Monitoring of photovoltaic systems and evaluation of building energy self-consumption

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Abstract. The spread of nearly zero energy buildings (nZEB), promoted by the strategies set in the path of decarbonisation, has made the integration of renewable energy systems (RES) in buildings a common and strategic practice; in particular, they most involve small to medium building integrated photovoltaic (BIPV) systems coupled with heat pumps (HPs). One major challenge deals with the implementation of high self-consumption (SC) schemes for the energy produced on site, essential to carry on a wider implementation of photovoltaic systems. The present paper addresses the effect of different sizing strategies on the SC levels of 3 systems installed on traditional and nZEB houses, with a peak power between 3.12 kWp and 5.98 kWp. The systems have been monitored recording the various energy flows involved. Different optimization strategies have been tested with the purpose of minimizing the interaction with the grid, according to SC and self-sufficiency (SS) indexes. The aim is to provide design guidelines for the correct sizing in a bottom-up approach. Results underlined the fundamental role of storage technologies. Approximately 6 Wp/m² assure an optimal energy employment without storage, with SS index below 35%; the integration of small storage, 3-7 kWh/kWp leads to SS and SC index above 60% and 88% respectively.

1. Introduction

The last report of the International Energy Agency (IEA) shows that the energy generation from solar PV has increased by 22% in 2019, reaching more than 600 GW of power installed and 720 TWh of total energy produced worldwide [1]. A further penetration can be achieved through a deeper and more accurate integration, in terms of both size and management: in this scenario the civil/residential sector can represent a relevant field of application for further increase of PV technology diffusion. As Figure 1 shows, the share of residential PV systems installations lies between 15% and 45% in most European countries [2]. The integration in the civil sector has been mainly driven by the randomness of the feed-in tariffs established by local governments. With the priority dispatch being expected to be dismissed in the close future, the spread of nZEBs could be regarded as a means to increase the penetration of RES in the construction market, especially through the spread of photovoltaic systems. The paper analyses low power size residential rooftop PV systems, regarded as the most common kind of application, in terms of numbers, in the civil sector. In Italy, indeed, the domestic application includes the largest number of system installed, that account for the 82% of the total system installed, as showed in Figure 1: about 33% is characterized by a peak power below 3 kW of peak power, a power installed of 4.8 kW is the most common PV power installed. Nevertheless, the share in terms of total power installed is around 15% [3], highlighting room for a wide margin of expansion. A precondition for a long-term penetration of RES in the civil sector is the increased direct utilization of the energy produced. The increasing electrification of building energy loads policy goes in this direction [4].
Currently most of the installed systems generate excess energy representing a possible threat for the grid balance. From this point of view, the exported energy can be regarded as wasted energy and so new systems must follow a high self-consumption profile strategy. The main factors that can positively affect the self-consumption of the energy produced are the size of the PV array [5] and the demand side management (DSM) of the electrical loads [6]. As the management of the building loads requires a high degree of user’s involvement and must thus keep a reasonable level of flexibility, priority must be given to an appropriate sizing. Sizing strategy can more easily benefit from the data acquired by the systems already installed. The present paper exploits a bottom-up approach to define new sizing criteria based on real operating condition data of installed systems. The objective function of the optimum design strategy is the maximization of the self-consumption: the future trend of PV system is bound towards undersized system, to guarantee a high level of energy directly used by the building even in a grid connected system [7]. This strategy goes along with an expected soon to be dismissed benefit system both for the energy sold to the grid and PV modules installation, following the constant decreasing cost of the technology, reduced to less than 1000 € for each kW of peak power installed [8]. The still relevant cost and environmental impact of the storage solutions disadvantage the oversized PV system. In this perspective the paper offers a view of the behaviour of PV system installed on three residential buildings: the systems and building characteristics are described in Section 2, Section 3 includes the analysis of data monitored and Section 4 shows the results of the size optimization process.

2. Analysis of the case studies
The analyzed PV plants have been experimentally monitored during a long period. The three residential buildings placed along the coast of middle Italy are characterised by typical mild climate conditions, with a minimum annual temperature of 2.5 °C and a maximum of 33.2 °C. Figure 2 shows the solar irradiation trend in three different daily sky conditions. Given the average solar irradiation, 1555 kWh/m² for each year, considering the case of a high quality, polycrystalline, well exposed module, an average annual energy production of 1100–1150 kWh is expected for each kW of peak power installed. All the systems investigated are rooftop configurations, that is the most common solutions in the residential sector [9]. The main data of both the buildings and related systems monitored are summarised in Table 1. The first case study, A, is a traditional residential building made of three apartments sharing a common conditioning system. The PV system consists of two strings of polycrystalline modules of 245 W peak power each: 12 modules have an azimuth of -25° and 8 panels are 65° due West, while the tilt angle is 20°. The case study B is still a traditional residential building, with a heat pump (HP) system for winter heating. The two strings of polycrystalline 230 W modules that make up the PV system have an azimuth angle of -42° and 48° with a tilt of 20° and 18° respectively. The third case, C, represents a nZEB house, with a HP plus fancoil system. The house mounts monocrystalline panels with a peak power of 240 W: the system develops in a single string of 13 modules with an azimuth of -7° and a tilt angle of 16°. In all the cases Heating Ventilation and Air Conditioning (HVAC) include a HP system, with a condensing boiler (CB) in not nZEB houses.
3. Analysis of the data monitored

The data acquired in the monitoring activity have been analyzed focusing the attention on the analysis of the energy flows between the system and the grid: the energy exported (\(E_{\text{EXP}}\)) and imported (\(E_{\text{IMP}}\)) have been collected as a monthly cumulative value to determine the overall energy flow (\(E_{\text{FLO}}\)), the sum of the precedent values, as a first parameter of the grid interaction of the PV system. The data of the systems production (\(E_{\text{PV}}\)) have been estimated through the solar radiation data provided by the Italian company of research on the energy system [10]. Through these data the energy self-consumed (\(E_{\text{SELF}}\)) by the building and the overall energy demand have been deducted. In case B, that includes an energy storage, the electricity stored (\(E_{\text{STOR}}\)) has not been monitored, but it has been estimated in the simulation.

Figure 3 illustrates the energy flows analysed. The data refer to the period 2014-2016: Figure 4, Figure 5 and Figure 6 shows the average values of the various energy flows over the monitored period for the cases A, B and C of Table 1 respectively. Data highlight how the system of Case A is undersized, because the energy production never equals or surpass the building demand, due to the high building dimension.

![Figure 3. Different energy flows among the building, the PV system and the grid](image)
Especially a high increase of the energy demand can be noticed, and thus energy imported from the grid, in the second half of the year, when all the three apartments are fully occupied. In Case B and C the $E_{\text{EXP}}$ and $E_{\text{IMP}}$ follow a common mirrored trend. The two cases are characterised by a bell-shaped energy production curve and a slightly variable demand, particularly the nZEB, due to the mild outdoor conditions and the high building inertia.

4. Proposal of optimized PV system sizing aiming at maximising the self-consumption share
The three systems analyzed show a not optimal size in the perspective of reducing the energy flows to the grid. The data have been recorded on a monthly base: the optimization process is thus affected by the time step of the data. The lack of sub-hourly monitored data does not allow to take into account possible building demand peaks: as the analysis is focused on small residential systems, the influence of intermittent peaks can be considered negligible on the annual average values. The authors have already addressed the same problem with other systems: results showed that to maximize the energy self-consumption occurs a PV system power at 30% of the HP power, while to minimize the grid
exchange the PV power can be sized at 60% or equal to the HP power if storage is integrated [11]. The optimization strategies have been developed on the energy flows and related self-consumption (SC) and self-sufficiency (SS) indexes, defined with the following equations:

\[
SC = \frac{E_{SELF}}{E_{PV}}
\]

\[
SS = \frac{E_{SELF}}{E_{TOT}}
\]

The values of the two indexes for the system monitored are described in Figure 7. In particular, the first case (A) shows an inverted trend, with a higher SC index, due to the increasing energy demand in the second half of the year. Case B shows an average SS index at 51.1%: the low self-consumption capacity is due to the conditioning system, as the heat pump does not provide cooling in summer. Even the nZEB of Case C shows low average values of SC index, 36.7%, and SS one, 23.4%. To highlight the wide room for improvements in terms of self-consumption, Table 2 resumes the results of an optimization process involving the PV system size and integration of storage. Without using an energy storage, to maximize the amount of energy used a reduction of 60-85% of the system peak power is suggested, approximately sized at 6 W/m², or 0.17 W/kWhe of electrical demand, leading the average SS-SC index around 60%. Case B, that already includes energy storage, reaches 0.27 W/kWhe. In this case the PV production is quite low, covering only from one quarter to one third of the overall demand.

![Figure 7. Self-consumption and self-sufficiency of the three systems, average 2014-2016](image)

**Table 2** Optimization of the system monitored

| Case study | Actual system optimization | Optimization with storage integration |
|------------|-----------------------------|---------------------------------------|
| A          |                             |                                       |
| PV power   | [kW]                       | SC index [%]                         | SS index [%]                         | Average index [%] |
| Base case  | 4.86                        | 54.5%                                | 33.0%                                | 43.7%              |
| Minimum E<sub>IMP</sub> | 3.67                        | 72.2%                                | 33.0%                                | 52.8%              |
| Minimum E<sub>EXP</sub> | 1.47                        | 100%                                 | 18.2%                                | 59.0%              |
| Minimum E<sub>FLO</sub> | 1.96                        | 96.2%                                | 23.3%                                | 59.7%              |
| B          |                             |                                       |
| PV power   | [kW]                       | SC index [%]                         | SS index [%]                         | Average index [%] |
| Base case  | 5.98                        | 31.2%                                | 51.1%                                | 41.1%              |
| Minimum E<sub>IMP</sub> | 4.14                        | 45.0%                                | 51.1%                                | 48.0%              |
| Minimum E<sub>EXP</sub> | 1.15                        | 100%                                 | 31.5%                                | 65.6%              |
| Minimum E<sub>FLO</sub> | 1.38                        | 96.1%                                | 36.3%                                | 66.2%              |
Case study

| Case study | Actual system optimization | Optimization with storage integration |
|------------|-----------------------------|---------------------------------------|
|            | PV [kW] | SC index [%] | SS index [%] | Average index [%] | PV [kW] | Storage capacity [kWh] | SC index [%] | SS index [%] | Average index [%] |
| Base case  | 3.12    | 23.4%       | 36.7%       | 30.0%            | 3.12    | 0                       | 23.4%       | 36.7%       | 30.0%            |
| Minimum EIMP | 1.20    | 60.7%       | 36.6%       | 48.6%            | 3.12    | 6                       | 56.7%       | 88.8%       | 72.7%            |
| Minimum EXP | 0.24    | 100%        | 12.1%       | 56.0%            | 1.2     | 4                       | 100%        | 60.2%       | 80.0%            |
| Minimum EFlo | 0.48    | 99.6%       | 24.0%       | 61.8%            | 1.44    | 4                       | 95.3%       | 68.9%       | 82.1%            |

With the integration of a medium size storage, the peak power can be increased. Excluding Case A, due to the high variable energy demand, house of Case B shows a doubled PV peak power, with a storage sized to twice the daily energy demand produced by the system installed. The nZEB, by contrast, can reach a PV power size three times higher, with a daily production based storage size. Based on annual electricity consumption, the size increases from 2 (B) to 2.5-3 (A and C) times, around 0.50 W/kWh.

5. Conclusion

The present paper analysed 3 monitored BIPV systems. Data show that the systems are oversized in terms of actual use of the energy produced, with average SC and SS indexes below 55%. Considering the results of the optimization simulation, different conclusions and relative benchmark can be defined:

- benefits in terms of SC can be reached by sizing the systems power approximately at 6 W/m² or 0.17 W/kWh. The low PV size exemplifies the need of storage; with a storage system, the PV size can be doubled in the traditional house, and set at 18 W/m² in the nZEB in terms of conditioned area, or 2.5-3 times higher in terms of annual electrical demand, around 0.50 W/kWh;
- an optimal storage size is between 3-7 kWh/kW of PV power, depending on the kind of building, showing small storage size perfectly suits in high SC schemes.

A connection among HP size, PV power, storage capacity, local solar radiation and climatic indexes related to the building energy demand represents a further step for the investigation to scale the assumptions to different location. As the PV systems price has remarkably decreased, the cost of low peak power high SC systems as the ones described in the results has becoming profitable from an economic and energetic point of view even without financial benefits. Frontiers in the increase of miscellaneous electrical load, e.g. electrical vehicle, will expand the SC capability of residential systems.

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