Methodology and Simulation of Electrical Grid Peak Shaving Strategy based on Photovoltaic and Storage Optimization: an Italian Residential Sector Case Study

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Abstract. The European Union has set some ambitious targets to reach the goal of net-zero greenhouse gasses by 2050. The outlined scenarios provide the use of Renewable Energy Sources (RES) on a large-scale, but to do so, different kinds of actions must be taken, because the ample amount of non-programmable electricity sources may cause grid management problems and a mismatch in the energy supply and demand. The vast increase of the Italian power demand, which typically occurs in the evening, necessarily requires a rapid increase in thermoelectric power generation. A possible solution to avoid this phenomenon is the optimization of photovoltaic production and storage and, simultaneously, the minimization of the Life-Cycle impact of these systems on the environment.

This work aims to identify a methodology that supports the analysis and design of a production, self-consumption and storage system, which services a residential user aggregate, in order to reach an electric power demand optimization. In particular, the target is to obtain a Peak Shaving of the electrical demand power curve, by setting a limit on the maximum absorption of power from the grid, and supplying the rest of the user's power needs through an electrical energy storage system, charged from the photovoltaic plant during the daily overproduction time.

To do so, 14 dwelling power consumptions have been aggregated and analysed, starting from a data monitoring that occurred in January and June of 2019. The energy consumptions considered, are in line with the Italian average ones.

The Peak Shaving strategy effectiveness has been evaluated by using a percentage parameter, that represents the number of power absorption peaks from the grid, avoided thanks to the storage system. In this study, some optimal system plant settings, in terms of maximum power absorption from the grid, photovoltaic nominal peak power and electrical storage capacity, are investigated to reach the set goals, and some solutions are presented, in light of the needs of the public grid where the system operates.

1 Introduction

Two of the central challenges of the 21st Century are to learn to mitigate and adapt to climate changes; for this reason, the EU has promoted several initiatives aimed at containing its long and middle-term effects, boosting the energy production from renewable energy sources (RES). The large-scale integration of RES in the electrical systems can generate technical problems and safety issues, due to their non-programmable nature. Various research activities have concentrated on the evaluation of the technical and safety concerns linked to rising implementations of RES in the current energy systems. In [1] an accurate technical analysis of electrical systems fully sourced from RES can be found.; the authors underline the importance of flexible power plants, storage technologies, and of Demand-Response (DR) activity. Zappa et al. [2], have analysed different scenarios relating to the whole European energy system, in order to explore the feasibility of a fully

RES electrical system; the authors have conducted their simulations while considering different operating conditions, including a significant load shift obtained by DR activity.

A series of researches have been conducted in order to identify the flexibility potential of dwellings [3]; Rahmani-Andebili [4] has created a predictive model which can correctly program the deferrable flexible loads and energy resources; in [5] a methodology for residential clustering and developing a flexibility strategy was identified. Furthermore, the use of a dwelling's thermal inertia can be considered an effective way to store energy [6,7]; in fact, this inertia is able to store heat and therefore anticipate or delay the ignition of heating and cooling systems, without influencing the internal comfort conditions [8]. Other available options to manage the load flexibility consist in applying the so-called "Power-to-X" or "Power-to-What" strategies [9-11]; as for the dwelling sector, the most promising and suitable solutions are Power-to-Heat, Power-to-Power and Power-to-Gas [12-15]; in [16], the flexibility potential of electrical heat pumps used for space heating and domestic hot water production (DHW) has been explored. Moreover, specific storage devices, like Phase-Change Materials (PCM), batteries, pressurized gas tanks, and biofuels injection in the natural gas grid (NG) must be adequately integrated into the existing energy systems [17].

As for the increase of the RES electrical energy production, the photovoltaic (PV) panel is a key technology, given that it is already commonly used and economically advantageous [18]; the installation of PV plants can also be considered a solution to the increase in the electrical consumption connected to summer climatization [19]. Further material development and efficiency, along with the integration of products, can be promoted by a simplified modelling tool [20], however, the remaining obstacles must be considered, for example the storage needs [21] or the future energy market mechanisms [22]. The PV plants can have a low impact [23] if they are integrated in existing dwellings and do not take up further land [24]. Lezama et al. [25] propose a dynamic algorithm for the management of the DR activities in residential dwellings equipped with PV systems and batteries.

This study is part of a research project aimed at characterizing and defining a strategy that can be used by the residential sector to participate in a program of demand-side management that can contribute to the optimization of the absorption load profile from the public grid.

In particular, this work presents an analysis methodology that is able to size the PV plant and battery storage systems. The main goal is to flatten the absorption load profile curve and to take into consideration other energy and environmental factors. This methodology can facilitate the choice of who will design the plant systems, which will not be centred around the maximization of self-consumption but will focus on the production and storage, which provides services to the grid.

The authors deem that their contribution to the literature in this research topic is substantially the methodological approach, which integrates on-field measurements with a simulation process; more specifically, the authors attempt to identify how the Peak Shaving strategies can represent a driver for the energy transition and can support the design of PV and storage plants. By combining several tools for statistical analysis, the dwellings' electrical power profiles have been analysed, and then processed to simulate an optimal solution. Moreover, this study represents an innovative approach never investigated in the Italian context, that sets as a goal an electrical-service that helps the grid management, and at once contribute to identify the potential role of Italian residential sector within the long-term strategy of progressively transforming the end users' energy impact.

2 Materials and Methods

This study is part of a research project that aims to characterize the Italian residential electrical users to evaluate the effectiveness of a Demand Response (DR) program. In previous works, by some of the authors, a wide data collection campaign has been carried out to build a database composed of 751 typical Italian dwellings. 14 most representative dwellings have been selected within the database, considering the average surface in plan, the family components numbers, and social conditions. By doing so, after the user has agreed, the selected dwellings have been equipped with electrical data sensors. The total data acquiring time has been two years.

In particular, all the dwellings are equipped with a NG boiler, and some of them have cooling appliances only for a few rooms. Washing Machines and Dishwashers are available in almost all dwellings, with average usage. Various other appliances are present, and the lighting is quite efficient. The consumptions are between

2100 and 3200 kWh/year and are in line with the Italian average values, which means the residential sector is not highly electrified and that it is characterized by low penetration of summer space cooling.

The monitoring obtained data has been aggregated in order to obtain a load cumulated profile of the 14 dwellings: by a static calculation sheet developed in Excel-VBA Environment, some simulations have been carried out, varying the design parameters of photovoltaic and storage systems, for the aggregate.

The simulations have been conducted considering the following constraints:

- Self-consumption from PV as long as the production is simultaneous with the load aggregate demand;
- Supply from the public grid, net of the self-consumption, as long as the power adsorption is within the fixed maximum limit;
- Storage charging, only from PV, in the moments where the production is higher than the demand;
- Selling to the grid of energy produced in surplus compared to the internal demand (aggregate loads and battery storage);
- Supply from storage battery systems for the portion of power demand that exceeds the fixed limit, until the complete discharge of the storage capacity.

The simulation aims to evaluate the Peak Shaving of the absorption power profile of the aggregate: in particular, the load curve must not exceed the fixed limit in terms of power.

The strategy effectiveness has been evaluated by the use of the indicator 'Number of Avoided Peaks': a an Avoided Peak in this case means those times of the 15-minute slot time of the real monitoring (before the simulations) that presents a power demand over the threshold, and, after the simulations, that 15-minute slot time presents a power adsorption equal to the fixed limit threshold.

The useful effects considered in the simulations are:

- Peak Reduction Percentage, that is the number of demand power peaks, in percentage, that have been managed to remain under the fixed limit;
- The amount of Sold Energy to the grid;
- The amount of Avoided Purchased Energy from the grid, that is the self-consumption.

The fixed limit, that the peaks must remain in, is an imposed threshold in terms of maximum adsorption power from the grid, and will be the maximum value that can be measured at the aggregate POC (Point of Connection; the grid interface) above which the Storage starts to supply the load. This means for example that if the limit is set at 6000 W until the load demand is lower than the threshold, the energy comes from the grid, or from the PV (if there is simultaneous production); when the demand is above the threshold, the surplus between the limit and the needed power demand will be supplied from the battery, and the power adsorption from the grid remains constants at 6000 W.

The variables considered, and their discrete variation ranges, are:

- PV plant Nominal Peak Power, between 3 kW and 30 kW;
- Storage System Capacity installed, between 5 kWh and 25 kWh;
- Maximum Absorption Power from the grid, between 4000 W and 8000 W.

This work has been conducted over two sample months, identified as significant for the winter and summer seasons (January and June 2019) and within these months, two weeks have been chosen, respectively when the temperature was more extreme. Doing so, the summer week shows higher use of dwelling cooling space systems, but also a PV very high production, while in the winter week the consumption was in line with the rest of the year, but the PV production was very low. This choice allows to have an extreme power overview over the year, and provides to have some margins over the rest of the seasons. The consumption of the aggregate in the summer week was 784 kWh, while in the winter one 592 kWh, with an increase of 32% in the summer, due to the cooling usage.

Below, in Figure 1, a simplified block diagram of the logic behind the simulation process is presented.

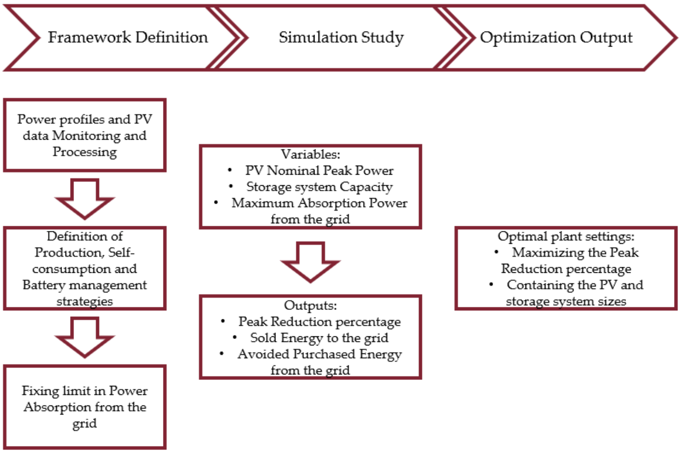

Fig. 1. Simulation Logic Block Diagram: three phases process description.

3 Results and Discussions

In this section, the results of simulations associated with the Peak Shaving strategy analyzed have been presented. By alternately discretely varying the three focused variables (PV Nominal Power, Storage Capacity and Maximum Absorption Power), the Aggregate behaviors with that technical plant settings, are simulated.

Below a particular system behavior with certain equipment is presented, to show the kind of strategy which was simulated. In Figure 2 the monitored load profile (without strategy) is presented with the dotted green line and the same profile with the application of the strategy is with the red line. The strategy applied in this case consists in a limitation of Power Adsorption to 6000 W, a PV plant of 15 kW, and a storage capacity of 10 kWh, in a week of January. Moreover, it is shown how the strategy allows the reduction of the power absorption from the grid only for the peaks that exceed the maximum fixed threshold and, of course, allows to reduce it also when the PV production is high, obtaining Peak Shaving values around an average of 2400 W and up to 4300 W.

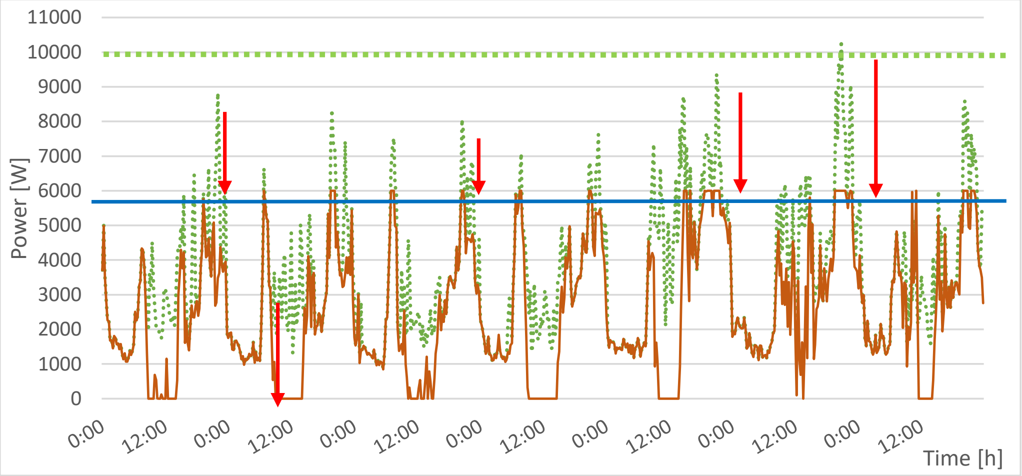

Fig. 2. 14 dwellings aggregate Power Adsorption profile from Grid in January Week: Pre (green) e Post (red) Strategy.

Below, some graphs that represent the Peak Reduction Percentage indicator (on the y-axis) in function of the PV nominal power (on the x-axis), and in function of the three variable Storage capacity (5, 10, 15 kWh) are presented. This is plotted for different thresholds of Maximum Absorption Power from the grid: 4000, 6000, 8000 W.

3.1 Absorption Power threshold at 4000 W, winter case

First, the property profiles in the case where the Maximum Power limit is set at 4000 W are investigated, relating to the winter January week.

In Figure 3 is possible to note how the Peak Reduction Percentage profile follows a quite-logarithmic increasing function and tends to 'saturate', i.e. to show a minimum cumulate percentage increase, around 12-15 kW of PV plant. The three storage capacities are presented in different colours and show the influence of that variable on the Peak Reductions. In Figure 3 is also reported the associated logarithmic equation for the 15 kWh curve, best approximal with a polynomial fourth-grade equation.

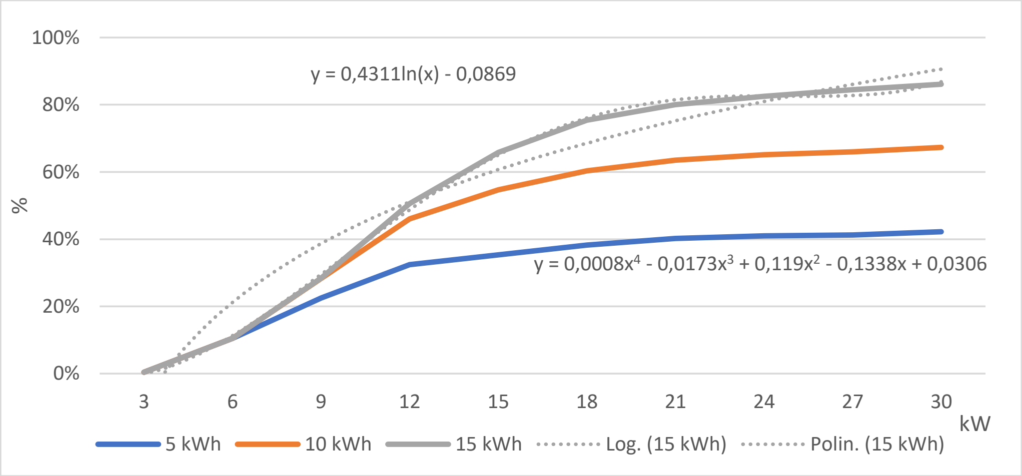

Fig. 3. Peak Reduction Percentage Result for Maximum Power limit of 4000 W.

Figure 4 reports the Energy sold to the grid and Avoided Purchased Energy from grid profiles (that is the self-consumed one). The selling of energy, clearly higher for smaller storage, increases with the rise of PV plant sizes and tends to be linear over 15 kW. The linearization means that the percentage increasing of the revenues for selling is constant, and therefore the selling is proportional to the kW capacity installed. The trend of the Avoided Purchased Energy follows the Peak Reduction Percentage trend, showing a saturation at PV values higher (15 – 18 kW): this because at these values the self-consumption simultaneous at the production is higher.

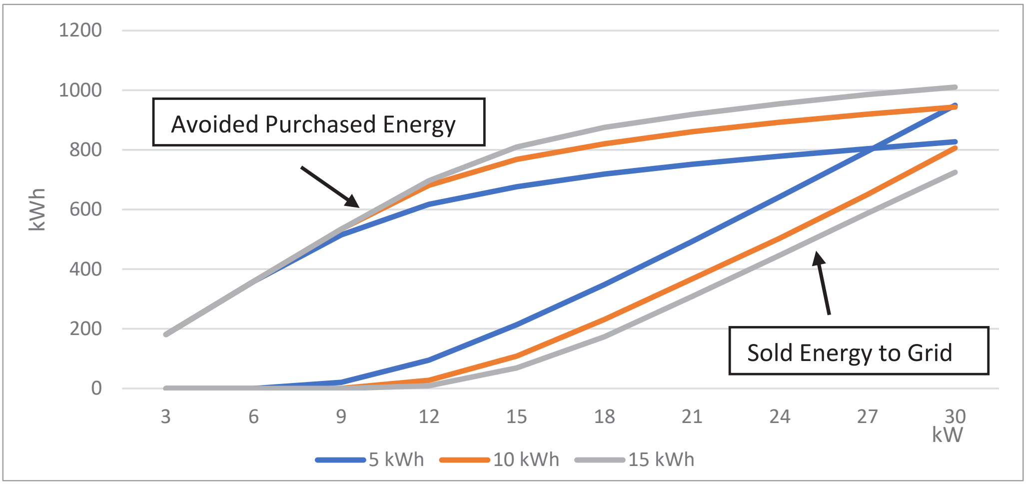

Fig. 4. Peak Shaving Strategy Results for Maximum Power limit of 4000 W.

3.2 Absorption Power threshold at 6000 W, winter case

Below, in Figure 5, the property profiles in the case where the Maximum Power limit is set at 6000 W are presented. On the same graph are plotted together with the Peak Reduction, the Avoided Purchased Energy and Sold Energy to Grid, with different y-axis scale (% on the left; kWh on the right).
The previous considerations are always valid; moreover, is possible to note how at rising in Maximum Power Absorption, the difference between the storage capacities has a low impact on the three proprieties investigated, and therefore the dependence from the battery size is low, and the saturation occurs more rapidly.

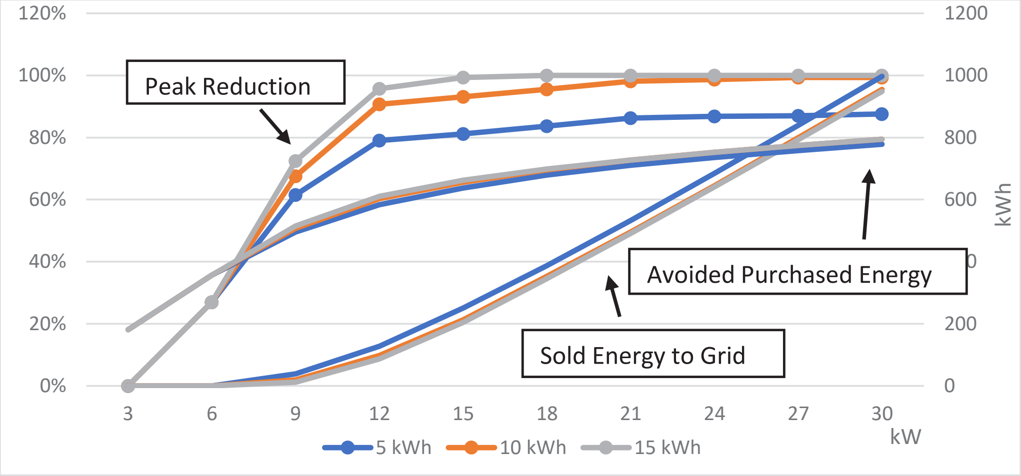

Fig. 5. Peak Shaving Strategy Results for Maximum Power limit of 6000 W.

3.3 Absorption Power threshold at 8000 W, winter case

Below, in Figure 6, the property profiles in the case where the Maximum Power limit is set at 8000 W is presented.
Is possible to note how at rising in Maximum Power Absorption, the saturation in the curve occurs at low Nominal PV Power values (12 kW at 6000 W and 9 kW at 8000 W), due to the fact that a greater Power limit

implies less energy to be supplied by Storage, and therefore, a higher possibility to supply all the peaks and to avoid the exceeding in Maximum Power limit. This behavior is more accentuated with greater Capacity Storage.

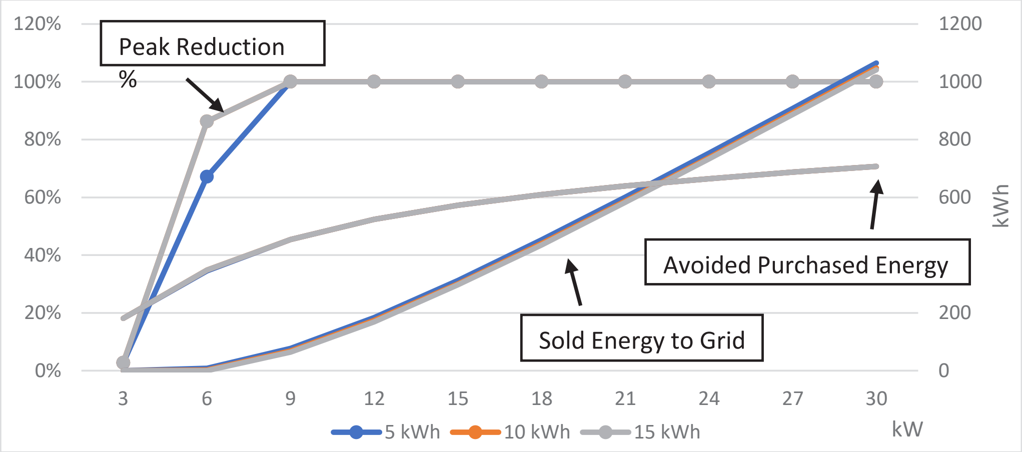

Fig. 6. Peak Shaving Strategy Results for Maximum Power limit of 8000 W.

Rising in Nominal PV Power, reasonably, the self-consumption and the selling of energy increase; on the other hand, there is not a high increase in Peak Reduction that can justify the higher investment: in view of a minimum-cost approach for the target of Peak Reduction, is more important when the Peak Profile curve starts to saturate.

3.4 Simulation comparison in winter case

Below, in Figure 7, a comparison between the three Maximum Power Absorption case studies previously showed is provided, in terms of Peak Reduction. This comparison is useful to analyse and draw considerations and final choices.
The blue lines relate to a Power limitation of 8000 W, the red ones to a 6000 W one, and the green ones to 4000 W. The different colour shades represent the different Capacity Storage sizes.

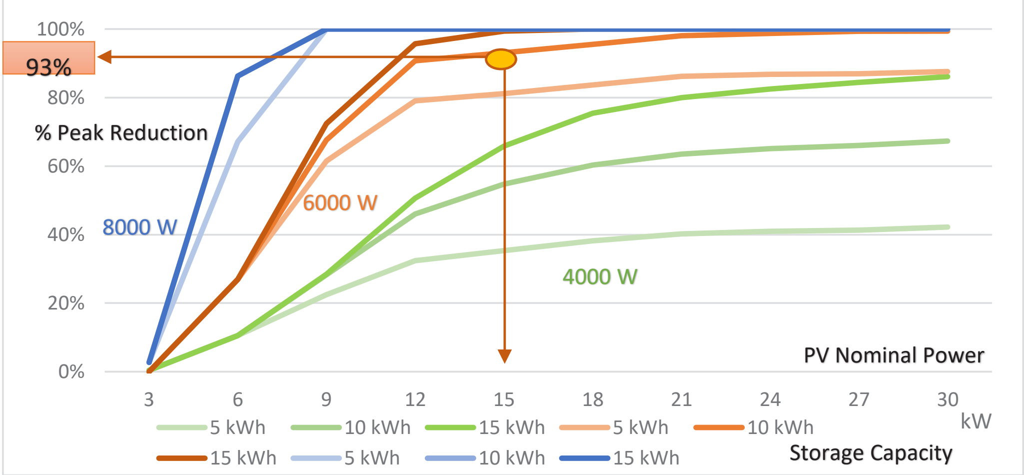

Fig. 7. Peak Reduction Percentage Comparison between different Maximum Power limit for January case.

Concluding, the best solutions, with the aim to optimize the costs and obtain enough energy yields, are:

- If the aim is to reach a Power limit of 8000 W, a PV Power of 9 kW and a Storage Capacity of 5 kWh;
- If the aim is to reach a Power limit of 6000 W, a PV Power of 12-15 kW and a Storage of 10-15 kWh;
- If the aim is to reach a Power limit of 4000 W, a higher PV Power and Storage Capacity are necessary, over the ranges of that simulation.

Excluding the 4000 W case, as it is expensive and inefficient for the discussed objectives, the 8000 W and the 6000 W cases will therefore be a choice dependent on the needs of the grid on which the system is operating, on the living environment, and the Aggregator's objectives.

Assuming that some peaks would not be reduced within the imposed power limit, the best plant setting which allows for a good compromise between the environmental benefits, the benefits that can be obtained from the grid and the user's benefits (energy savings and sales) would be the following: a limitation of power adsorption to 6000 W, a PV plant of 15 kW and a storage capacity of 10 kWh. Furthermore, it is important to note that the present simulations have been conducted during the month of January, when the meteorological conditions were not optimal in terms of PV production.

3.5 Simulation comparison in summer case

The same analysis has been conducted during the month of June 2019 by using aggregate electrical consumptions that present a higher energy demand, mostly due to the use of the space cooling systems (air-conditioners).

The results are largely similar to the ones obtained in the winter case, however, they somewhat differ.

The following figure (Figure 8) shows the graph which confronts the three maximum Power Adsorption limits which were considered, similarly to what is shown in Figure 7.

The blue lines relate to a power limitation of 8000 W, the red ones to a 6000 W one, and the green ones to 4000 W. The different colour shades represent the different Capacity Storage sizes, from 5 to 15 kWh.

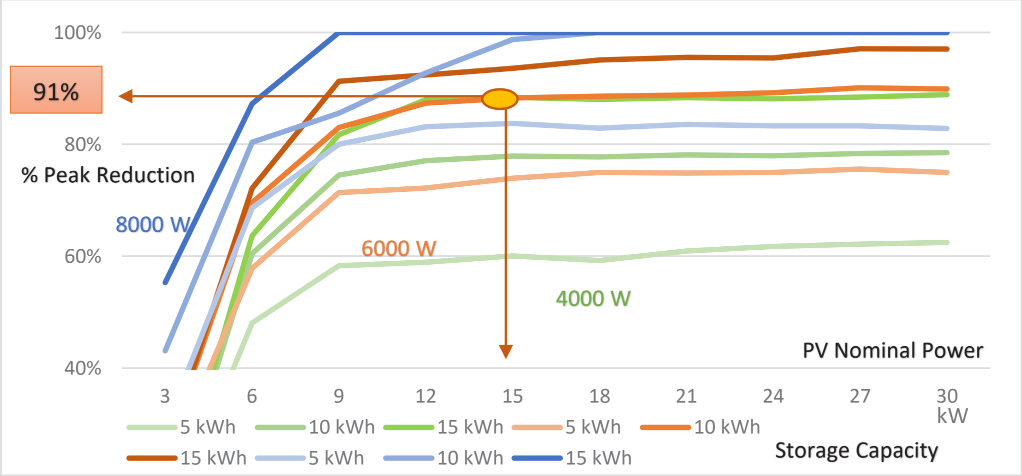

Fig. 8. Peak Reduction Percentage Comparison between different Maximum Power limit for June case.

The primary difference between the winter and summer case is that almost all of the curves saturate at approximately lower PV values (around 9 kW). This is due to the fact that the study was conducted in the summer month and therefore the productivity capacity of the 9 kW plant is similar to that of a 15 kW plant during the winter months. Furthermore, the sold and self-consumed energy values increase, even though the energy consumption also increases due to the use of air conditioning systems.

It is also important to note that there is a higher deviation between the different storage sizes because whenever there is a higher energy production, higher energy storage is able to accumulate more energy, and therefore deal with higher power peaks, like the ones demanded by the use of air conditioners.

The authors have observed that the winter case's plant settings, optimal for the current study, are indeed adaptable and efficient in the summer case as well. This is explained by the fact that the use of air conditioners during the summer is generally limited to 3 months per year: keeping in mind that the main goal is to reduce the plant's cost, the previous solution enables to reach Peak Reduction percentages over 90 %. During the months in which the PV production is higher than the one produced in January, and the use of air conditioners is absent (i.e. the spring and autumn period), the Peak Reduction percentage can reach up to 100%.

4 Conclusions

In this work, an analytic methodology that supports the design of a PV and storage residential system has been presented. A simulation to propose an optimized plant setting has been carried out based on data monitoring and post-processing of 14 dwellings' power consumption profiles. A virtual residential aggregate has been built and over one week of January and one week of June the simulation of a Peak Shaving strategy, based on the limiting of the maximum power absorption from the grid, has been conducted. The choice of analysing two extreme weather conditions (Winter and Summer), allows for a large security range in designing the technical system: in fact, both the PV production and the power consumption are brought to the extreme, due to the difference in solar irradiance and summer electrical cooling demand.

The Peak Reduction percentage parameter varies noticeably in relation to the size of PV and storage systems. Moreover, the evaluation of the minimum plant cost, environmental impact, and energy sold and auto-consumption, and optimal settings have been proposed: it corresponds to a limitation of power adsorption to 6000 W, a PV plant of 15 kW and a storage capacity of 10 kWh. These settings allow to reach a Peak Reduction percentage of 93% in the winter case, and 91% in the summer case. This means that probably a 100% Peak Reduction could be reached in the half-seasons, due to the absence of cooling demand and increase in the PV production, and consequently the storage's full capacity could more likely be reached.

This work defines a model and a methodology that can be scaled and adapted to different kinds of contexts, also not residential, and increases its value in case of dis-homogeneous aggregates, due to the differentiation of the electrical power demand.

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