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Technical and economic assessment of PV-coupled energy storage systems: A case study from Italy, based on field-data

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Susanna Mocci[1] ✉, *Simona Ruggeri*[1], *Noémie Poize*[2]

[1]*Department of Electrical and Electronic Engineering, University of Cagliari, Cagliari, Italy*
[2]*Auvergne Rhône-Alpes Energie Environnement, Villeurbanne, France*
✉ *E-mail: susanna.mocci@unica.it*

Abstract: Significant levels of low-carbon generation from renewables will radically modify the power quality of the network, causing contingencies and increasing the complexity of demand-generation balancing due to variable and relatively unpredictable power injections. Energy storage systems (ESSs) could support the integration of such amount of renewable energy limiting the negative impact on the network and boosting photovoltaic (PV) self-consumption, providing benefits also for the prosumers. For this purpose, coupled PV-ESS residential storage systems were developed in six European Mediterranean countries, through the EU StoRES project. In Sardinia (Italy), 13 pilots have been selected for the implementation of ESS, which consists of typical residential premises with existing rooftop PV systems under the net-metering scheme. The aim of this study is to provide the technical and economic assessment of the coupled PV-ESS systems, based on real data measured within the StoRES project monitoring phase (1 year). The analysis is supported by well-established indicators, employed to quantify the variation of the prosumer's electrical behaviour due to the integration of the electrical storage. Other outputs related to roundtrip efficiency shed light on battery real field operation.

1 Introduction

The European Union (EU), with the last strategic long-term vision, confirmed and reinforced the ambitious targets for the reduction of carbon emissions from the energy sector, envisaging the development and wide-scale deployment of low-carbon electricity generation [1]. Renewable energy sources (RESs) will allow reducing dependency on traditional sources for electricity production and thus decreasing the CO_2 emissions. However, significant levels of low-carbon generation from renewables (e.g. mostly wind and solar energy) will radically modify the power quality of the network, causing contingencies (i.e. overvoltage and overcurrent) and increasing the complexity of demand-generation balancing due to variable and relatively unpredictable power injections.

These targets are reflected in the Italian National Energy and Climate Plan, in which the residential sector is involved by installing RES in residential premises, also with energy storage systems (ESSs) in order to improve the flexibility and security of the system [2]. Indeed, since network reinforcement is no more recognised as a suitable solution to increase the hosting capacity of the systems, ESS could support the integration of such amount of renewable energy limiting the negative impact on the network and boosting photovoltaic (PV) self-consumption, providing benefits also for the prosumers. For this purpose, coupled PV-ESS residential storage systems were developed in six European Mediterranean countries, through the EU StoRES project [3, 4]. In Italy, 13 pilots have been identified for the implementation of ESS in the territory of Ussaramanna (Sardinia region). The pilots consist of typical residential premises with existing rooftop PV systems under the net-metering scheme. The technical solution is designed accordingly to fulfil the energy needs of each pilot and, at the same time, to ensure the optimal utilisation of the integrated storage system. The aim of the paper is to provide the technical and economic assessment of the coupled PV-ESS systems, based on real data measured within the StoRES project monitoring phase. The analysis is supported by well-established indicators, i.e. the self-consumption and self-sufficiency rates, employed to quantify the variation of the prosumer's electrical behaviour due to the integration of the electrical storage. Other outputs related to roundtrip efficiency shed light on battery real field operation.

The main results derived from the coupled PV-ESS plants are described in the next sections. Because of ESS high cost and limited knowledge concerning technical aspects, large-scale deployment is still difficult. Technical solutions are necessary to remove concerns related to storage integration to the electricity grid and thus, achieve further resilience in the energy system.

2 Case study

2.1 Coupled PV-ESS pilot sites

In the StoRES project, 13 coupled PV-ESS residential storage systems were developed in the Municipality of Ussaramanna, Sardinia (map in Fig. 1). The installation of the storage, metering and communication systems has been completed in March 2018 for all the pilots identified. Regarding the supporting storage technology, lithium-ion (Li-ion) and lithium-iron phosphate ($LiFePO_4$) batteries have been chosen, since they offer high-energy conversion performance, long lifetime and low self-discharge rate (preferable for long-life PV applications). The sizing of the battery has been calculated according to the PV power and the load profile (range 4–8 kWh).

Different system configurations that support PV and ESS technologies have been identified. Both DC-coupled and the AC-coupled system configurations can supply storage solutions [4]. The chosen type of coupling is the AC side, preferred for retrofit installation, with PV inverter already installed (Fig. 2). PV systems are under the net-metering scheme 'Scambio sul Posto' (SSP). The turnkey prices of the ESS not including the PV

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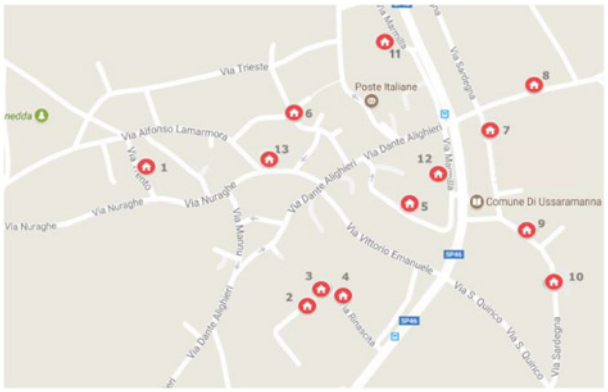


Fig. 1 *Pilot sites in Municipality of Ussaramanna-Italy*

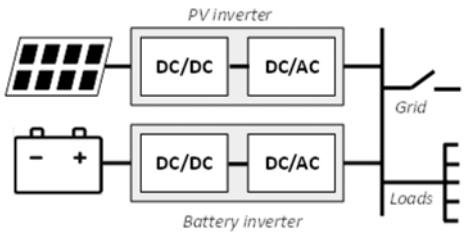


Fig. 2 *AC coupled storage systems*

installation is around 1260 €/kWh (VAT included, average values including inverter and installation).

3 Objectives and data analysis

3.1 Main objectives

By storing the energy produced locally and using it when production is not enough, the self-consumed energy increases. Installing an ESS on an existing residential PV system can increase the percentage of self-consumed electricity from about 30% without storage to around 60–80%. The ESS operation mode in the implemented pilots is the optimisation of the self-consumption (default mode).

In addition to the flat electricity pricing, most of the electricity authorities have launched variable electricity tariffs for the residential sector. A residential ESS has the capability to shift electricity demand from peak to off-peak hours, and to decrease the peak dependence from the power grid, by maximising the exploitation of the PV production. Moreover, residential ESSs can contribute to reducing the CO_2 emissions, by integrating more RES generation in the power mix.

3.2 Energy flows

The energy flows monitored on the pilot sites at a 15 min timestep are [kWh]:

- *PV production*: the energy yield delivered by the PV plant.
- *Load consumption*: the energy consumed by the building.
- *Battery charge*: the energy charged in the battery.
- *Battery discharge*: the energy delivered by the battery to the consumer.
- *PV direct use*: the share of the PV production which is directly consumed by the consumer (without being stored).
- *Grid import*: the energy withdrawn from the grid to cover the consumption.
- *Grid export*: the excess energy coming from the PV plant which feeds in the grid.

The following energy balance has to be respected for all timesteps:

$$\text{Load} = \text{Production} + \text{Discharge} - \text{Charge} + \text{Import} - \text{Export} \quad (1)$$

Another important indicator collected together with the previous ones is the state-of-charge (SOC) of the battery, which represents the energy-charged compared to the nominal capacity of the battery.

3.3 Main indicators

The self-consumption rate (SCR) represents the share of the PV production which is used to cover the load and to charge the battery. The higher the SCR is, the more the PV production is used for the domestic load.

$$\text{SCR}\ (\%) = \frac{\text{PV direct use} + \text{Charge}}{\text{Total PV production}} \quad (2)$$

Thanks to (1) it can be stated that

$$\begin{aligned}\text{PV direct use} &= \text{PV production} - \text{Charge} - \text{Export} \\ &= \text{Load} - \text{Discharge} - \text{Import}\end{aligned} \quad (3)$$

Then the SCR is also defined as follows:

$$\text{SCR}\ (\%) = \frac{\text{PV production} - \text{Export}}{\text{Total PV production}} \quad (4)$$

The self-sufficiency rate (SSR) represents the share of the consumption which is covered by the PV production and by the battery discharge. The higher the SSR is, the more the electricity bill is impacted.

$$\text{SSR}\ (\%) = \frac{\text{PV direct use} + \text{Discharge}}{\text{Total load consumption}} \quad (5)$$

Considering relation (3) the SSR can be defined as follows:

$$\text{SSR}\ (\%) = \frac{\text{Load consumption} - \text{Import}}{\text{Total Load consumption}} \quad (6)$$

The roundtrip efficiency of the battery system is defined as follows:

$$\eta(\%) = \frac{\sum_n \text{Monthly energy discharged (kWh)}}{\sum_n \text{Monthly energy charged (kWh)}} \times 100\% \quad (7)$$

4 Results and discussion

The monitored data has been collected for more than 1 year for all the 13 pilot sites (July 2018–September 2019), however, due to technical issues, only 12 pilot sites lead to results that can be exploited. The coupled PV-ESS solution enables to cover >50% of the load consumption (Figs. 3 and 4).

In Fig. 5, the SCR calculated for each pilot plant, with and without storage (light blue bar and orange bar, respectively) is shown. The SCR increase in % (black bar) can be then deducted from these values.

The annual SCR has an average increase of 120% thanks to storage equipment, as shown in Fig. 6, whereas the maximum increase is 180% (in Pilot P3, Fig. 5).

As regards seasonal rates, average values were calculated for each pilot site, considering the three seasonal periods used for the average profiles (summer/interseason/winter). These rates are compared to their value without any storage, so as to better assess how batteries

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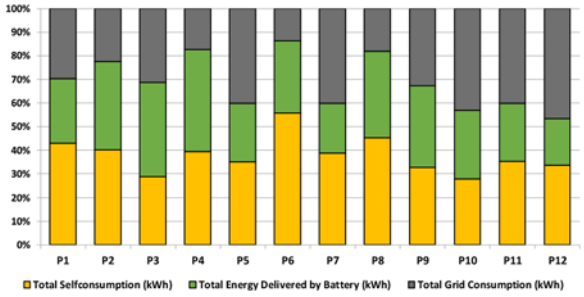


Fig. 3 *Contribution of each source to the annual consumption of the pilot sites*

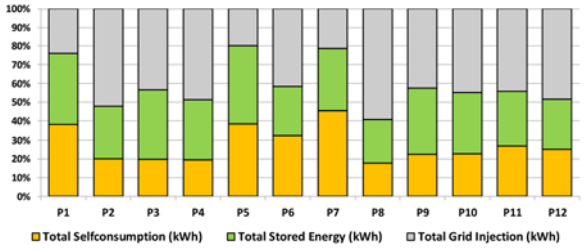


Fig. 4 *Share of the different uses of the local production for each pilot site*

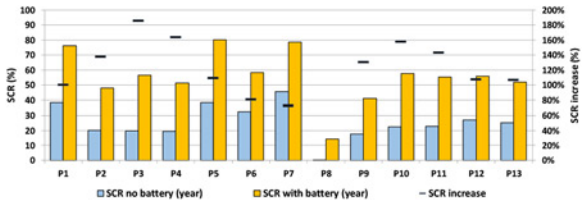


Fig. 5 *Variation of SCR for each pilot plant*

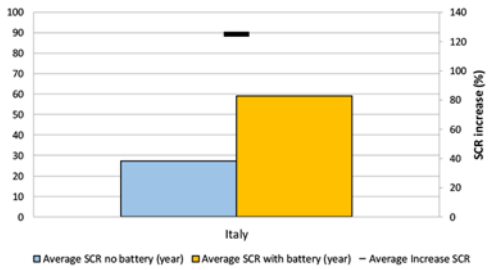


Fig. 6 *Average variation of the SCR for the 12 pilots*

improve self-consumption. In all the cases, SCR is higher in winter than in summer, since in summer the battery is not big enough to store all the production and there is some grid export (Fig. 7*a*), whereas in winter consumptions are higher and the whole PV production can be used for the load consumption (Fig. 7*b*).

Then, the self-sufficiency rates are calculated for each pilot plant, with and without storage. As regards seasonal rates, average values were calculated for each of the pilot sites, considering the same three seasonal periods used for the average profiles (summer/interseason/winter). These rates are compared to their value without any storage, so as to better assess how batteries improve self-consumption. Fig. 8 shows the SSR calculated for each pilot plant, with and without storage (green bar and orange bar, respectively). The self-sufficiency rate has an average annual increase of 80% thanks to storage equipment (Figs. 8 and 9); the maximum increase is 140% for site P3.

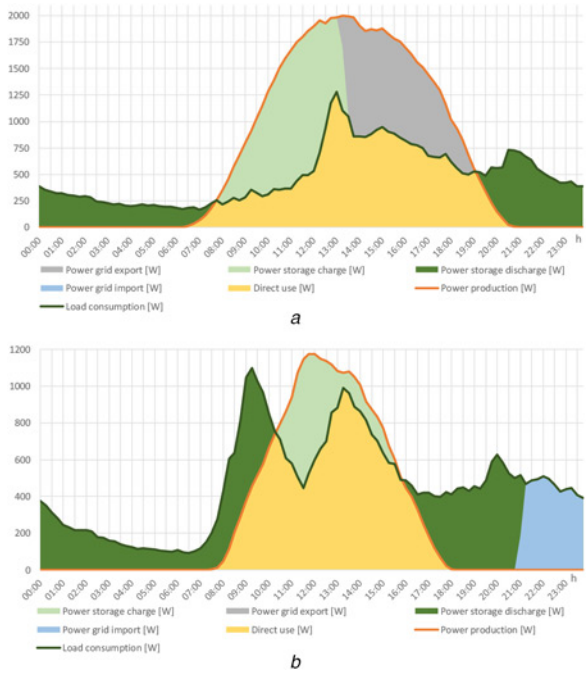


Fig. 7 *Working days average profiles for the pilot site n.1 (3 kW PV–6 kWh ESS)*

a Summer
b Winter

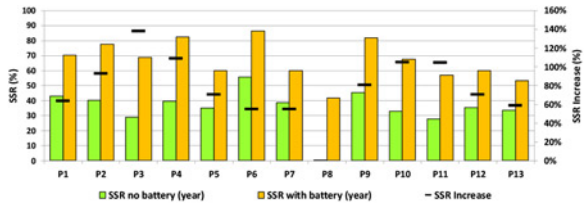


Fig. 8 *Variation of SSR for each pilot plant*

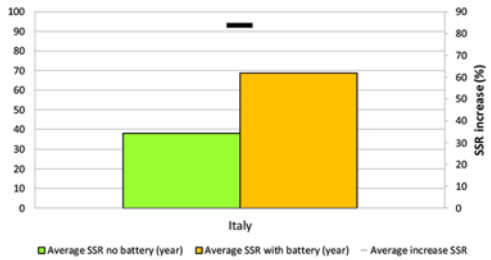


Fig. 9 *Average variation of SSR for the 12 pilots*

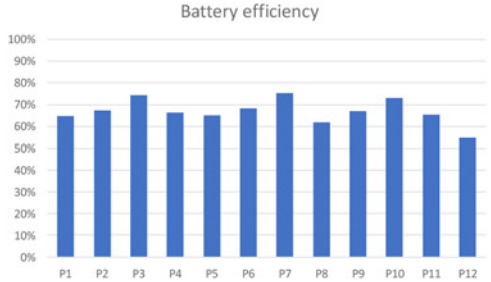


Fig. 10 *ESS efficiency for the 12 pilots*

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All the graphs underline the notable increase of the indexes in the majority of the pilot sites. This indexes' increase implies that the interaction of the pilot installations with the utility grid is reduced, leading to savings from electricity bills and less power losses.

Finally, the roundtrip efficiency of the storage systems is calculated (Fig. 10). The average efficiency of the 12 pilot plants is 67%.

4.1 Cost and benefit comparisons

Under the current conditions, including policies, pricing schemes, frameworks, costs, ESS utilisation etc., adding ESS to the existing PV system does not provide financial benefit to the end-users. PV systems under the net-metering scheme can be seen as systems connected to a virtual infinity ideal battery. The operational and capital expenses associated with the ESS installation are still high, and there is a need for new policies to promote residential ESSs integration [5].

The current opportunities for the ESS exploitation do not fully utilise the energy storage capabilities of the installed capacity. Aggregators can control and manage any unexploited capacity of a number of residential ESSs, in order to provide services to the power grid and hence, to create additional financial benefits for a residential ESS installation. However, the current policy framework and the power grid infrastructures do not allow this full battery capacity exploitation. Modifications of the current policy legislations and electricity infrastructures need to be undertaken in order to minimise the requirements for the provision of ancillary services from residential ESSs. In this regard, encouraging preliminary results on different ESS operation modes have been reached in the pilots in Greece and Cyprus (e.g. peak reduction on the grid).

It is worth notice that Italy recently has launched new schemes to promote residential ESS, including a 50% subsidy on the ESS purchase cost, and an income tax deduction, creating the 'fly' effect with the largest number of systems installed in 2019 and foreseen in the next years. Moreover, in the Italian *RES 1 Decree* (2019) PV plants up to 100 kW on buildings can again benefit from new incentives, and the net production quota consumed on-site is awarded a premium provided that, on an annual basis, the self-consumed energy is higher than 40% of the net production of the plant. This bonus related to self-consumption opens new opportunities to the storage market.

5 Conclusion

The coupled PV-ESS solutions have been tested in the pilot sites at the selected residential premises in Sardinia and by taking into consideration the different local specificities. The installation of the systems in all pilot locations has been completed in the first quarter of 2018. Communication devices employed along with the coupled PV-ESS system allowed the local monitoring of the prosumer data (>1 year). The integration of ESS with the existing PV installations allows the increase of self-consumption, permitting even higher shares of PV-generated electricity. Nevertheless, adding ESS to the existing PV system does not provide financial benefit to the end-users, since the related capital costs are still high. Nevertheless, the connection and coordination of an increasing number of ESSs lead to new challenges for the maximum exploitation of their technical and economic potentials. Since the legislation barriers constitute the main obstacle preventing storage technology full exploitation in the grid, promotion of storage through regulation can be achieved by allowing frameworks that support self-consumption of RES-generated electricity. Thus, *ad-hoc* supporting programs to remove barriers relating to ESS implementation are needed, mostly in a weak context like islands and rural areas (e.g. operation in microgrid).

6 Acknowledgments

The StoRES project was co-financed by the European Regional Development Fund (ERDF) through the Interreg MED Programme.

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