented to maximise self-consumption for each PV-BESS configuration.

The details of the system constraints and of the proposed methodology are presented in the following subsections.

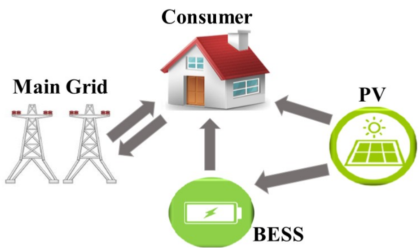

Fig. 1. Schematic representation of the system considered for the PV-BESS sizing methodology proposed in this paper.

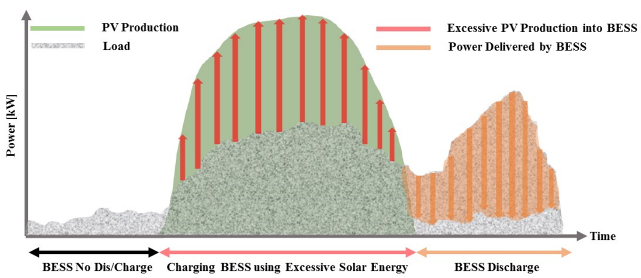

Fig. 2. Example of time evolutions of powers for the system shown in Fig. 1..

B. System Constraints

The system is considered as single node i connected to the main grid j. In power flow calculation, main grid (node j) is considered as a slack bus. All components of the system (PV, BESS and loads) are connected to the main grid (node j) via considered single node i.

Generally speaking, equality and inequality constraints must be considered during power flow computation and optimisation procedure [16]. The load profile $P_c(t)$ and PV production $P_g(t)$ for each time instant t is considered as input parameters. The equality constraint of the resistance and reactance between node i and slack node j are considered as R_{ij} and X_{ij}, respectively.

Inequality constraints are considered as optimisation boundaries. Voltages V^{min}, V^{max} are described in equation (1), while the voltage phases θ^{min} and θ^{max}, are addressed in (2), for each time instant t.

$$V^{min} \leq V(t) \leq V^{max} \tag{1}$$

$$\theta^{min} \leq \theta(t) \leq \theta^{max} \tag{2}$$

Line thermal limits S_{ij}^{max} are also taken into account, as reported in (3), where S_{ij}^{max} is the maximum apparent power magnitude through nodes i and j. Also this constraint must be met at any time instant t.

$$\mid S_{ij}(t) \mid \leq S_{ij}^{max} \tag{3}$$

The BESS constraints are defined in (4) and (5)in accordance with rated capacity E^{Nom} and maximum and minimum power P_r^{max} and P_r^{min}.

$$0.1 \times E^{Nom} \leq E(t) \leq 0.9 \times E^{Nom} \tag{4}$$

$$P_r^{min} \leq P_r(t) \leq P_r^{max} \tag{5}$$

$$E(t) = \begin{cases} E(t-1) + \eta_c \int P_b(t)dt, & \text{if charging} \\ E(t-1) + \frac{1}{\eta_d} \int P_b(t)dt, & \text{if discharging} \end{cases} \tag{6}$$

The energy of the BESS at any time instant t is $E(t)$, which is defined by (6) and updated accordingly. The efficiencies of charging and discharging of the BESS are η_c and η_d, respectively. $P_b(t)$ is the active power exchanged by by BESS at any time instant t, which is positive and negative over charging and discharging respectively.

C. Optimisation procedure and objective function

The PV-BESS management system has been designed to restrict buying and selling energy from/to the main grid. To achieve this goal, BESS energy management is performed by means of the GA-MPOPF reported in [15]. In particular, the GA-MPOPF implemented in [15] optimises the life-time of BESS in terms of BESS degradation cost reduction; this feature is not considered in this paper, while the GA-MPOPF is used for optimising BESS Soc in order to increase prosumers self-consumption. The usage of BESS is optimised day-by-day. In particular, the SoC hourly value is considered as an input of the GA for each day (24h), and GA-MPOPF optimises these values in order to minimise the gross energy exchange in accordance with all constraints. In this regard, the gross energy exchange over a given time horizon T is defined as:

$$E_{gross} = \int_0^T |P_c - P_g + P_b|.dt \tag{7}$$

The GA starts with a randomly-generated population of possible SoC values for the 24 SoC variables representing the hourly values in each day. The maximum number of iterations is set to 2000. The crossover probability is set to 0.8, while mutation probability is set to 0.2. It should be noticed that, during optimisation procedure, GA-MPOPF is always requested to meet the system constraints described in Section II-B.

Regarding the sizing of PV-BESS system, the PV rated power is chosen based on the maximum value of P_g, which represents the PV power profile over one year. In particular, different values of the sizing coefficient $S_n (n = 1, 2, ..., N)$ have been chosen to scale the rated power of PV system according to (8).

$$\begin{gathered} PV_s^n = S_n \times max(P_g(t)) \\ t \in 1, 2, ..., t_{end} \end{gathered} \tag{8}$$

Similarly, for BESS sizing, the coefficient $K_m (m = 1, 2, ..., M)$ is introduced and BESS rated power and/or capacity is defined by (9), in which B_c is the base BESS rated power and/or capacity chosen in accordance with user yearly gross energy.

$$B_s^m = K_m \times B_c \tag{9}$$

The first step of PV-BESS system sizing procedure consists of setting, $S_n = 1$ and $K_m = 0$ and calculating the residual power P_R by (10).

$$P_R(t) = P_c(t) - S_n \times P_g(t) \tag{10}$$

Once $P_R(t)$ has been obtained, the GA-MPOPF optimisation tool for the first PV size (PV_s^1) and BESS size ($B_s^1 = 0$) is applied for evaluating the gross energy exchanged by the prosumer. After that, the GA-MPOPF is applied again for B_s^2 with same PV size (PV_s^1): this procedure will continue until all BESS sizes are considered ($K_m = M$). Then, the next PV size (PV_s^2) is selected and the optimisation procedure is performed again for all BESS sizes. Optimisation will be completed when all PV and BESS sizes are considered within the procedure,as highlighted in Fig. 3. This reports the flow chart of the proposed procedure, which consists of two parts: the blue part of the flow chart addresses PV sizing and residual power evaluation. The estimated residual power is then used as input data of the optimisation tool described by the orange part of the flow chart, which addresses BESS sizing and energy management for achieving optimal self-consumption through the GA-MPOPF tool. In this regard, the objective function of self-consumption FF_{s-c} is reported by (11). This objective function represents the gross energy exchanged by the prosumer, namely the amount of energy that the user either draws from or delivers to the electric grid.

$$FF_{s-c} = \int_0^T |P_R + P_b|.dt \tag{11}$$

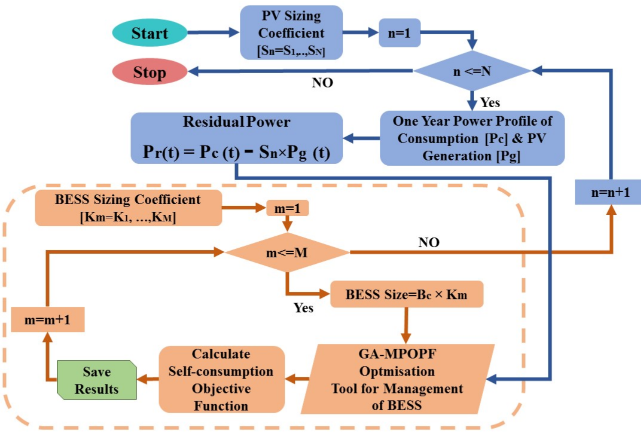

Fig. 3. Flow chart of proposed procedure for sizing and managing PV-BESS

III. Case of Study and Data Set

To take into account seasonal effects of electricity consumption and PV production, the analysed data refer to one year. The residential actual yearly power demand and PV production are obtained from [17], which gives various data of single households in terms of electricity consumption and PV production along with their online addresses. The data are sampled hourly, and the rated power demand is equal to 7.5 kW. Some of the online IP addresses are provided in [18] and different online addresses represent different households data sets. In this paper, the data of a single household user has been analysed (from September 26,2018 to September 25,2019), for overall 8760 hours.

The commercial user power profile is obtained from [19], namely the active power profile of a secondary school located in Minneapolis-USA, whose data set covers the period of one year (from January 1, 2004 to December 31, 2004). The rated power demand is equal to 2.4 MW. The PV production data has been obtained from the website of The Independent Electricity System Operator (IESO) [20], and it refers to LittleLong-Ontario-Canada and covers the period from January 1, 2010 to December 31, 2010. Although the data of electricity consumption and PV production are not referred to the same period and location, latitude and longitude of the regions are close to each other, thus all data sets can be assumed consistent to each other.

TABLE I
SIZING RANGE OF PV-BESS

	Case 1	Case 2
PV size range (kW_p)	0 - 9	0 - 3000
PV size steps (kW_p)	1.5	500
BESS size range (kWh)	0 - 100	0 - 5000
BESS steps (kWh)	10	500

IV. RESULTS AND DISCUSSIONS

The optimisation is performed for one year considering a household user (case 1) and a commercial user (case 2). The sizes of PV and BESS for cases 1 and 2 have been set in accordance with Table I. Regarding BESS, it is always assumed charging and discharging at 1 C, so its rated power always equals its capacity. In addition, charging and discharging efficiencies have been set both at 0.9, leading to an overall round-trip efficiency of 0.81. As first result, it has been found that all the system constraints given in Section II-B are satisfied for every PV-BESS combination and for every considered time interval. This is due to self-consumption, for which delivering of active power from/to PV-BESS

Fig. 4 shows the amount of yearly gross energy for different sizes of BESS and PV for case 1. Beside this, the yearly gross energy without any BESS and PV is given as a reference (approximately 11.42 MWh). It can be seen from this figure that employing a PV with 1.5 kW_p (green line), increases the self-consumption by approximately 2 MWh and that the role of BESS is quite limited. On the other hand, considering a PV with 7.5 kW_p (blue line), increasing the size of BESS from 0 kWh to 100 kWh improves the saved gross energy significantly (from -17% to more than 80%). This fact is highly depending on PV production because the BESS can use the excessive energy coming from PV to get charged and release it whenever needed. From the same figure, it can be seen also that most of the total improvement of self-consumption (approximately 65%) is achieved by a BESS size of 30 kWh, whereas increasing BESS size from 30 kWh to 100 kWh determines just minor improvements (about 20%).

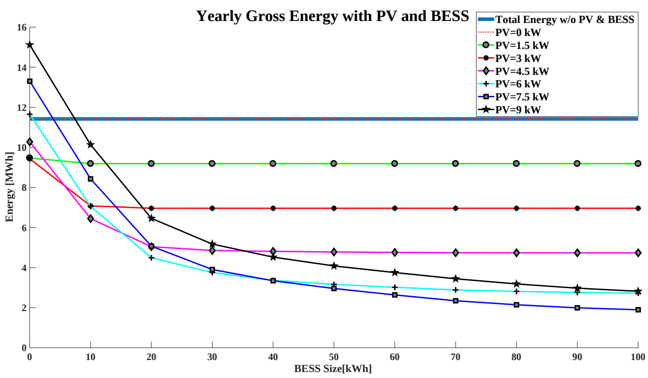

Fig. 4. Yearly Gross Energy with different sizes of BESS and PV (case 1)

Fig. 5 shows the cumulative yearly gross energy of system for all PV and BESS sizes considered for case 1. It can be seen from this figure that the most amount of saved gross energy occurs by the PV with 7.5 kW_p and BESS with 100 kWh (approximately 9.5 MWh). It can be seen also that the most significant part of saved gross energy (approximately 7.5 MWh) is achieved with a BESS size of 30 kWh. This means that although the improvement of self-consumption increases with BESS size, it should be considered that the saved gross energy increase is 2 MWh by varying the BESS size from 30 kWh to 100 kWh; this amount of energy is just 20% of total saved gross energy, while the BESS size is increased by 330%. This means that increasing the size of BESS becomes increasingly less effective, which is an interesting outcome of the procedure proposed in this paper. In addition, Fig. 5 reveals also that the same self-consumption can be achieved by different PV-BESS combinations; since these correspond to different features, for example installation costs and/or net energy exchanged with the main grid, this means that the proposed procedure could be refined further, by monitoring additional variables that helps identifying the most suitable solution for each user.

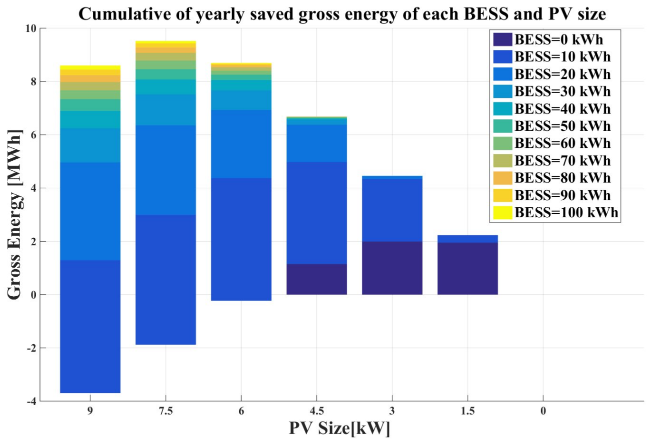

Fig. 5. Cumulative yearly saved gross energy for different BESS and PV sizes (case 1).

Fig. 6 addresses the residual power with and without BESS. In addition, PV production and electricity consumption profiles are shown by green and black lines, respectively. The PV size is 7.5 kW_p and the BESS size is 30 kWh. All the data belong to the first 15 days of case 1. In this figure, the red line represents the residual power of the system considering PV production and electricity consumption, as in (11), while blue line displays the optimised residual power profile in presence of BESS. As it can be seen from this figure, taking into account PV-BESS system and considering the optimisation provided by the proposed GA-MPOPF algorithm, in the days with enough excessive PV production (negative residual power), the self-consumption target is almost completely fulfilled. However, in days without excessive PV production the self-consumption target can not be followed completely since BESS can not store enough amount of energy to fulfill the self-consumption target. Consequently, if the size of BESS is big enough, all the excessive energy produced by PV in other days (i.e. days 8 and

9) can be stored and used in upcoming days (i.e. days 12-15) to achieve self-consumption target completely. Because of this fact, the improvement of self-consumption with bigger BESS size always occurs up to a certain limit (a very big BESS size), beyond which no further improvement is achieved.

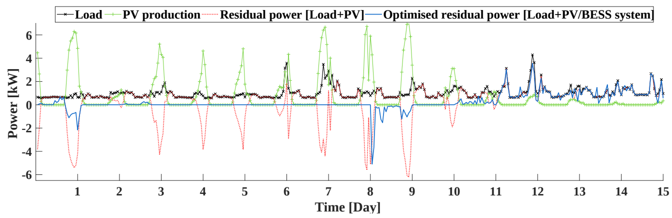

Fig. 6. Residual power before and after optimisation (PV with 7.5 kW_p BESS with 30 kWh) for the first 15 days of case 1.

Fig. 7 represents the amount of yearly gross energy achieved for different sizes of BESS and PV for case 2, together with that achieved without any BESS and PV as reference (light blue line, 5.49 GWh). As it can be seen from this figure, in the case of PV with 500 kW_p (green line), self-consumption is increased by about 1 GWh, while the role of BESS for increasing self-consumption of system is almost negligible. The optimal result is achieved by PV with 1500 kW_p and BESS with 5 MWh, which lead to an overall self-consumption improvement of approximately 40% (2.2 GWh). However, the improvement of self-consumption with BESS size from 0 MWh to 2 MWh is more than 75% of the overall one, as already detected in case 1. in particular, increasing the size of BESS from 2 MWh to 5 MWh still improves self-consumption, but just approximately 20%, while the BESS size is increased by 250%, confirming the outcome of case 1. In addition, installing a PV with 3000 kW_p almost always leads to increasing the yearly gross energy unless a very large BESS is employed, meaning that such a large PV is absolutely oversized.

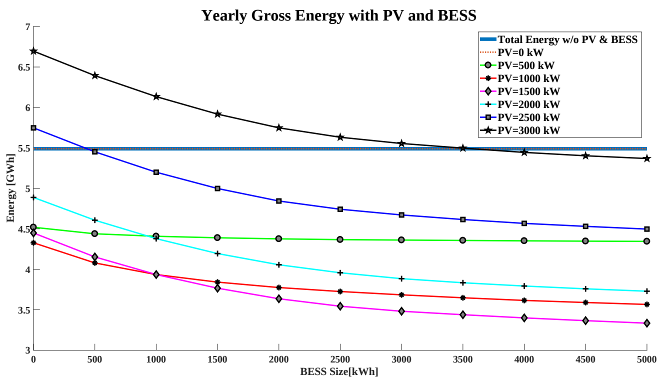

Fig. 7. Yearly gross energy for different sizes of BESS and PV (case 2)

Fig. 8 indicates the cumulative yearly saved gross energy for all PV and BESS sizes considered for case 2. It can be seen from this figure that the maximum of the saved gross energy is achieved by the PV with 1500 kW_p and BESS with 5 MWh size (approximately 2.2 GWh). It can be seen also that the most significant part of this saved gross energy (around 80 %) is achieved by a BESS size 2 MWh. Moreover, increasing the BESS size improves self-consumption, but increasingly less effectively, thus confirming the outcome of case 1.

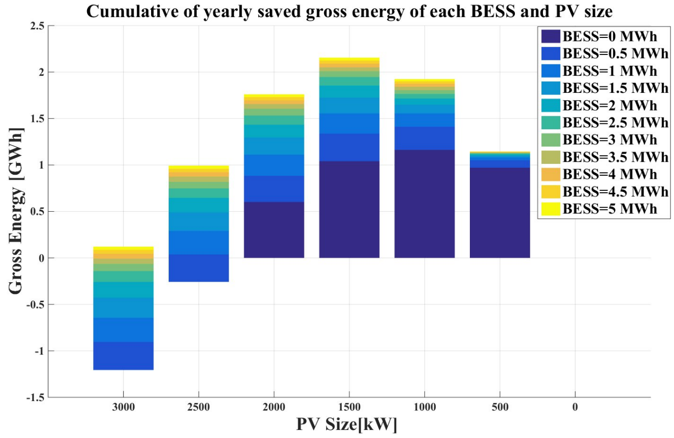

Fig. 8. Cumulative yearly saved gross energy for different BESS and PV sizes (case 2).

Fig. 9 shows the residual power with and without BESS achieved for case 2. In addition, PV production and system consumption profiles are shown by green and black lines, respectively. The PV size is 1500 kW_p and the BESS size is 2 MWh. The data refer to the first 15 days of case 2. In this figure, the red line represents the residual power of the system considering PV production and load profile, while the blue line displays the optimised residual power profile in presence of BESS. As it can be seen from this figure and by considering that the optimisation is performed day-by-day, the BESS cannot save all energy coming from PV in days with excessive PV production and relatively small load demand (i.e. days 4 or 5) due to its limited size. Because of this, the excessive energy delivered by PV is exchanged with the main grid. However, for most of the days, the self-consumption target can be almost completely fulfilled. These results show that the proposed optimisation method is working properly.

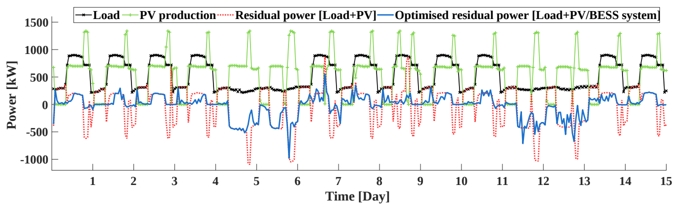

Fig. 9. Residual power before and after optimisation (PV with 1500 kW_p, BESS with 2 MWh) for the first 15 days of case 2

V. CONCLUSIONS

In this paper a tool based on Genetic Algorithm Multi-Period Optimal Power Flow for sizing and managing PV-BESS system has been presented. The proposed procedure aims at giving a self-consumption map depending on both

PV and BESS sizes. Based on this, the user can select the most suitable solution for him/her in accordance with his/her habits and self-consumption target. The obtained results show that appropriate sizing and management strategy of PV-BESS system can increase the saved gross energy of residential and commercial electricity users, by maximising self-consumption. In particular, the results show that the gross energy is reduced more than 80% (approximately 10 MWh) and 40% (approximately 2.2 GWh) for a residential and a commercial user, respectively. The results also show that the improvement of self-consumption with bigger BESS size always happens up to a very big BESS size, although BESS becomes increasingly lee effective.

The proposed optimisation methodology is fully adaptable and configurable to different users (i.e. residential, commercial and industrial) and power systems (i.e. Medium Voltage, Low Voltage networks), as well as able to replace or include different renewable energy sources (i.e. wind power plants) and energy storage units. The proposed tool is going to be available online in few months.

The present study takes into account only technical aspects of self-consumption, thus no economical aspect has been considered. The future research will be devoted to an economical assessment of PV-BESS system, by giving to self-consumption an economical value.

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