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Impact of consumption profile discontinuities on the feasibility of a PV plant

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Abstract

The revenues of a grid-connected photovoltaic plant are strongly related to the local climatic conditions. In addition, since self-consumed electricity is much more valuable than that traded with the main power grid, also consumption profile plays a key role in the profitability of a PV system. Self-consumption to total PV production ratio depends on the temporal mismatch between energy generation and demand. The amount of energy that is not self-consumed may be very high in the case of a consumption profile with several discontinuities. This study is focused on the analysis of a grid-connected PV system serving a compressed natural gas (CNG) fueling station. These facilities are energy-intensive users, characterized by high variability of electricity demand due to intermittent operation of gas compressors: in a few seconds the total load may change from 100% to 5% and vice versa very frequently during the day. The analysis was based on data acquired on the field for the compression station and those already present in the literature for solar irradiation. The influence on plant design of the time step used for the analysis was studied in detail. The outcomes showed that the typical and well-assessed design approaches of a PV pant may lead to errors when used for the design of systems with several consumption profile discontinuities.

Keywords: Photovoltaic plant, discontinuos load, self-consumption,

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1. Introduction

Grid-connected roof-top photovoltaic (PV) power plants may cover the demand for electricity in many low populated regions of Europe [1]. However, an energy balance with cumulated annual values does not deliver the right picture of the actual potential of a photovoltaic system [2]. The temporal mismatch between demand and PV production is a big limitation to the utilization of the energy generated by these systems [3]. Some authors [4] used individual household load profiles based on a time series with a resolution of 1 second from [5] to asses this issue. They noted that a correct design of the PV plant strongly depends on the actual coincidence between the PV output and load demand. Other studies showed that the energy consumption of a household and its time profile may vary over the years, and this has strong effects on the amount of the energy that may be self-consumed [6].
There are many publications on PV-battery system optimization, [7-9], but none of them investigated the influence of different simulation timestep on self-consumption estimation. Regarding PV simulation approaches, many databases have been released over the last decades. Among these, PVGIS is a free web application that has been developed for more than 10 years by the European Commission Joint Research Centre at the JRC site in Ispra, Italy. This application allows the user to get data on solar radiation and photovoltaic system energy production, at any place in most parts of the world [10]. PVGIS data sources and calculation methods have been validated in many publications [11].

Nomenclature

C_s	Effective capacity of storage system [kWh]
CNG	Compressed natural gas
DOD	Depth of discharge
EStG	Energy sold to the grid [kWh]
η_s	Storage efficiency [%]
P_s	Storage nominal power in charge/discharge [kW]
P_{PV}	Nominal peak power of photovoltaic modules [kW]
PV	Photovoltaic
PVp	Photovoltaic production [kWh]
T	Ratio between Energy Sold to the Grid and total PV production [%]

2. Aim of the work and methodology

This study starts from a real case of PV plant estimation made by the Department of Energy, Systems, Territory and Construction Engineering (DESTEC) of the University of Pisa and EotPlus s.r.l. (an Italian company operating in the field of energy saving) for a CNG fueling station located in Northern Italy. For confidentiality reasons of some details are omitted in this paper regarding the plant of interest. The CNG station is equipped with a three-stage reciprocating compressor of 132 kW providing CNG at 250bar and serving a gas tank storage suitable for vehicle refueling at 220bar. Another smaller reciprocating compressor is installed and used only in case of a failure of the main one. A 10kW chiller for gas cooling and other auxiliaries including illumination are installed. The number of start-stop operation of the compressor is recorded and collected for scheduled maintenance (more than 60 events for each day). An important parameter proposed for the feasibility and sizing analysis is the Energy Sold to the Grid (EStG) to total PV production (PVp) ratio (Eq. 1). This percentage represents the part of PV production that could not be self-consumed (also in case of storage capability) and is traded with the main power grid. Self-consumed electricity is much more valuable than the traded one because of difference between selling and buying prices.

$$T = \frac{EStG}{PVp}\ \% \qquad \text{Eq. 1}$$

To analyze the feasibility and profitability of a new grid-connected PV plant dedicated to the CNG station, preliminary studies with annual and monthly time bases have been carried out. For PV estimation the well-known PVGIS application (version 5rc) [12] has been adopted to estimate the potential PV production of the site of interest. This led

to the estimation of the average monthly and yearly energy production of a PV system connected to the electricity grid or isolated, with or without energy storage. The calculation considered the geolocation with real 3D terrain profile, solar radiation, temperature, wind speed, type/size of PV modules and their installation position. For the current investigation, PV panels integrated in the covering structure has been considered. This choice led to a 0° slope angle and an azimuth angle of 10° (-90° is East, 0° is South and 90° is West).
The solar radiation data used in PVGIS have mostly been calculated from satellite data. For this work the method developed by the CM SAF consortium called "PVGIS-CMSAF" [13-15] has been selected. This data set was already used in the previous version of PVGIS and covers Europe, Africa and parts of South America. Efficiency of the system has been set to 17% according to previous validation carried by the authors with real PV plants located in the same geographical area. Energy demand, for a preliminary estimation, resulted from energy bills of the past two years as average monthly consumption. The preliminary approach gave interesting global energetic estimation but was unsuitable to estimate the parameter T.

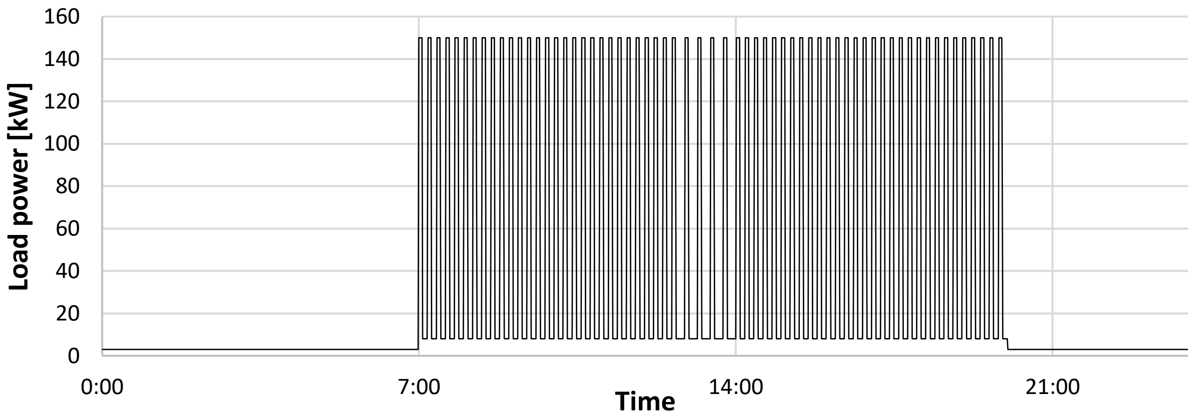

Figure 1. Reconstructed load profile, regular working day.

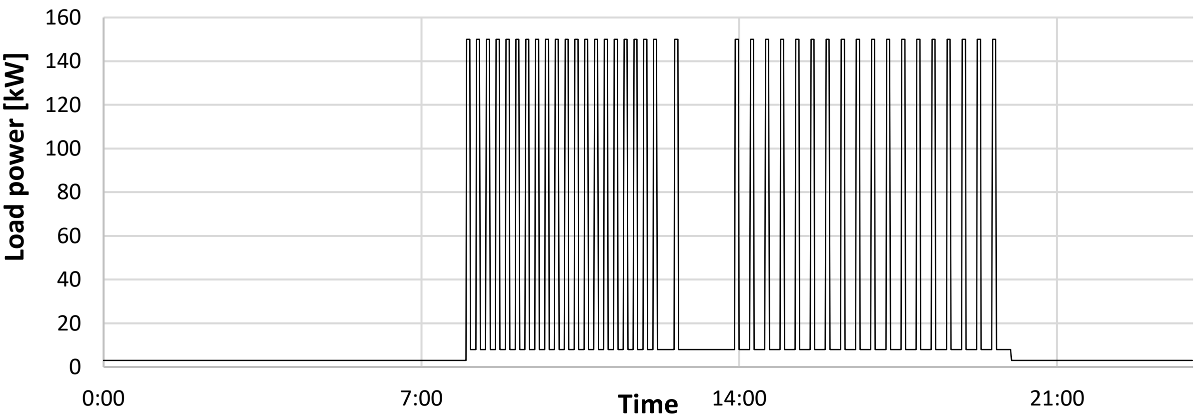

Figure 2. Reconstructed load profile, typical Sunday.

The aim of the present study is the evaluation of timestep impact on the simulation of a PV grid-connected plant, with and without storage system, coupled to an energy-intensive consumer like a CNG fueling station. In particular, four different time steps have been studied (1 day, 1 hour, 15 minutes, 1 minute). Consumption data collected by the electricity vendor are measured every 15 minutes: this is the smallest timestep achievable without carrying additional measurements with usual electric meters (in Italy). This timestep is not sufficient to have a detailed analysis of the actual energy exchanged with the grid. For this reason, a load profile, with 1-minute resolution, has been reconstructed by considering the total number of compressor on-off operation and the real values measured every 15 minutes. During the opening hours of the station, energy demand is quite constant from Monday to Saturday except for the hour from 13.00 to 14:00 (less vehicles served by the CNG station during lunch time). For the same reason on Sundays less energy is consumed. All nights, after closing time, a constant load of 3kW is recorded, probably due to illumination and other auxiliary services. In Figure 1 and 2 a regular day and a Sunday load profiles are reported. These reconstructed profiles give a year total consumption of 307111 kWh, very close to that that have been measured (average of past two years: 307150 kWh).

A 1-minute resolution is needed for the PV plant production, as well. PVGIS may apply the CMSAF model to past years, with real measured satellite data, and give as an output the PV production estimation every minute. To avoid year to year variability, the simulation of last ten years (2007-2016), with same parameters, has been carried out to obtain an average profile for PV yearly production of a 1kW PV plant. These results may be scaled easily to the desired power size P_{PV}. The load profile and the PV production are then elaborated and the comparison between the values of energy demand and energy production has been estimated minute after minute. The total year EStG and PVp are evaluated for calculation of the parameter *T*. A similar estimation was carried out by assuming the presence of a storage system with known effective capacity C_s (related to the real Depth of Discharge, DOD), nominal power P_s and efficiency η_s. The storage management was conceived to maximize the energy recovery but respecting the constraints (P_s, C_s). The model allows the setting of the variables reported in Table 1 for calculation of the energy balance and the value of *T*, both in the case of absence and presence of a storage.

Table 1. Variables used in the investigations

Variable name	Description
P_{PV}	Nominal power of PV modules [kW]
C_s	Storage system effective capacity [kWh]
P_s	Storage system nominal power [kW]
η_s	Storage system efficiency [%]
Timestep	Desired timestep, starting from 1 minute

3. Results and discussion

A preliminary approach based on PVGIS monthly analysis is often used for the design of small and medium PV plants. In Figure 3, the energy consumption and PV production for each month are reported. In this case study, with a load characterized by high variability of electricity demand due to intermittent operation of gas compressors, the underestimation of the energy released to the grid during compressor shutdowns is a relevant and challenging issue (Figure 4). To investigate this aspect, a more detailed simulations have been carried with different timestep (1 minute, 15 minutes, 1 hour, 24 hours), P_{PV} (20-30-40 kW) with and without storage (P_s=3kW C_s=10kWh η_s=98%). In Figure 5, the values of *T* for each case are reported.

Daily simulations (24h) shows no benefit in comparison to monthly analysis because in every conditions *T* is equal to 0%. Hour and 15 minutes timesteps barely recognize the existence of energy released to the grid. Only the 1-minute simulation clearly shows the real magnitude of this event. Without storage system, a significant part of PV production (from 9% for a 20kW plant to 28% for a plant with twice the size) might be not self-consumed and be released to the grid with an economic penalization. In addition, the benefit coming from the adoption of a storage system is appreciable only with the smallest timestep: a significant reduction of *T* may be achieved, up to 10%.

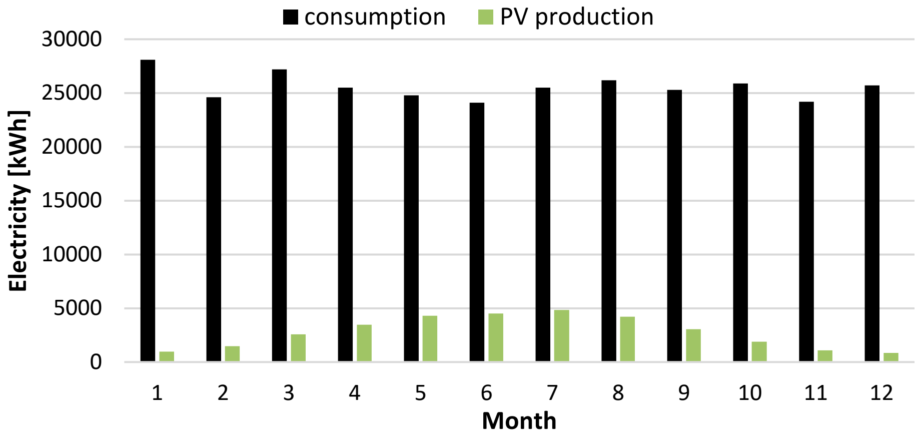

Figure 3. PVGIS-CMSAF monthly analysis and energy consumption.

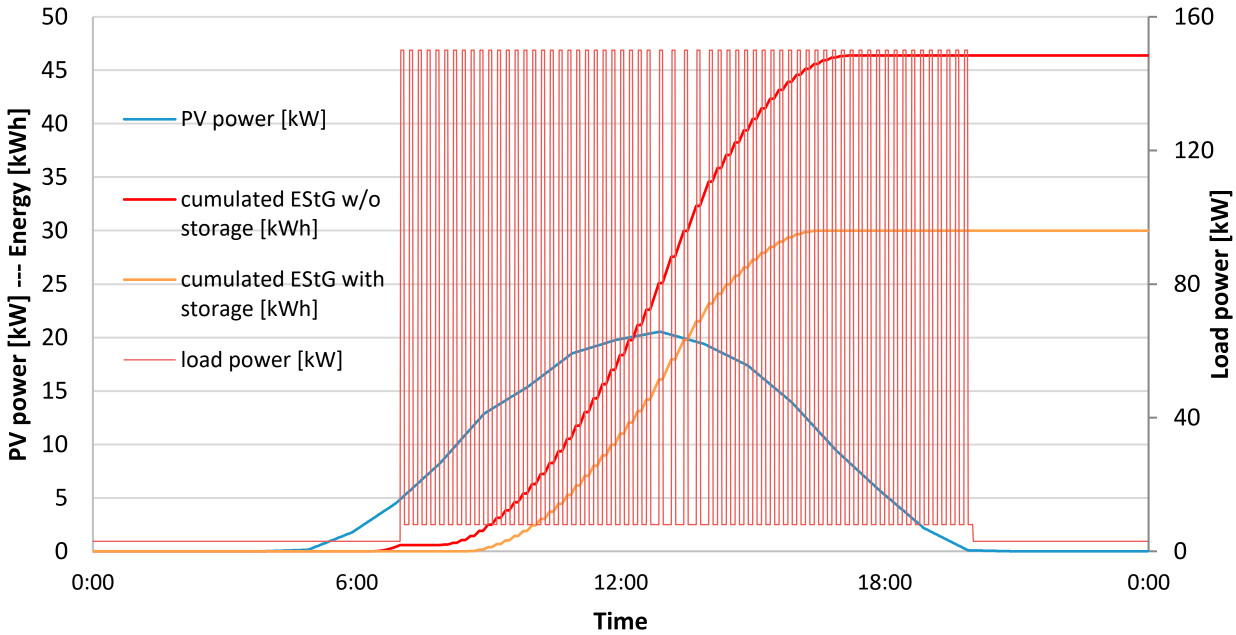

Figure 4. CNG plant power request, PV power production and cumulated energy sold to the grid during a regular summer day (1 min).

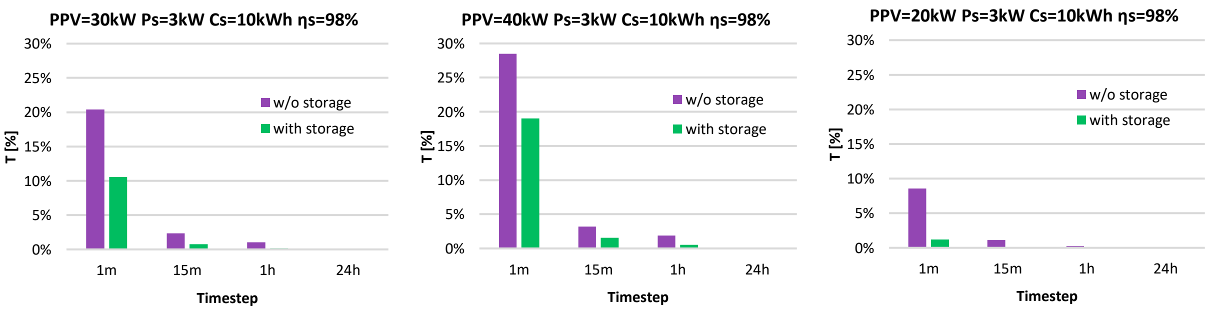

Figure 5. T for different timestep and P_{PV}, with and without storage.

To estimate the economic impact of these errors a very simple economic analysis is introduced by considering the cost of energy bought from the main power grid (0.07 €) and the remuneration granted by energy sold to the electricity vendor (0.035€). These values could be significant affected by market and taxation fluctuations but are representative of current pricing and subsidy levels in Italy. If the self-consumed energy is overestimated, also the electricity cost saving will be erroneously estimated. Errors in *T* evaluation have been converted in overestimations of cost saving (Figure 6). The error increases with PV plant size and it is bigger, up to 17%, in the cases without a storage system.

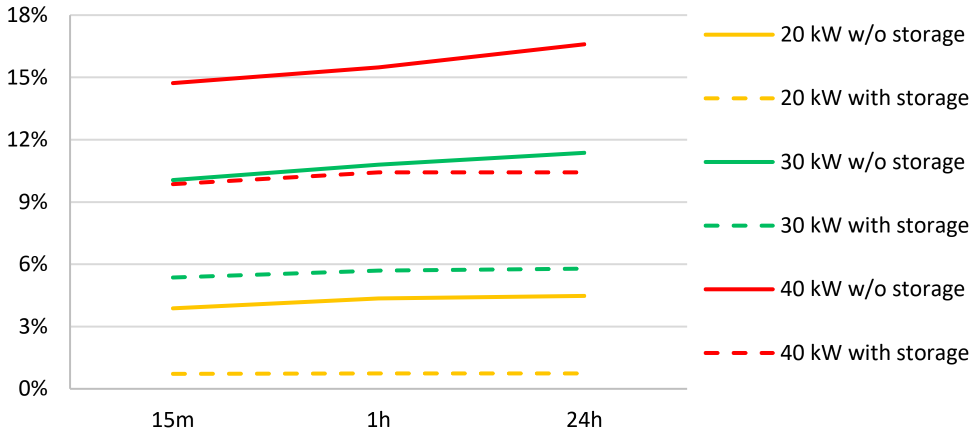

Figure 6. Electricity cost saving overestimation with different timesteps.

In Italy, the quarter of hour is the smallest timestep achievable without performing additional measurements and using the usual electric meters provided by the electricity vendors. These results indicate that, in case of high variable loads, only real-time load measurements should be used for self-consumption estimation. Even the energy demand averaged on 15 minutes does not provide a correct estimation of the real energy exchange. Such errors in cost-saving estimation are not negligible and over the entire life of PV modules represent a relevant economical penalization.

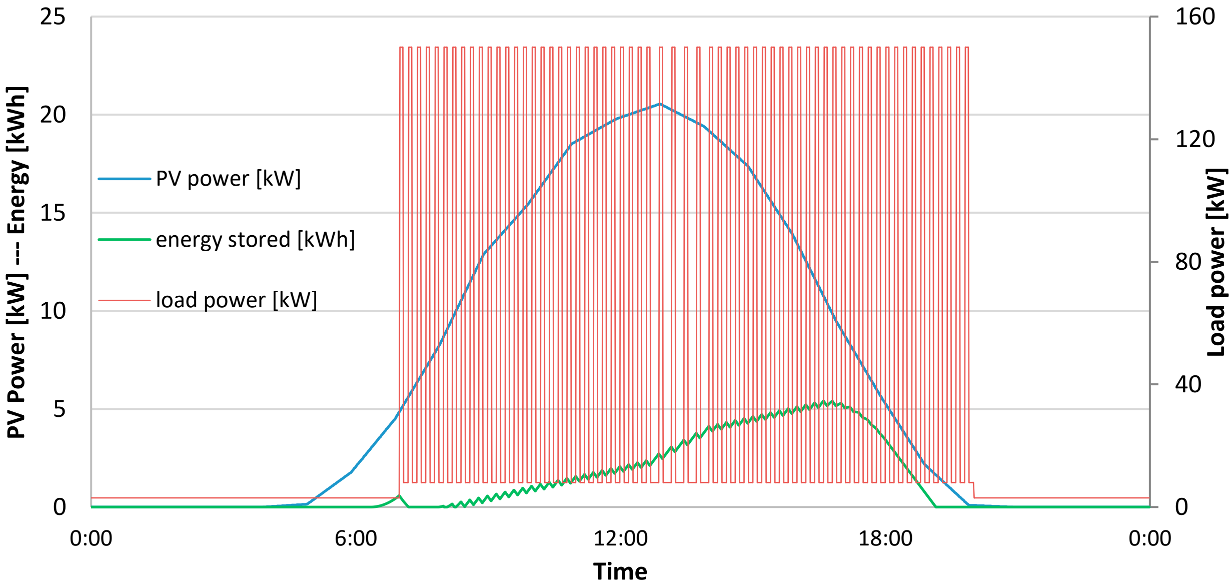

Figure 7. CNG plant power request, PV power production and energy stored during a regular day in summer (1 min).

A further analysis allowed the estimation of the impact of the storage. In Figure 7 the CNG plant energy request, the PV production and the energy stored in the batteries are reported for a regular summer day the case of a 30kW PV plant (P_s=3kW C_s=10kWh η_s=98%). The energy stored (green line) reveals many quick charge/discharge operations corresponding to the on-off states of the main compressor, with a slower daily trend. With P_{PV} fixed at 30 kW, different combinations of storage capacity and nominal power have been simulated to investigate their influence on the parameter *T* (Figure 8).

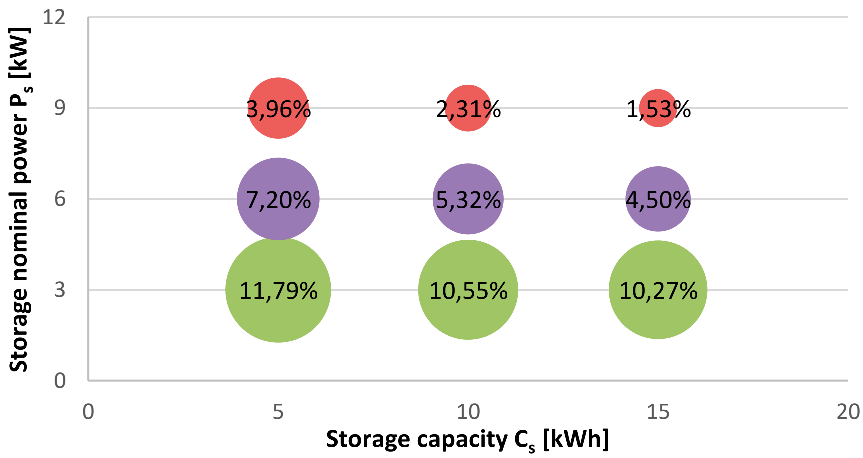

Figure 8: Influence of C_s and P_s on the parameter *T* (P_{PV}=30kW η_s=98%, 1min analysis)

Both C_s and P_s affect the quantity of energy stored and not released to the grid, but the influence of nominal power is greater. However, a high value of P_s may change the daily cycles with relevant effects on storage requirements. In these cases, both lithium battery and supercapacitors should be considered and compared in techno-economic studies.

4. Conclusion

With a load characterized by high variability of electricity demand, the underestimation of the energy released to the grid represents a relevant and challenging issue. To investigate this problem, a case study based on a CNG plant with strong load variations has been analyzed. A preliminary design based on PVGIS monthly analysis is often used for small and medium PV plant design, but this approach did not provide accurate results in terms self-consumption estimation in the investigated case study. Detailed simulations have been carried out with different timestep (1 minute, 15 minutes, 1 hour, 24 hours), with and without storage systems.

Results showed that even the energy demand based on a 15 minutes average does not provide a correct estimation of the energy exchange with the grid. Such errors in cost-saving estimation are not negligible and could represent a relevant economical penalization over the entire life of PV modules. Both the storage capacity and power affect the quantity of energy self-consumed but the influence of nominal power is greater.

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