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# Performances and economic analysis of small photovoltaic–electricity energy storage system for residential applications

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**Abstract**

Currently, the need to address the issues arising from the uncontrolled growth of photovoltaic installations, such as intermittence and unpredictability of the generation that cause loss of balance in the grid, becomes unavoidable. Promising solutions for minimizing grid injection are the combination of photovoltaic generation with electricity energy storage and load management, the latter commonly known as Demand Side Management. These strategies together with incentives for self-consumption or energy independence from the network will allow facilitating the integration of the always-increasing generation of renewable energy. In Europe, the usage of residential energy grid-interactive energy storage systems for buffering of surplus photovoltaic generation is becoming a field of growing interest and market activity, as a consequence of the less attractive photovoltaic feed-in-tariffs in the near future and incentives to promote self-consumption. This study aims to evaluate the energy exchange with the grid and the rate of self-consumption of combined photovoltaic–electricity energy storage systems dedicated to residential and small commercial prosumers. More specifically, several combinations of sizes of photovoltaic plant, annual household consumptions and electricity energy storage capacity were evaluated. This analysis aims to identify which arrangement among photovoltaic power, electricity consumption and battery capacity allows reaching the highest ratio of self-sufficiency and consequently minimizing the energy exchanged with the grid. Moreover, the financial analysis of the photovoltaic–electricity energy storage system has been performed for verifying the economic viability of the photovoltaic–electricity energy storage systems under the Italian current market and economic circumstances.

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## Introduction

It is predictable that renewable energy sources (RES) will play a foremost role in mitigating climate change and resource depletion as well as contribute to satisfy the continued growth of the electricity demand.[1]

The sharp drop in the cost of photovoltaic (PV) technologies will reach competitiveness with the energy purchased from the grid in the next future, giving rise to further spread of PV plants.

In Western Europe, it is estimated that the installed power of roof top PV plants will be higher than 4000 MW under a low scenario or 8000 MW under a high scenario.[2]

Table 1 shows how the top power from solar renewable source is divided between different country of different continents and the role of Italian market elaborated by IRENA.[3]

Therefore, it is possible to prognosticate that the future energy supply will be strongly influenced by RES energy production, which depends on local weather conditions and, in some cases, is limited to daytimes period.[4]

As a consequence, the mismatch between demand and supply poses increasing threat to the stability of the electricity system. In particular, the PV generation often exceeds the power demand during daytime, which means hat excess electricity production is fed into the grid and sold to an electricity supplier and bought back again in the night-time.[5]

The intermittent nature of PV systems introduces potential technical challenges that affect mainly the quality of power and voltage (voltage fluctuation, harmonics, low power factor). Large-scale PV integration in the distribution network causes voltage rise within the network, and this voltage rise is significant in case of single-phase PV system connections. The intermittent nature of PV causes uneven generation and hence might exceed the capacity of the connected transformer. Inverters connected with PV sources, non-linear customer loads and power electronics devices introduce harmonics in the distribution network that causes overheating of transformers, tripping of circuit breakers and reduces the life of connected equipment.[6]

Therefore, a high penetration of the PV power production at the customer's level brings problems to the distribution grid, because intermittent electricity production can worsen the neutral current of the low voltage grid.

Significant research and development works are undertaken to investigate and mitigate the observed potential technical challenges to ensure a reliable and uninterrupted power supply to the consumers; in this context, batteries are one of the most promising

**Table 1.** Renewable energy electricity generation in the world (Irena, 2016) www.arera.it/it/dati/ees5.htmwww.arera.it/it/dati/ees5.htm Data and Statistics - IRENA REsource Available from: http://resourceirena.irena.org/gateway/dashboard/ (2017, accessed 4 December 2017).

| | China | Germany | Japan | USA | Italy | Spain |
|---|---|---|---|---|---|---|
| Electricity generation (GWh) | 39745.7 | 38726.3 | 35974.0 | 34441.4 | 22954.7 | 13859.0 |

cost-effective solutions to overcome these technical barriers and to reach the full deployment of PV systems.

Unbalance between energy demand and production can partly solve increasing self-consumption with different methods, energy storage, as well as active load shifting.[7] In a self-consumption or zero-export scenario, EES as well as self-consumption are key factors for the renewal of electrical grids, while helping utilities by shifting demand to off-peak hours and smoothing out the load on the system.

The Fraunhofer Institute calculates that if battery supply matches the household demand, up to 66% more solar PV can be installed since solar feed-into the grid is restrained.

Typically, the effectiveness of EES is investigated by examining its potential to increase the share of electricity generated by PV residential system self-consumed by the household.[8]

Many researches are focused on battery energy storage combined with distributed generation, such as residential PV, for example in Battke et al.[9] and Moshövel et al.[10] Furthermore, some researchers analyzed the optimization of charging efficiency from a PV system to a battery in a residential energy system.[11] In addition, some studies indicate that storage technologies aim households to reduce the amount of electricity that is bought at retail prices and the one to be sold at wholesale prices.[12]

Pivotal factors for battery choice at the household level comprise cost and economic benefits of the system. At the end of 2014, the cost of residential battery storage systems was EUR 1000/kWh, and consequently, several projections suggest that battery storage will cost EUR 200/kWh with a payback times of around 6–8 years for European countries.[13]

Moreover, the feasibility of the electric storage has been investigated under the hypothesis of policy support in the form of feed-in tariffs and/or additional premiums for self-consumed electricity.[7]

Many studies have focused on the development of the optimal sizes of PV and battery storage considering the government incentive and economic feasibility. Bertsch et al.[14] have presented a simulation model to identify the most profitable sizes of PV and battery storage systems based on residential customers' perspective. Weniger et al.[15] have found out that in a long-term scenario, the conjunction of PV systems with batteries will be not only profitable but also the most economical solution. Brusco et al.[16] carried out a research on feed-in tariff scheme for promoting the integrated photovoltaic battery (PV-BES) systems for grid-connected end users.

They have used an optimization algorithm to determine the incentive and optimal sizes of the PV and battery energy storage systems. The sizes of the PV and battery storage system were calculated so that the percentage of self-produced energy is at least 50% and the percentage of self-consumed energy is at least 80%.

On the other hand, Linssen et al.[17] carried on an economic analysis of PV battery systems and the influence of different consumer load profiles. Their analysis revealed a considerable impact of the load profiles on the modeling results regarding total costs, cost-effectiveness and cost optimal system configuration in terms of PV and battery size of battery supported PV systems for private households.

Akter and Mahmud[18] have demonstrated that the shortage of energy during the high loads and excess of energy during the higher output of solar PV system can be reduced with the design of a proper energy management scheme.

The aim of this paper is to investigate different scenarios of residential PV systems combined with battery energy storage.

More specifically, three size of PV plant (2.4, 2.7 and 3.0 kWp) combined with three annual household consumptions (3000, 3500 and 4000 kWh) and two different size of EES have been considered for evaluating the performances of each of the proposed combinations. This straightforward analysis aims to identify which combination among PV power, electricity consumption and battery capacity (BC) allows to reach the high ratio of self-sufficiency and consequently minimizes the energy exchanged with the grid.

Moreover, the financial analysis of the PV–EES system has been performed for verifying the economic viability of this system under the current market and economic circumstances.

## Material and methods

### *Electricity storage*

On the market, several storage technologies exist and they can be classified according to energy form of the storage systems, such as mechanical, electrochemical, chemical energy, electrical, and thermal.

The main battery characteristics are:

- Capacity ©, measured in Ampere-hour (Ah), indicates the theoretical value of the intensity of current that the battery is able to provide for a process of discharge of 1 hour durations.
- Stored energy ($E_{ST}$), measured in Watt-hours (Wh), indicates the amount of energy stored in the battery and it is given by the integral value of the capacity of the product to the average discharge voltage.
- State of charge (SoC) identifies the remaining capacity of a battery (0% = empty; 100% = full) and it is a function of the load current and the operating temperature.
- Depth of discharge (DoD) describes how deeply the battery is discharged (100% = empty; 0% = full).
- Discharge voltage (cut-off voltage) is the minimum allowable voltage, generally defines the "empty" state of the battery.
- Life cycles is the number of charge–discharge cycles to which a battery can complete before losing considerable performance. A fully charged battery that can only deliver 60–80% of its original capacity may be considered at the end of its cycle life.
- Calendar life is the number of years the battery can operate before losing considerable performance capability.

The operating life of a battery is deeply affected by the amplitude of the charge and discharge cycles, the DoD and other operational conditions such as the temperature.

In order to preserve the normal aging of the same battery, the SoC is typically maintained in a range between 10% and 90% and the maximum values of DoD stood at around 80%.

Nowadays, the most used technologies for the electrochemical accumulators are lead acid battery (LA), nickel cadmium (NiCd), nickel metal hydride battery NiMH), lithium-ion (Li-ion), sodium nickel chloride (Ni-NaCl), etc.

Figure 1 shows the prices index for lead-acid and lithium storage system.[19]

The Li-ion technology is by far the favored than the other. The lithium, being the lightest metal (equivalent weight: $6.94\,g\,mol^{-1}$) and the more electropositive, possesses a high specific capacity equivalent to about $3.8\,Ah\,g^{-1}$.

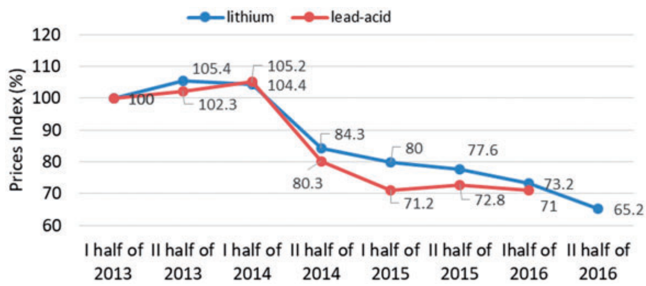


**Figure 1.** Prices index for lead-acid and lithium storage system.

### *Electricity production*

The energy yield from the PV modules ($E_{PV}$) is calculated taking into account the global solar irradiation ($G_\beta$) that strikes the PV panel, the performance characteristics of the PV module as well as the angles of tilt, orientation and the area of PV modules ($A_{PV}$).

$$E_{PV} = A_{PV} \cdot G_\beta \cdot \eta_{PV} \cdot \eta_{inv} \cdot \eta_m \quad (1)$$

In equation (1), $\eta_{PV}$ is the conversion efficiency of the PV cells, $\eta_{inv}$ is the efficiency of the inverter and $\eta_m$ accounts for the losses due to mismatch. The conversion efficiency of the PV cells (equation (2)) is a function of the temperature of the PV cells ($T_{PV}$),[20] which is in turn a function of the operating conditions (equation (3)).

$$\eta_{PV} = \eta_{STC} \cdot \left[1 + \mu \cdot (T_{PV} - 25) + 0.12 \cdot \ln\left(\frac{G_\beta}{1000}\right)\right] \quad (2)$$

$$T_{PV} = T_a + \left(\frac{NOCT - 20}{800}\right) \cdot G_\beta \cdot \left(1 - \frac{\eta_{STC}}{\tau_v \alpha}\right) \quad (3)$$

The nominal operating cell temperature ($T_{NOCT}$) is provided by the technical data sheet of the PV module. It is defined as the temperature reached by open circuited cells in a module under total irradiance of 800 W/m$^2$, ambient temperature of 20°C and wind speed of 1.0 m/s. The transparency of the front glass is taken into account by the terms "$\tau_v\alpha$."[21]

The degradation of PV panels and the small decrease of resulting power is neglected.

## Simplified model of PV–EES system

PV–EES systems can be discriminated in relation to the connection of the battery between DC (direct current) and AC (alternating current) coupled systems.[15] The DC power produced by the PV system is suitably modified by DC/DC power converters and solar inverters in order to be consistent with the voltage and power quality requirements of the utility grid.

Whenever a storage unit is coupled to the generation unit, an additional power converter is usually required to adapt the different voltage levels, allowing bidirectional power flows. The combination of a standard PV generation unit and an additional battery storage is known as hybrid inverter, where both the PV field and battery pack are connected to the same power conversion unit.

On the contrary, in AC coupled storages, a battery inverter connected to the same electrical network via AC power converters can be considered. Any exceeding energy production is stored in the EES and used when required by the residential loads.

Since the main goal of this paper is to perform an economic analysis of small PV–EES connected to the grid, a simplified layout of a PV–EES system is analyzed.[22] The simplified system, depicted in Figure 2, consists of the PV system, the PV inverter, the battery storage with charge regulator and inverters and a control unit. Such layout is considered economically efficient and suitable for being integrated in existing domestic applications.[7] No other requirements are necessary for revamping existing PV generation units in the considered topology

This system layout does not require any modification of the existing generation unit since the battery pack is interfaced with the AC side of the PV system.

In fact, the control strategy implemented in the AC coupled storage can be based on the active power and reactive power control theory, where the synchronization to the AC side grid is executed independently on the operating condition of the PV system, by exploiting a

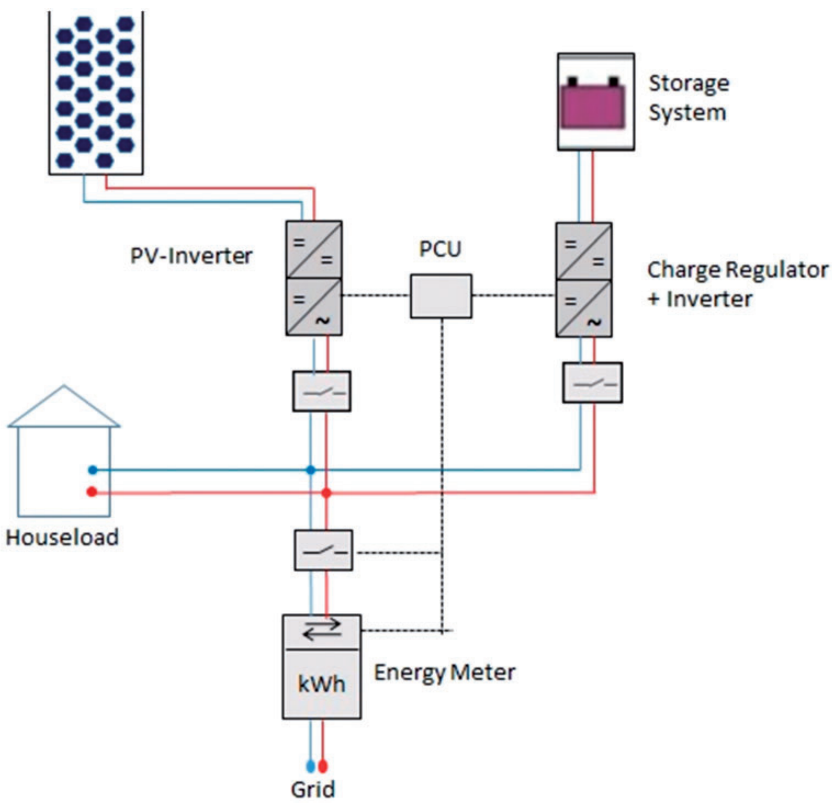


**Figure 2.** Possible configuration of a combo PV–EES system.
PV–EES: photovoltaic–electricity energy storage.

PPL-based algorithm providing the grid voltage phase and allowing to properly generate an AC side voltage addressing the exceeding power generated by the PV system or required by the local load. This feature can be obtained by simply manipulating the monitoring data usually accessible in all standard inverters.

In this study, the adopted operation strategy aims to optimize the self-consumption: the PV electricity output ($E_{PV}$) is used directly on-site for compensating the house load ($E_{h\text{-}load}$). The energy produced by the PV plant that exceeds the simultaneous $E_{h\text{-}load}$ is stored in the EES. As long as the battery does not reach the maximum state of charge ($SoC_{max}$), the surplus of PV power is supplied to the battery ($E_{EES}$). Supplementary PV power surplus is driven to the grid ($E_{exp}$). When the load exceeds the generated PV power, the battery is discharged until the minimum state of charge is reached. The grid ($E_{imp}$) supplies further energy request. Thereby, both surplus and deficit scenarios can arise.

In the following, the flowchart (Figure 3) and the main equations used in the developed algorithm are reported.

*Surplus scenarios:* $E_{PV}(\tau) > E_{h\text{-}load}(\tau)$.

As long as the battery does not reach the maximum state of charge ($SoC_{max}$), the resulting spare PV power (S) charges the battery, restricted by the battery inverter power.

The battery is able to accept the whole surplus $E_{exp} = 0$, that is:

$$E_{EES}(\tau - d\tau) + E_{PV}(\tau) - E_{h-load}(\tau) < SoC_{max} \quad (4)$$

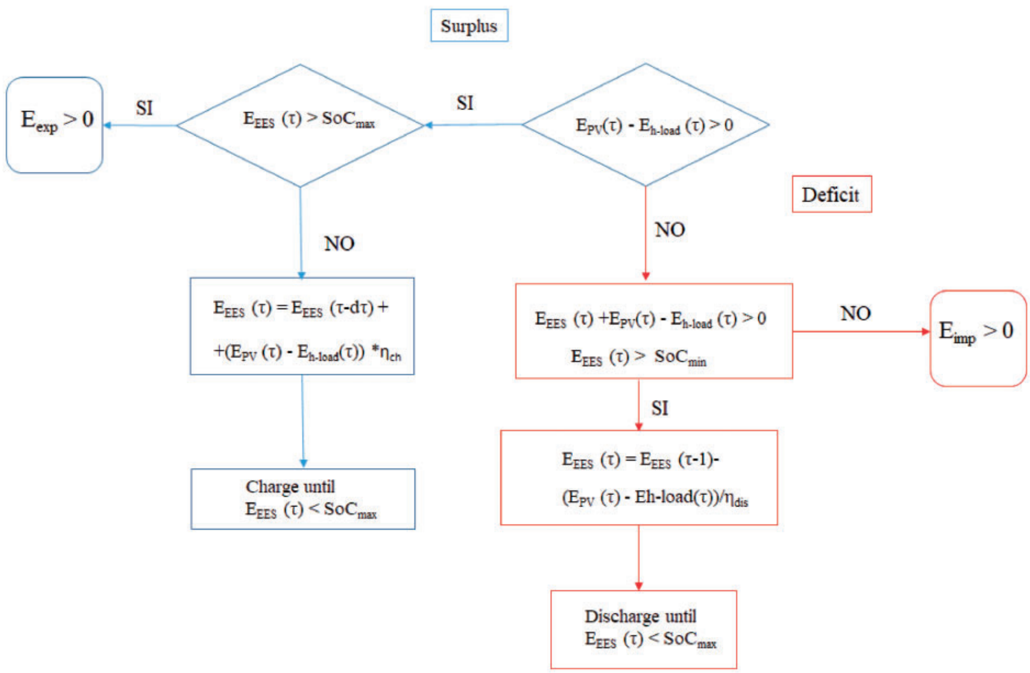


**Figure 3.** Flowchart of the calculation procedure.

Otherwise, the surplus PV power will be injected into the grid ($S_2$); $E_{exp} > 0$.

$$E_{EES}(\tau - d\tau) + E_{PV}(\tau) - E_{h-load}(\tau) > SoC_{max} \tag{5}$$

*Deficit scenarios:* $E_{PV}(\tau) < E_{h\text{-}load}(\tau)$

To compensate the emerging deficit (D), the EES is discharged up to the (SoC) min is reached; additional load is covered by energy drawn from the grid ($E_{imp}$).

The electric load can be entirely satisfied by the energy stored within the battery

$$E_{EES}(\tau - d\tau) + E_{PV}(\tau) – E_{h-load}(\tau) > DoD \cdot SoC_{max} \tag{6}$$

When the electricity consumptions cannot be totally satisfied by the energy stored in the battery, the house load ($E_{house\text{-}load}(\tau)$) is partially delivered by the battery

$$E_{EES}(\tau - d\tau) + (E_{PV}(\tau) - E_{h-load}(\tau)) < DoD \cdot SoC_{max} \tag{7}$$

While the residual $E_{h\text{-}load}(\tau)$ is supplied by the grid $E_{imp}(\tau)$.

Figure 3 shows the flowchart of the followed calculation procedure.

In the previous scenarios, Boolean conditions have been considered for simplifications and make clear the energy management method. Of course, in real cases, hysteresis thresholding for edge detection using two different thresholds is used. In this way, fast commutations between the two scenarios are avoided.

## Operational scenarios

The baseline scenario is a PV-household with a lithium-based battery system. Three annual household consumptions and three size of PV plant have been selected. The annual household consumption is 3000, 3500 and 4000 kWh/year, while the PV peak power is 2.4, 2.7 and 3.0 kW, which replicate the classes most diffused in Italy.[23] Moreover, the different combinations of $E_{h\text{-}load}$ and PV plant size are coupled with two BC of EES, that are 3.3 and 6.5 kWh. The arising different arrangements are summarized in Table 2.

The different scenarios which arise are characterized by ratios among yearly electric generation and yearly electric consumption ($E_{PV}/E_{h\text{-}load}$) from 1.15 to 1.5. However, the ratio among yearly electric consumption ($E_{h\text{-}load}/E_{BC}$) and BC ranges between 1.1 and 3.3.

**Table 2.** Studied PV–EES system arrangements.

| | Battery capacity 3.3 kWh | | | Battery capacity 6.5 kWh | | |
|---|---|---|---|---|---|---|
| PV power, kWp | $E_{h\text{-}load}$, kWh/year | $E_{h\text{-}load}$, kWh/year | $E_{h\text{-}load}$, kWh/year | $E_{h\text{-}load}$, kWh/year | $E_{h\text{-}load}$, kWh/year | $E_{h\text{-}load}$, kWh/year |
| 2.4 | 3000 | 3500 | – | – | – | – |
| 2.7 | 3000 | 3500 | 4000 | 3000 | 3500 | 4000 |
| 3.0 | 3000 | 3500 | 4000 | 3000 | 3500 | 4000 |

PV–EES: photovoltaic–electricity energy storage.

*Specifications of PV–EES system.* The PV plant is located Catania (37°lat, 15°long), Italy; the PV modules are southward oriented with a tilt angle of 15°, which corresponds to the most diffuse inclination of the tilted roofs in the south of Italy.[24] The electricity yield was calculated through the PV-GIS software version 5 using hourly time series of solar radiation data. More details on the PV-GIS methodology and development can be found in key reference papers[25]

In Figure 4, the tilted irradiation ($\beta = 15°C$) is depicted.

The daily variation in electricity consumption has to be defined in order to determine the flow of energy for the users as well the incoming and outcoming energy to/from the battery or the grid.

As regard the electric load profile, it has to be determined according to the several typologies of the domestic appliances as well as the user habits. In this study, an average load profile for Italian household with a resolution of 1 hour has been used. Figure 5 shows the average profile of the hourly electric consumption expressed as percentage of the daily $E_{h\text{-load.}}$

The electric building load has been considered constant during all the year; hence, the changes in consumption between winter and summer season are neglected.

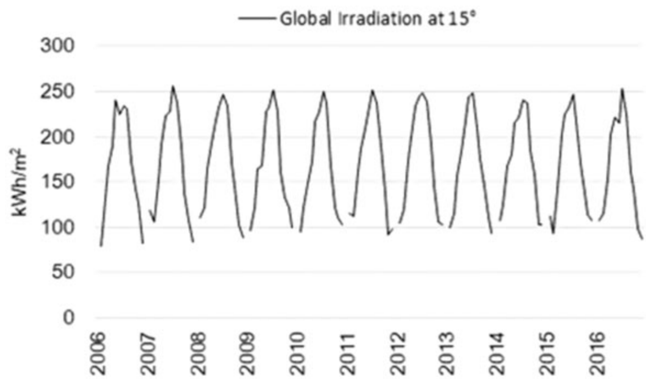


**Figure 4.** Time series of horizontal solar irradiation.

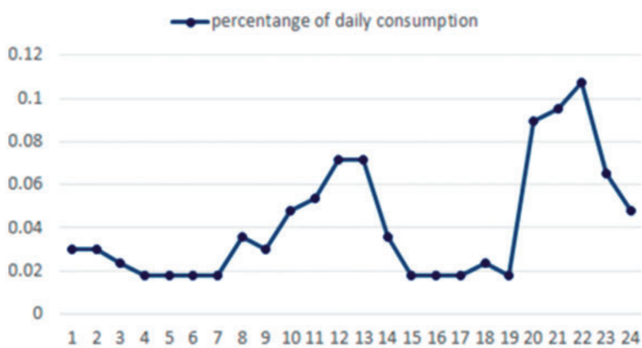


**Figure 5.** Profile of the hourly electric consumption.

**Table 3.** Specifications of the EES system.

| | | |
|---|---|---|
| Nominal system capacity | 3.3 kWh | 6.5 kWh |
| Nominal system performance | 1.6 kW | 2.5 kW |
| Dimensions (W × H × D) | 600 × 690 × 186 mm | |
| Weight | 45 kg | 65 kg |
| Depth of discharge | 90% | |
| Energy management | EMS VS-Pro | |
| Mains connection | 230 V AC, 1-phase, 50 Hz | 230 V AC, 1-phase, 50 Hz |
| Ambient conditions | +5°C to +30°C | |
| Warranty on batteries | 10 years or 4000 cycles | |

EES: electricity energy storage.

EES with different nominal capacity are investigated as such, a larger BC leads to higher rate of self-consumption.

The technical specifications of the two lithium-ion EES used in this study are reported in Table 3.

The EES is modeled neglecting the effects of the discharging power, the temperature and the battery aging; moreover, a constant average efficiency of 90% has been assumed for the storage unit. The maximum depth of discharge has been limited to the 10% of the maximum capacity $SoC_{max}$.

The state of charge of the battery is restricted to a range between 10% and 90% of the nominal BC. In the calculation, constant losses of 32% were assumed, including the losses from charging and discharging the batteries.

*Assessment criteria.* Assessments criteria have been calculated with the purpose to compare the performances of the different PV–EES configurations. Specifically, the realized self-consumption rate ($R_{SC}$), the degree of autarchy ($R_{AUT}$),[15] the mismatch ratio ($R_{MS}$) and the discharge ratio ($R_{EM}$) have been determined.

The self-consumption rate is defined by the ratio between the energy self-consumed $E_{sc}$ (direct consumption or via battery) and the overall produced energy $E_{PV}$:

$$R_{SC} = E_{SC}/E_{PV} \tag{8}$$

The degree of autarchy defines the share of the load consumption that is supplied by the PV–EES system; it has been calculated by the ratio between energy self-consumed $E_{sc}$ and the load demand $E_{h\text{-load}}$.

$$R_{AUT} = E_{SC}/E_{h-load} \tag{9}$$

The mismatch ratio defines the share of energy that is injected in the grid; it has been calculated by the ratio between energy exported in the grid $E_{exp}$ and the overall produced energy $E_{PV}$.

$$R_{MS} = E_{exp}/E_{PV} \tag{10}$$

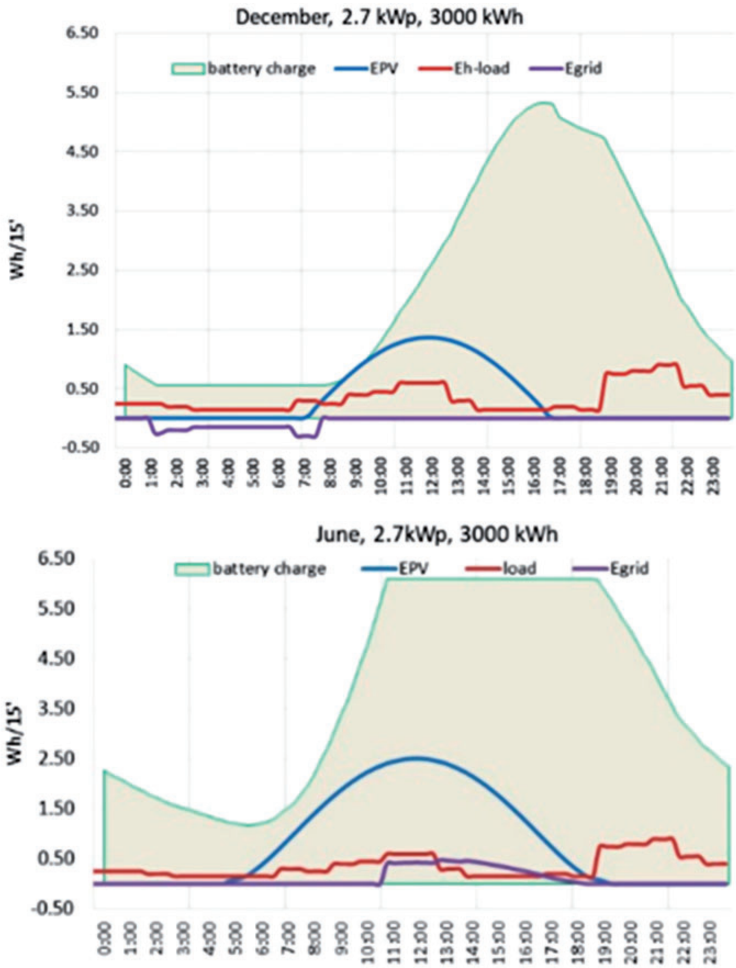


**Figure 6.** Daily energy balance (June–December).

Finally, the discharge ratio indicates the percentage of day when the battery reaches the $SoC_{min}$, that is the EES is empty, which is calculated by the ratio between the day with battery empty/365.

## Results and discussion

Starting from the above-mentioned operational conditions, the energy balance for each PV–EES system investigated has been calculated.

Figures 6 shows the trend of the PV energy generation ($E_{PV}$), the electric building load ($E_{h\text{-}load}$), the state of battery charge as well as the energy exchange with the grid.

Specifically, the depicted data are referred to 2.7 kWp PV plant, 3000 kWh of house load consumption, EES capacity of 6.5 kWh for two different month (Gagliano et al., 2013).

From this figure, it is evident that without the energy storage system, the self-consumption is limited to the intersection between the $E_{PV}$ and the $E_{h\_load}$ curves. Thereby, peak solar power production is exported to the grid during its maximum output. This leads to an oversupply of renewable energy in relation to demand, especially in distribution networks, which can potentially leading to voltages that exceed tolerable limits and a restriction in the development of renewable energy resources. In the previous examples, the EES is continuously charged during the day and may become fully charged; a deficit occurs in December and a surplus in June. However, the EES allows a huge reduction of the feed-in to grid.

Moreover, the monthly energy balance has been calculated for each configuration of the PV–EES system. In Figure 7, the monthly variation of the self-consumed energy ($E_{sc}$), PV energy generation ($E_{PV}$), electric building load ($E_{h\text{-}load}$), as well as the imported ($E_{imp}$), and or the exported energy ($E_{exp}$), by the grid, for some of the studied arrangements, are depicted.

The first three arrangements, reported in Figure 7, are characterized by a ($E_{PV}/E_{h\text{-}load}$) quite similar, from 1.15 to 1.30 while the ratio among yearly electric consumption ($E_{h\text{-}load}/E_{BC}$) and BC ranges between 2.5 and 3.3.

Clearly, these combinations between PV energy generation, house consumptions and BC produce both surplus and deficit. However, the energy deficit is lower than the energy surplus. Otherwise, the four arrangements, which have a ratio among yearly electric consumption and the BC ($E_{h\text{-}load}/E_{BC}$) by 1.7, abruptly reduce the energy exchange with.

Figure 8 depicts the annual energy balance for all the examined different combinations of PV–EES system.

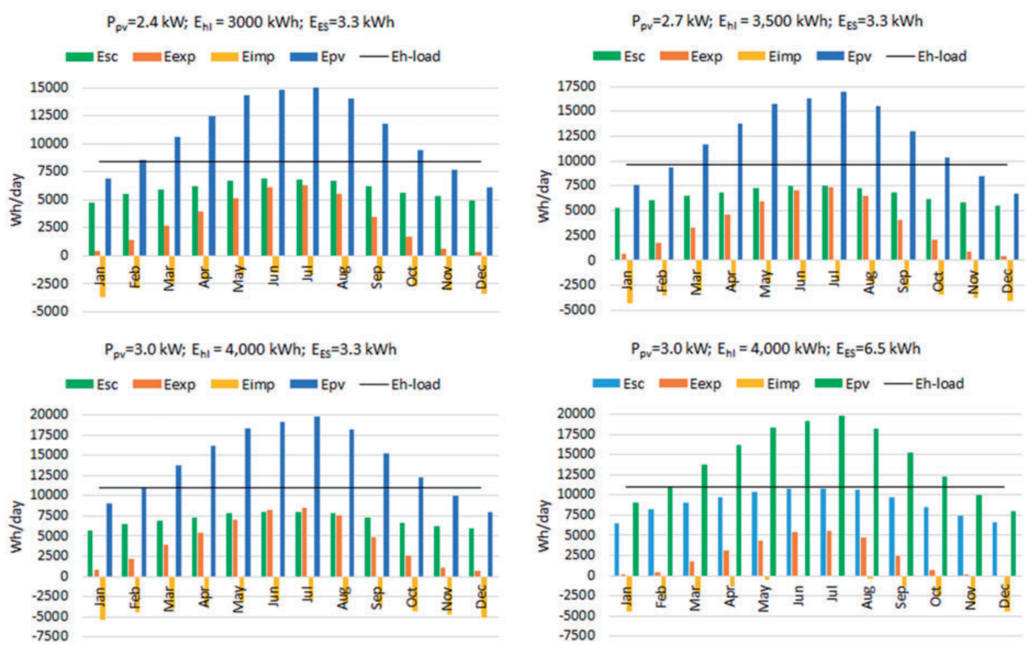


**Figure 7.** Monthly energy balance.

It is possible to observe that all the examined configurations require the exchange of energy with the grid, which ranges from 631 to 1735 kWh/year for $E_{exp}$ and from 426 to 1486 kWh for $E_{imp}$.

Under a constant capacity of the battery, the increase of the ratio $E_{PV}/E_{h\text{-}load}$ produces the rise of the energy injected into the grid.

Consequently, it is confirmed that the amount energy self-consumed ($E_{SC}$) increases with the growth of the BC.

Finally, the realized self-consumption rate ($R_{SC}$), the degree of autarchy ($R_{AUT}$), the mismatch ratio ($R_{MS}$) and the discharge ratio ($R_{EM}$) have been calculated.

Table 4 reports the variations of these assessment criteria in function of the PV plant sizes, the yearly energy consumptions and the BC.

As previously pointed out, substantial differences arise between the PV–EES system with BC of 3.3 kWh with respect to the one with BC of 6.3 kWh.

Anyway, some similarity can be highlighted. Indeed, the self-consumption ratio rises with the growth of the energy needs for fixed PV size.

The realized self-consumption rate reaches the highest value by 73.3% when the size of the EES is the highest, while for the lower BC the maximum value is by 58.2%.

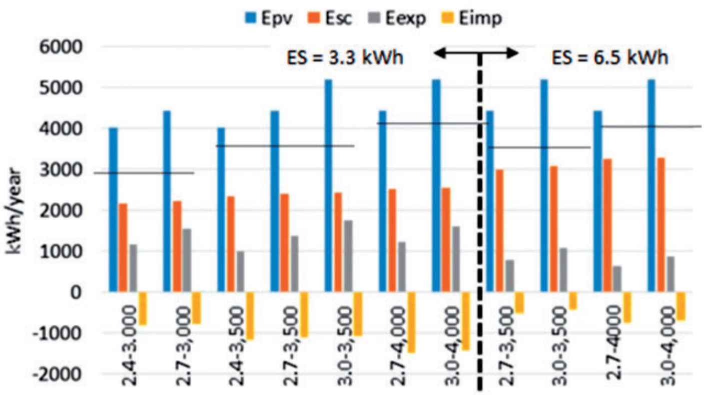


**Figure 8.** Yearly energy balance (P = 2.4 kWp).

**Table 4.** Assessment criteria in function of the PV plant sizes.

| EES | 3.3 kWh | | | | | | | 6.5 kWh | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $E_{hload}$ | 3000 kWh | | 3500 kWh | | | 4000 kWh | | 3500 kWh | | 4000 kWh | |
| PV-size | 2.4 | 2.7 | 2.4 | 2.7 | 3.0 | 2.7 | 3.0 | 2.7 | 3.0 | 2.7 | 3.0 |
| $R_{SC}$ % | 54.1 | 50.0 | 58.2 | 53.9 | 46.6 | 56.8 | 49.1 | 67.2 | 59.1 | 73.3 | 63.3 |
| $R_{AUT}$ % | 72.5 | 73.7 | 66.8 | 68.2 | 69.2 | 62.8 | 63.9 | 84.9 | 87.8 | 81.1 | 82.3 |
| $R_{EM}$ % | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 49.2 | 44.7 | 99.4 | 98.96 |
| $R_{MS}$ % | 28.6 | 34.6 | 24.6 | 30.6 | 33.4 | 27.7 | 30.8 | 17.3 | 20.8 | 14.3 | 16.6 |
| Cycles year | 384 | 406 | 383 | 407 | 426 | 404 | 426 | 285 | 301 | 291 | 312 |

PV: photovoltaic; EES: electricity energy storage.

**Table 5.** $R_{AUT}$ in function of the ratios $E_{PV}/E_{hload}$ and $E_{hload}/E_{BC}$.

| | $E_{PV}/E_{hload}$ | | | |
|---|---|---|---|---|
| $E_{hload}/E_{BC}$ | 1.10–1.19 | 1.20–1.29 | 1.30–1.39 | 1.40–1.49 |
| 1.1–2.0 | **$81 > R_{AUT} < 88\%$** | | | |
| 2.0–2.7 | $63\% < R_{AUT} < 69\%$ | | $72{,}5\% < R_{AUT} < 74\%$ | |
| 2.8–3.3 | | | | |

Otherwise, the degree of autarchy shows an inverse behavior, and it decreases with the growth of the energy needs for fixed PV size.

$R_{AUT}$ reaches the highest value 87.8% when the BC of the EES is the highest, while for the lower BC the maximum value is by 73.7%.

The mismatch ratio has values always lower than 35%. The minimum values of $R_{EM}$ are obtained with the higher BC.

The discharge ratio is around 100% for all the combination, excepted for the two PV–EES with BC of 6.5 kWh and $E_{h\text{-}load}$ of 3500 kWh/year, which shows an $R_{EM}$ lower than 50%.

The last parameter reported in Table 4 is the number of cycles of charge and discharge.

Evidently, the selection of higher batter capacity allows reducing the number of cycles of charge and discharge up to 285.

Considering that the autarchy ratio of PV plant, which is not coupled with an EES system, is always lower than 40%, clearly, a combined PV–EES system significantly increases the self-sufficiency of the household PV plant.

In addition, the analysis developed has evidenced that different combinations between PV size, electric consumptions and BC significantly influence the performance of the PV–EES system.

Thereby, it is worth of interest to classify the rate of autarchy that could be achieved by the different arrangements of the PV–EES system. Table 5 shows the possible range of $R_{AUT}$ in function of the ratios $E_{PV}/E_{hload}$ and $E_{hload}/E_{BC}$.

This analysis indicates that the ratio $E_{hload}/E_{BC}$ is the parameter that mainly influences the rate of autarchy achievable. Indeed, only PV–EES system with $E_{hload}/E_{BC}$ from 1.1 to 2.0, allows to reach rate $R_{AUT} > 80\%$.

This result can be extended to other combinations of PV–EES system characterized by the equal proportion between PV size, electric consumptions and BC.

## *Economic analysis*

At the end of this study, the economic analysis has been developed for evaluating the feasibility and convenience of the different solutions regarding the costs and revenues.

The economic viability of the combined PV–EES system is highly dependent of the avoided costs, which are function of the current price of the energy, the different prices between the energy imported or exported by the grid, as well as by the prices of the EES systems.

Moreover, the economic analysis has to appraise the incentive scheme that allows compensating production and consumption.

Two different modalities of compensation for excess of electricity are provided: energetic called "net-metering" that guarantees a credit in kWh and economical called "net billing" that assurances a credit in monetary unit.

In Italy, presumers can make use of net-metering ("Scambio Sul Posto"). The principle of "Scambio Sul Posto" is based on the balance of the energy fed in and consumed. More specifically, the owner of such plants will receive a compensation equal to the difference between the value of electricity exported to the grid and the value of the electricity consumed in a different period. If more energy is fed in than is consumed, plant operators are entitled to have an economic compensation. If they feed in less than they consume, the difference is subject to a payment.

For Italian market, the gross price of electricity consumed and paid in the bill (including tax, services, charges, etc.) is around 0.20–0.25€/kWh. However, the excess of electricity fed in the grid is assessed around 0.09–0.10€/kWh.

To determine the costs of a solar and storage system, a market research was conducted. According to the current Italian market, it was established that the investment cost of a solar system is by 2200€/kWp (after tax), while the cost of lithium ion batteries, is roughly 1000€/kWh. Among the costs, the annual costs of 100€ for maintenance as well as 80€ for insurance are included.

The operating costs were evaluated by assuming the unit cost of electricity equal to 0.25€/kWh. The price includes VAT and taxes according to the statistic of Italian Regulatory Authority for Energy.[26]

In the cost evaluation, taxes, VAT, charges and subsidies have been included. In particular, it was included the financial incentives by 50% on capital costs for a period of 10 years provided by Italian government.

In particular, the following financial indices have been evaluated:

The net present value (NPV), which is the sum of the discounted values of incoming and outgoing cash flows, i.e. revenues ® and costs ©, over the whole lifespan (T), taking into account the discount rate r:

$$NPV = \sum_{t=0}^{T} \frac{R_t - C_t}{(1+r)^t} \tag{11}$$

where r is the discount rate and it was assumed equal to the cost of capital, which can be calculated according to the weighted average cost of capital (WACC):

$$WACC = \frac{K_d \cdot D + K_e \cdot E}{D + E} \tag{12}$$

Here, WACC is the cost of the invested capital, $K_d$ is the interest rate for Debt (D) and $K_e$ is the opportunity cost of Equity (E). The interest rate for debt and the opportunity cost of equity are referred respectively to the active and passive interest rates charged to households and consumers, according to the statistics of Bank Italia (2017),[27] set at 3.0% (over 5 years loan life) and 9.0%; assuming a leverage ratio of 50%. Consequently, the value of WACC is 6.00%.

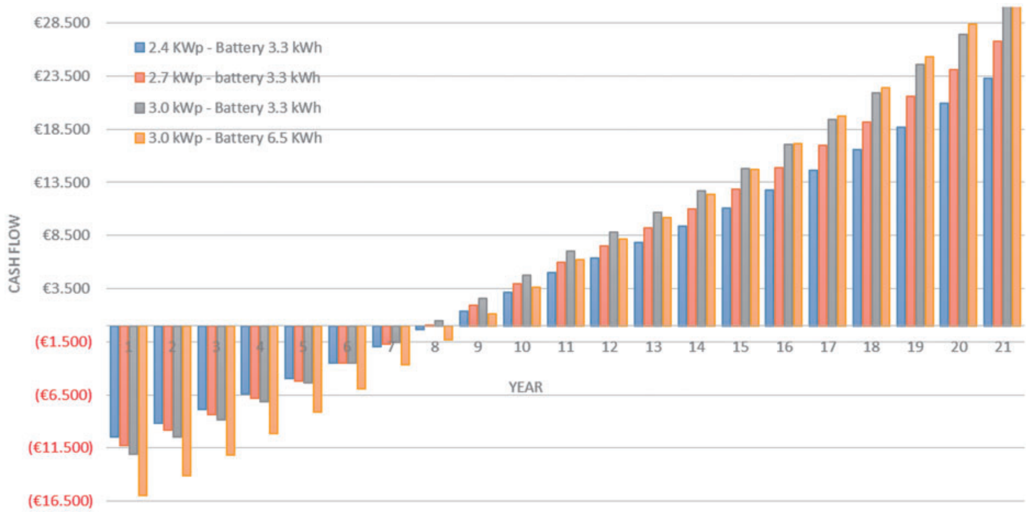


**Figure 9.** Cash flows of the more significant scenarios.

The internal rate of return (IRR), which is the discount rate that makes NPV of all cash flows from the investment equal to zero:

$$0 = \sum_{t=0}^{T} \frac{R_t - C_t}{(1 + IRR)^t} \tag{13}$$

IRR needs to be greater than the discount rate r, given that the discount rate is assumed as the global cost (interest rate and opportunity cost) of the invested capital.

The payback period (PP) is used as an alternative to NPV. It is the time required after an investment to recoup the initial costs of that investment.

Unlike NPV, the PP fails to account for the time value of money. For this reason, PPs calculated for long investments have a greater potential for inaccuracy, as they encompass more time during which inflation may occur and skew projected earnings.

The discounted payback period (DPP) is used to determine the profitability of a project. The DPP gives the number of years it takes to break even, from undertaking the initial investment and by discounting future cash flows.

In Figure 9, the cash flows of the more significant scenarios are reported.

Moreover, in Table 6, all calculated financial indices are summarized for all scenarios.

It is possible to observe that all the examined configurations are characterized by satisfactory economic results with regard to the different indicators considered.

Specifically, the DPP is lesser than 10 years for almost all the scenarios excepted for the cases with BC of 6.5 kWh and $E_{hload}$ of 3500 kWh/year.

Thus, under the financial point of view, the differences evidenced among the PV–EES equipped with the lower BC respect to the PV–EES equipped with the higher BC are considerably smoothed.

Moreover, there is the paradox that the PV–EES systems which allow to reach the highest autarchy rate are that one with the worsen financial performances.

**Table 6.** Financial indices for all scenarios.

| EES | 3.3 kWh | | | | | | | 6.5 kWh | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3000 kWh | | 3500 kWh | | | 4000 kWh | | 3500 kWh | | 4000 kWh | |
| $E_{hload}$ | $P_{peak}$, kW | | $P_{peak}$, kW | | | $P_{peak}$, kW | | $P_{peak}$, kW | | $P_{peak}$, kW | |
| | 2.4 | 2.7 | 2.4 | 2.7 | 3.0 | 2.7 | 3.0 | 2.7 | 3.0 | 2.7 | 3.0 |
| NPV | 7.992,82 | 7.610,73 | 9.899,24 | 9.485,45 | 9.209,02 | 11.278,66 | 11.071,66 | 8.360,03 | 8.210,39 | 10.272,48 | 10.246,62 |
| IRR | 14.0 | 13.0 | 15.0 | 14.0 | 14.0 | 15.0 | 15 | 12.0 | 11.0 | 13.0 | 12.0 |
| PP | 7.18 | 7.44 | 6.7 | 6.97 | 7.18 | 6.56 | 6.8 | 7.86 | 7.99 | 7.44 | 7.55 |
| DPP | 9.33 | 9.77 | 8.54 | 8.97 | 9.33 | 8.33 | 8.65 | 10.69 | 11.03 | 9.76 | 9.95 |

EES: electricity energy storage.

This result is influenced by the remuneration of surplus energy that does not take in account of the costs for the whole electric system, because by offsetting exported and imported electricity.

## Conclusions

This study aims to identify the energy exchange with the grid and the rate of self-consumption of combined PV–EES systems dedicated to residential and small commercial prosumers. The developed analysis aims to identify which combinations among PV power, electricity consumption and BC allow to reach the high ratio of self-sufficiency and consequently minimize the energy exchanged with the grid.

In particular, it was found out that the realized self-consumption rate reaches the highest value by 73.3% when the size of the EES is the highest, while for the lower BC the maximum value is by 58.2%.

While $R_{AUT}$ reaches the highest value 87.8% when the BC of the EES is the highest, instead for the lower BC the maximum value is by 73.7%.

Considering that the autarchy ratio of PV plants, which are not coupled with an EES system, is always lower than 40%, it is manifested that a combined PV–EES system significantly increases the self-sufficiency of the household PV plant.

Noticeably, the ratio $E_{hload}/E_{BC}$ is the parameter that mainly influences the rate of autarchy achievable. Indeed, only PV–EES system with $E_{hload}/E_{BC}$ from 1.1 to 2.0, allows to reach rate $R_{AUT} > 80\%$.

This result can be extended to other combinations of PV–EES systems characterized by the equal proportion between PV size, electric consumptions and BC.

Finally, the performed financial analysis evidences the economic viability of these systems under the Italian current market and economic circumstances.

The aim to increase the household electricity self-sufficiency achieved by using PV–EES systems represents an important opportunity for the entire electric system, since huge amounts of electricity can be delivered by renewable sources at a much lower cost.

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## Appendix

### *Notation*

| | |
|---|---|
| A | Net surface area, $m^{-2}$ |
| E | Energy, kWh |
| G | Solar irradiation, $kWh/m^{-2}$ |
| P | Power, W |
| t | Time lapse, h |
| T | Temperature, °C |
| $\alpha$ | Solar absorptance, – |
| $\beta$ | Tilt angle, ° |
| $\eta$ | Efficiency, – |
| $\mu$ | Temperature coefficient, %/°C |

| | |
|---|---|
| $\tau$ | Time, hour |
| $\tau v$ | Solar transmittance, – |

## Subscripts

| | |
|---|---|
| ch | Charged |
| ds | Discharged |
| exp | Exported |
| imp | Imported |
| h-load | House electric load |
| inv | Inverter |
| m | Mismatch |
| pv | Photovoltaic |
| sc | Self-consumption |