Title

The economic viability of a feed-in tariff scheme that solely rewards self-consumption to promote the use of integrated photovoltaic battery systems

Authors (name and surname)

Giovanni Brusco, Alessandro Burgio, Daniele Menniti, Anna Pinnarelli, Nicola Sorrentino

Affiliation

Department of Mechanical, Energy and Management Engineering, University of Calabria, Rende, 87036, Italy

Corresponding author

Alessandro Burgio (alessandro.burgio@unical.it)

Address

Alessandro Burgio / University of Calabria
via bucci, 42C
87036, Rende, CS
Italy

HIGHLIGHTS

- A FIT scheme for grid-connected integrated PV-battery systems is discussed.
- The FIT tariff scheme solely rewards self-consumption.
- An optimization problem minimizes the tariff and it sizes the integrated systems.
- The saving on bill is approximately 50%, the end user attains 25% self-sufficiency.
- The self-generation is 50% at least, the self-consumption is 80% at least.

ABSTRACT

With reference to an integrated photovoltaic battery (PV-BES) system for grid-connected end users, a feed-in tariff scheme is discussed in this article. This scheme solely rewards self-consumption. Zero is the generation price paid for the generated renewable energy, and zero is the export price paid for the renewable energy delivered to the grid. This feed-in tariff scheme, referred to as S-FIT, also excludes the net-metering service and the possibility that the grid recharges or discharges the batteries.

To calculate the incentive tariff, an optimization problem is adopted. The problem returns the minimum value of the tariff so that the subsidy given to the end user is equal to the difference between the instalments paid for the integrated PV-BES system and the savings obtained from the electricity bill. The period during which the end user has secured this grant is ten years.

The S-FIT scheme is applied to the case of the Italian Public Administration from 2011 to 2015. Consequently, the real values of temperature, irradiation, and energy consumption are measured every 15 minutes, and the real electricity prices over the period 2011-2015 are considered. The optimal solution returned by the optimization problem allows for a significant reduction of the electricity bill by 49.56%; moreover, the self-produced energy is equal to at least 50%, whereas the self-consumed energy is equal to at least 80%.

The optimal solution that is calculated using 2011 data is applied for 2012 to 2015. Although the electricity prices were subject to a radical change during this period, the optimal solution still allows for a significant reduction of the electricity bill; in particular, this reduction is equal to 44.98% when the PV-BES system is adopted, whereas it is equal to 33.65% when only the PV system is adopted. In both cases, the optimal solution ensures self-produced energy of at least 50% and self-consumed energy of at least 80%.

This article ends with an assessment of the impact of the integrated PV-BES system on the load profile from the grid perspective and the satisfactory degree of self-sufficiency achieved by the end user.

***Index Terms* — Battery storage; Economical analysis; Feed-in tariff; Optimal sizing; Photovoltaic system; Support policy.**

1. INTRODUCTION

Among the contributions in the literature concerning the study and the economic viability of integrated photovoltaic and battery energy storage (PV-BES) systems for industrial or dwelling applications, including those benefitting from an incentive policy, Ref. [1] stands out among the many studies because the conclusion is the opposite of the majority of the contributions. In 2012, McKenna et al. state that in the UK, the PV-BES combination is not economically efficient because even in the presence of the incentive feed-in tariff policy, there is no economic convenience when adopting lead-acid batteries even if ideal batteries with an optimistic life expectation are considered. In addition, based on well-formulated considerations, McKenna et al. claim that this conclusion, *batteries in the UK do not pay,* is also valid for the case of Germany and the Australian States of Queensland, Victoria and Western Australia.

Three years before, in 2009, the study of PV-BES systems on the German FIT policy was already being addressed in Ref. [2]; in this reference, Braun et al. present a PV-BES system developed within a French-German project called Sol-ion. They conclude that the adoption of the Sol-ion system is a profitable operation for lithium-ion battery system prices below 350 €/kWh.

One year later, Ref. [3] arrived at the same conclusion; Hoppmann et al. state that in 2013, investment in storage batteries in Germany was economically viable for small PV systems even when not considering feed-in policies or demand-side management. The authors conclude that a promotion policy of battery storage will be necessary only in the short term.

In 2014, the study of PV-BES systems on the German FIT policy is again addressed in Ref. [4]. Like many other academics, Weniger et al. also seek to identify the storage system price at which residential PV-BES systems become economically sustainable. In reality, the authors question which factor primarily influences the break-even price and conclude that the main factor is the rate of interest, followed by the PV system price, the retail price of electricity and the feed-in tariff. Consequently, Weniger et al. suggest evaluating the profitability of PV-BES systems and focusing on the future development of retail electricity prices instead of the development of new feed-in tariffs. The authors state that the integration of PV systems with batteries will be the most economical solution in a long-term scenario.

A further contribution to the study of PV-BES systems on the German FIT policy was made in 2015 by [5]. In the reference, Linssen et al. show that the use of realistic load and production profiles is mandatory to allow for reliable statements concerning both the technical parameters and economic feasibility. The authors also conclude that the break-even price for the integrated system is approximately 900 €/kWh without a battery energy storage support scheme and approximately 1200 €/kWh when considering the German support scheme. Linssen et al. conclude by underlining that the individual taxation of revenues can significantly lower the break-even costs.

The study of PV-BES systems on the German FIT policy in commercial applications is addressed in 2016 in Ref. [6]; in the reference, Merei et al. focus their attention on this sector due to the significant opportunity for economic savings. Indeed, commercial buildings usually have ample space for the installation of photovoltaic panels, and their load profiles have a high correlation with the generated solar energy. A supermarket in Aachen with yearly electricity consumption of 238 MWh is the case studied in the reference; in this commercial application, the authors conclude that battery storage significantly increases the self–consumption of PV produced energy, but even with unrealistic battery prices of less than 200 €/kWh, batteries cannot offer an economic solution.

The German incentive system was used as inspiration in Ref. [7]; in this reference, Mulder et al. affirm that since 2012 in Belgium, the use of lead-acid batteries up to 5 kWh is also affordable without subsidies, regardless of the increase in the cost of electricity. In view of the gradual decrease of the cost of lithium batteries, this latter technology will be attractive in the short term. Specifically, if the price of electricity increased by 4%, 4 kWh lithium batteries will be an attractive option in 2017 even without subsidies.

Currently, Italy does not have a specific FIT policy for battery energy storage systems; the only concession to customers for the installation of batteries is a tax deduction equal to 50% of the investment costs spread over 10 years. All residential and commercial customers can install BES systems, which do not necessarily have to be integrated with a PV plant. In the case of batteries integrated with PV systems, the installation of a bidirectional electric meter is required to prevent the annulment of the incentives, where they exist, for the PV system. An analysis of the costs/benefits of the PV-BES system in residential applications is reported by the Italian total public-controlled Research into Electrical Systems company in Ref. [8]. The results presented in the reference show that in the case of an existing PV system subsidized by a feed-in tariff, the adoption of a BES system further increases the annual economic benefit of approximately 150 euros. In the case of a PV system that is not subject to a feed-in tariff, the additional annual economic benefits increase to approximately 170 euros. The calculated annual benefit is estimated net of the costs of the initial investment.

In most of the articles cited above that are mentioned in the noteworthy review presented in Ref. [3], the analysed incentive schemes already exist; therefore, these schemes include input data in the economic-financial evaluation of an integrated PV-BES system, like solar radiation or user load profiles. On the contrary, a proposal for a new incentive scheme for PV-BES systems on the Greek island of Corvo is presented in 2011 in Ref. [9]. Two diesel generators of 120 kW and two of 160 kW serve the island and its approximately 400 inhabitants. To calculate the subsidy for remunerating the adoption of PV-BES systems, Krajacic et al. estimate the fuel savings achieved from the adoption of batteries; they conclude that for a residential battery storage system with a capacity of up to 40 kWh mounted with a 4 kW inverter, the feasible remuneration scheme is a fixed tariff of 53.8€/kWh, multiplied by the storage capacity.

Two further proposals for a new incentive scheme for PV-BES systems in Australia are presented in 2014 in Refs. [10,11]; in these references, Ratnam et al. study 145 residential customers who were randomly selected from customers located in the low voltage Australian distribution network operated by the Ausgrid distributor.

For these customers, the authors assume the use of a photovoltaic system mounted on a rooftop and a battery storage system with a capacity initially fixed at 10 kWh. The authors also propose a role and the respective algorithm that efficiently manages the batteries to grant economic benefits to the residential customer and simultaneously alleviate the utility burden associated with peak demand and reverse power flow. The economic benefits are derived from the proposed FIT schemes. One of these schemes consists of a generous constant FIT of 0.4$/kWh; this value is higher than peak load price but is lower than the FIT offered in 2010 by the New South Wales Government, which paid a generation price of 0.6$/kWh. The proposed FIT schemes enable an overall average savings of $350/yr and $100/yr per user.

Four algorithms for the battery storage system operation are also proposed in Ref. [12], where the residential storage at the local and grid levels for Portugal is analysed. In the reference, Santos et al. use these algorithms to implement four rules and achieve the same number of different objectives. The first objective is to minimize the energy exchange between the grid and the customer, i.e., the grid zero role; the second and third objectives aim to reduce the peak demand from the grid and the peak energy injected into the grid, respectively. The last objective is to facilitate the integration of wind power from the grid. Each storage role is studied with respect to the four scenarios that represent the incentive for the customer to adopt the battery storage system. The authors concluded that the grid zero scenario is better able to derive profits from a self-consumption incentive scenario that rewards the customer with an on-site consumption tariff of the generated energy of 0.17€/kWh by a feed-in tariff of 0.17€/kWh and a buy tariff of 0.17€/kWh.

In this article, an incentive scheme for PV-BES systems that does not exist to date is also considered.

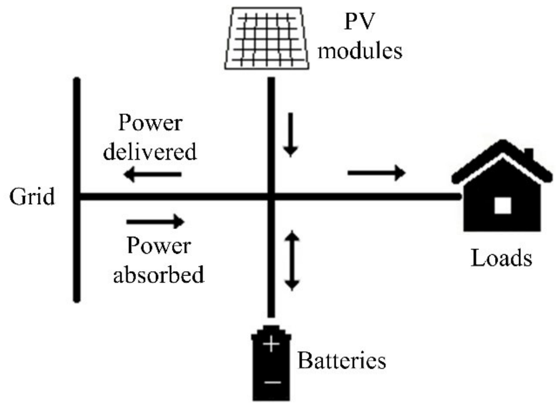


Fig. 1 An integrated photovoltaic battery (PV-BES) system

For a typical integrated PV-BES system for an end user connected to the distribution network, such as that shown in Fig. 1, the incentive scheme of this article only rewards the end user with a fixed incentive that is paid for each self-consumed kWh. The self-consumed energy is a non-negative number:

$E_{sc}(\Delta t) = E_{PV}(\Delta t) - E_d(\Delta t)$ (1)

where E_{PV} and E_d denote the energy produced by the PV system and the energy delivered to the grid, respectively, in the time interval Δt. Moreover, zero is the generation price paid for the energy generated by the PV system, and zero is the export price paid for the PV energy delivered to the grid. This feed-in tariff scheme, called S-FIT, also excludes the net-metering service and the possibility that the grid charges or discharges the batteries.

Therefore, bearing in mind the definition of a feed-in tariff as reported by Couture in Ref. [13], Sun in Ref. [14] and Ritzenhofen in Ref. [15], to name a few, the incentive scheme considered in this article might be classified as unconventional because it forces the government to pay for the energy generated by exploiting renewable sources that is not delivered to the grid.

To adhere to the S-FIT scheme as in Eq. (1), the operation of the integrated PV-BES system in Fig. 1 must comply with two rules. The first rule states that the PV system supplies the local electrical loads first and then recharges the batteries. The second rule states that the grid does not recharge or discharge the batteries. Given the S-FIT scheme and the two relevant rules, the problem of determining the incentive value expressed as €/kWh must now be addressed.

In many countries, the value given to incentives is typically determined by the national government in view of the type of renewable resource (solar, wind, biomass) and the technical and economic parameters (size, investment, cost) to ensure secure profitability for the investor — namely, the end-user. In the last decade, the promotion of generation systems that exploit renewables has gained immense approval in almost all countries around the world. The World Energy Outlook 2015 [16] has estimated that subsidies granted to renewable source plants around the world amounted to $135 billion in 2014 with an average growth rate of 25% per year since 2008. In 2014, Germany, the USA and Italy accounted for almost 50% of the total.

However, this beneficial situation may have an unexpected backstory: it cannot be forgotten that subsidies are calculated on electric bills; therefore, the above-mentioned $135 billion was paid by small, medium and large companies and public administrations as well as by citizens and less affluent families. These latter users are probably no longer willing to comply with the uncontrolled application of additional incentive policies implemented through market-independent FIT schemes. Consequently, the value of any new incentive scheme to promote the exploitation of renewable energy sources, to be eventually equipped with storage systems, must be adequately and reasonably determined. In particular, the respective extra cost burden on the bill should be as small as possible to stimulate market growth but avoid mere speculation. By doing so, a future incentive policy can identify the broadest possible consensus.

The incentive for the S-FIT scheme of this article is determined by an optimization problem that returns the minimum value of the incentive, which corresponds to the break-even point of the investment. More specifically, the optimization problem calculates the incentive in €/kWh so that the end-user receives a yearly subsidy equal to the difference between the instalments that the end-user pays for the integrated PV-BES system and the savings that the end user obtains to reduce his electric bills. The period during which the end user has secured this grant is ten years.

Since the optimization problem also returns the optimal size of the photovoltaic system and the battery storage system, the end user pays for the best photovoltaic battery combination that meets the constraints of the PV-BES model, including performance requirements. An example of a performance requirement is the percentage of self-generated electricity and the percentage of self-consumed energy. In this article, these percentages are set to at least 50% and 80%, respectively.

To verify the feasibility and the economic viability of the S-FIT scheme, a building at the University of Calabria in southern Italy has been evaluated. The electricity consumption of this case study was measured every 15 minutes from 2011 to 2015. As a result of this dense measurement harvest, it is possible to affirm that the load profiles are repeated in almost the same way. In particular, the data measured in 2011 are representative of the long-term habits of the case study, thus they are used as input data for the numerical simulations.

The numerical results show that the S-FIT scheme for integrated PV-BES systems is both feasible and convenient for the considered case study. In 2011, the end user obtained savings of €9,179.82, which is 49.56% of the electric bill. The user pays €16,835.59 for instalments for the PV system and the battery storage system, and he receives a subsidy of

€7,655.77. Since the subsidy is evidently higher than the instalments, the adoption of the S-FIT scheme is favourable for the end user, manufacturers and the market in general.

After 2012, electricity prices vary dramatically; up to 2012, the peak load electricity price was always higher than the off peak price. After 2012, this historical certainty gradually disappears until the opposite became true in 2015. The peak load price collapse evidently leads to a reduction in savings on electric bills and, consequently, a reduction in the cost-effectiveness of the investment in an integrated PV-BES system for self-generation and self-consumption.

To quantify the implications of the considerable reduction of peak load prices on the economic viability of the integrated PV-BES system, the authors calculate a situation in which the optimal solution obtained using the 2011 data were applied to the years 2012 to 2015. The numerical results show that in the period 2011-2015, the adoption of the S-FIT scheme, together with the integrated PV-BES system, allows for a satisfactory reduction of the electric bill of approximately 44.98% instead of 33.65%, as is the case when only the PV system is adopted. On the other hand, the excessive reduction in peak load electricity prices forces the end user to contract a debt, year by year, that in the five years amounts to €9,653.29, i.e., 26.21% of the subsidy that the user receives during the period 2011-2015.

It may be the case that the distortion of the electricity prices for Public Administrations occurred in Italy at the end of 2014. This temporary and sporadic anomaly, like the event reported by Sioshansi in Ref. [17]: due to the over-generation phenomenon, the Texas retailer TXU offered free electricity between 9 pm and 6 am in November 2015. If this were the case, then we can consider these price distortions a temporary and sporadic anomaly. The S-FIT scheme of this article is a valid alternative for promoting integrated PV-BES systems and sustaining both self-generation and self-consumption.

This article ends with an assessment of the different contributions of the batteries during the months of the year and of the 25% electricity self-sufficiency achieved by the end-user due to the integrated PV-BES system.

2. THE MODEL OF THE INTEGRATED PV-BES SYSTEM AND THE OPTIMIZATION PROBLEM

This section describes the model of the integrated PV-BES system shown in Fig. 1 with an optimization problem, which returns three values, namely the minimum value of the incentive S-FIT, the optimal size of the photovoltaic system PV and the optimal capacity of the battery energy storage system BES.

Because none of the equations of the optimization problem refers to the regulatory framework of a specific country, the international perspective of the problem is ensured, and both residential and commercial customers are candidates that are eligible for the installation of a PV-BES system awarded by the S-FIT scheme.

Assume that k is the index over the T time intervals along Δt and that the input data for the optimization problem are the solar irradiation G(k), the load profile P_{LOAD} (k) and the rated power of the battery storage system P_{BES}. The optimization problem is:

Minimize **S-FIT**

subject to:

$$\text{Balance} = \text{Savings}(.) + \text{Subsidy}(.) - \text{Costs}(.) = 0 \tag{2}$$

$$\text{Savings}(.) = \text{Electr.bill}_{\text{w/out PV-BES}} - \text{Electr.bill}_{\text{with PV-BES}} \tag{3}$$

$$\text{Electr. Bill} = \sum_{k=1}^{T} \text{Ea}(k) * \text{Price}(k) \tag{4}$$

$$\text{Subsidy}(.) = \sum_{k=1}^{T} \text{Esc}(k) * \mathbf{S\_FIT} \tag{5}$$

$$\text{Costs}(.) = \text{Instalment}(\mathbf{PV}) + \text{Installment}(\mathbf{BES}) \tag{6}$$

$$\text{Instalment}(\mathbf{PV}) = f(\text{Loan\_rate}; \text{Loan\_length}; \text{Amount}(\mathbf{PV})) \tag{7}$$

$$\text{Instalment}(\mathbf{BES}) = f(\text{Loan\_rate}; \text{Loan\_length}; \text{Amount}(\mathbf{BES})) \tag{8}$$

$$P_{PV}(k) = \mathbf{PV} * G(k) * \theta(k) * \eta_{PV} \tag{9}$$

$$E_{PV}(k) = \mathbf{PV}(k) * \Delta t \tag{10}$$

$$E_{LOAD}(k) = P_{LOAD}(k) * \Delta t \tag{11}$$

$$P_{BES}(k) \geq 0 \qquad \text{if } (E_{PV}(k) - E_{LOAD}(k)) \geq 0 \tag{12}$$

$$P_{BES}(k) \leq P_{PV}(k) - P_{LOAD}(k) \qquad \text{if } (E_{PV}(k) - E_{LOAD}(k)) \geq 0 \tag{13}$$

$$|P_{BES}(k)| \leq m * P_{BES} \qquad \text{if } (E_{PV}(k) - E_{LOAD}(k)) \geq 0 \tag{14}$$

$$SOC(k) = SOC(k-1) + (P_{BES}(k) * \Delta t / BES) * \eta_{charge} * 100 \qquad \text{if } (E_{PV}(k) - E_{LOAD}(k)) \geq 0 \tag{15}$$

$$P_{BES}(k) < 0 \qquad \text{if } (E_{PV}(k) - E_{LOAD}(k)) < 0 \tag{16}$$

$$P_{BES}(k) > P_{PV}(k) - P_{LOAD}(k) \qquad \text{if } (E_{PV}(k) - E_{LOAD}(k)) < 0 \tag{17}$$

$$|P_{BES}(k)| \leq P_{BES} \qquad \text{if } (E_{PV}(k) - E_{LOAD}(k)) < 0 \tag{18}$$

$$SOC(k) = SOC(k-1) + (P_{BES}(k) * \Delta t / BES) * (1/\eta_{discharge}) * 100 \qquad \text{if } (E_{PV}(k) - E_{LOAD}(k)) < 0 \tag{19}$$

$$E_{BES}(k) = P_{BES}(k) * \Delta t \tag{20}$$

$$E_{GRID}(k) = E_{PV}(k) - E_{LOAD}(k) - E_{BES}(k) \tag{21}$$

$$E_d(k) = E_{GRID}(k) \qquad \text{if } E_{GRID}(k) > 0 \text{ else } E_d(k) = 0 \tag{22}$$

$$E_a(k) = E_{GRID}(k) \qquad \text{if } E_{GRID}(k) \leq 0 \text{ else } E_a(k) = 0 \tag{23}$$

$$E_{sc}(k) = E_{PV}(k) - E_d(k) \tag{24}$$

$$\sum_{k=1}^{T} E_{PV}(k) \geq 0.5 * \sum_{k=1}^{T} E_{LOAD}(k)$$ 25

$$\sum_{k=1}^{T} E_{sc}(k) \geq 0.8 * \sum_{k=1}^{T} E_{PV}(k)$$ 26

m = Recharge_Current/Discharge_Current 27

SOCmin ≤ SOC ≤ SOCmax 28

PV≥0; BES≥0, S-FIT≥0 29

k=1, 2, … T 30

The constraints of the optimization problem are now discussed in the order in which they are numbered. The constraint (2) imposes that the variable *Balance* must equal zero; this variable is the sum of three terms: the cash flows, where the first is *Saving*, defined by (3) as the difference between the electric bills with and without the PV-BES system. The electric bill is calculated in (4) considering the electric energy absorbed by the grid Ea(k) and the electricity price Price(k). The second term is *Subsidy*, which it represents the euros the end user receives yearly thanks to the S-FIT scheme; Subsidy is calculated in (5) considering the S-FIT value and the self-consumption Esc(k). The last term is *Costs*; it is calculated in (6) as the sum of the instalments for the PV system and the BES system, defined in (7) and (8), respectively.

Equation (9) calculates the power PV(k) produced by the photovoltaic system as the product of the rated power PV, the irradiance G(k), and the function θ(k) to account for the ambient temperature, the parameter η_{PV}, to account for the combined photovoltaic system losses. Consequently, Eq. (10) returns the energy $E_{PV}(k)$ generated by the PV system.

Given that Eq. (11) calculates the energy $E_{LOAD}(k)$ consumed by local loads, the difference between $E_{PV}(k)$ and $E_{LOAD}(k)$ is calculated; when this difference is positive, the renewable supply exceeds the demand, batteries can be charged and the power $P_{BES}(k)$ delivered to the batteries is positive, as in (12).

The equations from (13) to (15) govern the operation of the battery storage system when the renewable supply is higher than the demand; thus, excess renewable power is available to recharge the batteries. In particular, Eq. (13) sets the power $P_{BES}(k)$ lower or equal to the exceeding power, whereas Equation (14) limits the power $P_{BES}(k)$ up to the batteries' rated power P_{BES}, which is multiplied by the coefficient m defined in (27) as the ratio between the recharge current and the discharge current. The state of charge (SOC) of the batteries consequently changes; Eq. (15) calculates the new value of the SOC by updating the previous value, adding a quantity that depends on the power $P_{BES}(k)$, the battery storage capacity BES and the coefficient ηcharge, which accounts for power losses during the recharge.

The equations from (16) to (19) govern the operation of the battery system when the renewable supply is lower than demand; these constraints are complementary to those from (13) to (15).

The equations (20) and (21) return the energy absorbed or delivered to the batteries and the energy absorbed or delivered to the grid, i.e., $E_{BES}(k)$ and $E_{GRID}(k)$, respectively.

Equation (22) sets the value of Ed(k) equal to the energy delivered to the grid while Eq. (23) sets the value of Ea(k) equal to energy absorbed from the grid. Equation (24) calculates the self-consumption as the difference between the energy generated by the photovoltaic system and the energy delivered to the grid.

Equation (25) requires that the yearly self-generation be at least 50% of the yearly load energy demand; similarly, Eq. (26) requires that the yearly self-consumption be at least 80% of the yearly self-generation. Equation (27) returns the coefficient m as the ratio between the recharge and the discharge battery current; evidently, this coefficient takes into account the battery technologies and the ability to charge the batteries with the current m times the discharge one. As an example, m is higher than 1 when Li-ion batteries are used, and m is lower than 1 when lead-acid batteries are used. Equation (28) provides a lower and upper bound for the SOC value. Finally, Eq. (29) requires that decision variables be non-negative numbers, whereas Eq. (30) sets k as the index over the T time intervals, each along Δt.

3. THE CASE STUDY: TECHNICAL, ECONOMIC AND REAL DATA

In this section, the authors present the case study used for the numerical experiments reported in section 4.1; the authors also illustrate how the electrical energy generated by the photovoltaic system is calculated and provide technical specifications of the battery storage system. Economic data, the amortization system used to determine the investment instalments, and the electricity prices are presented. Finally, the authors illustrate the measurement harvest of the energy consumption, the obtained load profiles and the selection of the representative load profiles of the case study in the long term.

3.1 The case study

A building at the University of Calabria, illustrated in Fig. 2, was studied. This building has eight floors; laboratories and office are distributed on each floor. In 2011, the electric energy consumption was approximately 133 MWh, 29% of which was for internal lighting, whereas the remaining 71% was for other electrical appliances. The electric bill was about nineteen thousand euros, 21% VAT not included.

Fig. 2 The case study

3.2 Photovoltaic electricity generation

The measurements of irradiance and ambient temperature were collected every 15 minutes for all five years, from 2011 to 2015, returning values of 35,040/yr. To calculate the energy generated by the PV system, a reduction/increase in the rated nominal power of the PV modules was calculated as a function of the operating temperature of the photovoltaic cell; this reduction/increase is 0.4982% for each Celsius degree higher/lower than the standard temperature of 25 Celsius degrees. The operating temperature of the photovoltaic module is calculated as:

$$T_{module} = T_{amb}(k) + \alpha * G(k) \tag{31}$$

where $T_{amb}(k)$ is the mean value of the ambient temperature in the time interval k, α is a constant equal to 0.050°C/(W /m^2), and G (k) is the mean value of the radiation in the time interval k. Therefore, the parameter θ (k), which is useful for Eq. (9), of the optimization problem is:

$$\theta(k) = (1 - (T_{amb}(k) + 0.05G(k) - 25) * 0.4982) \tag{32}$$

Power losses due to the tiltmeter shading and local shading are void; power losses due to reflection and in dc and ac circuits are 4%; power losses in the inverters are 2%; and power losses from mismatching are 3%. As a consequence, the coefficient η_{PV} in Eq. (9) of the optimization problem is 0.91.

3.3 Battery energy storage system

The storage system is equipped with lithium-ion batteries. This technology is preferred among storage technologies for this type of application due to their superior practicability and high modularity [18,19]. For the operation of the battery storage system, the following assumptions are made: the round trip efficiency is 82%; equal values for power losses during the recharge and discharge (η_c=η_d=0.90) processes are considered; the minimum value for the state of charge (SOC_{min}) is 20%; the maximum value for the state of charge (SOC_{max}) is 98%; and the self-discharge phenomenon is negligible. Finally, the recharge current is assumed as being equal to the discharge current, which is m set equal to 1 in Eq. (14) for the optimization problem.

3.4 Economic input data: unit costs, the French amortization system and instalments

Italian market prices in 2011 are used as a reference for the determination of the unit cost for both the photovoltaic system and the battery system. These unit costs are assumed as being equal to 1,800.00 €/kWp and 800.00€/kWh, respectively. Unit costs account for the laying and the maintenance of both the systems. The instalments for the photovoltaic system and the battery storage system are calculated using the well-known French amortization system, which is characterized by equal annual payments. The values of the loan rate and the loan length are 5% and 10 years, respectively.

3.5 Electricity prices and the three F1, F2 and F3 time-slots

The case study considered in this article refers to the Italian Public Administration; therefore, the electricity prices do not coincide with those of the consumers' market but are instead determined by national administrative action. More specifically, the electricity prices are the result of a public tender operated by Consip Spa; this company is a public joint stock company held by the Italian Ministry of Economy and Finance, which serves the Public Administration sector throughout a procurement process. Electricity prices vary according to the type of user (e.g., customers connected to a low or medium voltage grid, electric vehicle charging stations, public street lighting), the day of the week and the hour of the day; in particular, three time ranges — F1, F2 and F3 — are defined. As reported in Table I, from Monday to Friday, the F1 range covers the peak-load hours, the F3 range covers the off-peak hours, and the F2 range covers one hour at sunrise and four hours in the early evening. On Saturday, the F2 range covers the daytime while the F3 range covers night-time; on Sunday and holidays, the F3 range covers both t daytime and the night-time use.

Table I – The three time-ranges: F1, F2 and F3

	From Monday to Friday	Saturday	Sunday and holidays
7 am - 8 am	F2	F2	F3
8 am - 7 pm	F1	F2	F3
7 pm - 11 pm	F2	F2	F3
11 pm - 7 am	F3	F3	F3

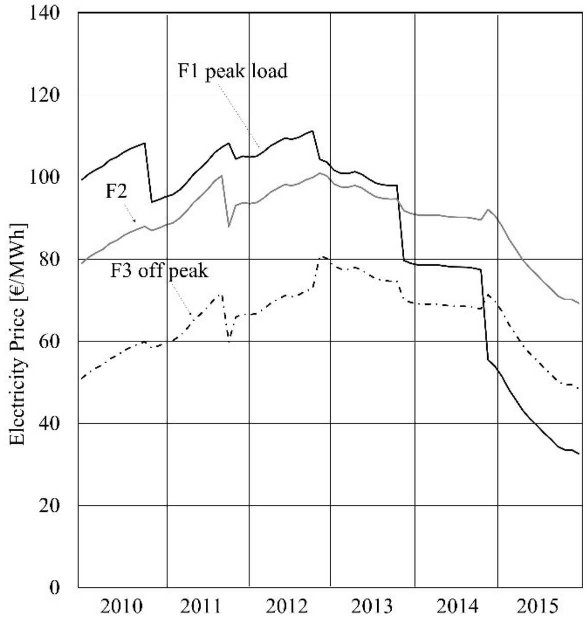


Fig. 3 Electricity prices from 2010 to 2015

Figure 3 reports the electricity prices from 2010 to 2015 for a Public Administration body connected to the medium voltage grid that forms the case study. These prices pay for the electricity generated and the transmission/distribution losses; they do not include the general charges of the electric power system or the national taxes on electricity. To also take into account these charges and taxes in the numerical experiments reported in section 4, the authors have analysed the electricity bills of the case study from 2011 to 2015. They estimated that, on average, these charges and taxes represent 36.26% of the bills in 2011, 42.83% in 2012, 47.89% in 2013, 54.72% in 2014 and 48.48% in 2015.

The movement in the electricity prices is a crucial point in the economic evaluation of an integrated system for PV-BES, as discussed in this article. Referring to Fig. 3, the peak-load prices have always been the highest, precisely as in 2010, when the peak-load price in January was approximately 99.29€/MWh and was almost perfectly double the off-peak price.

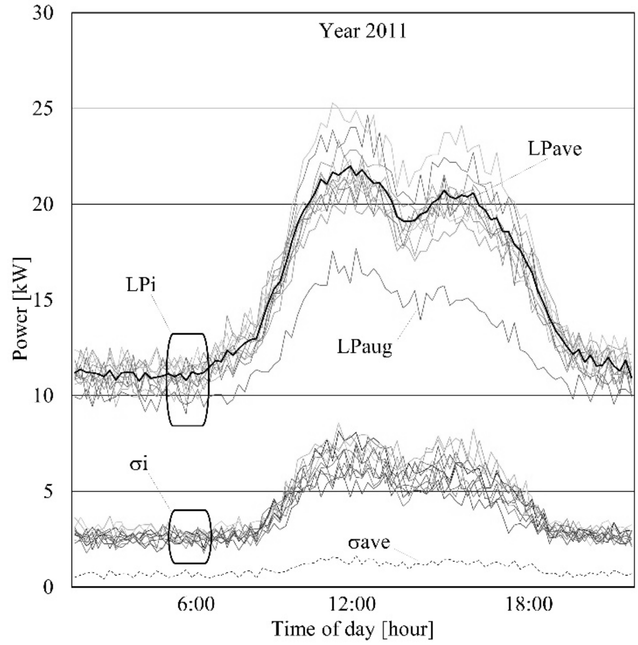
The electricity prices in the three-year period of 2010-2012 may be considered representative of the historical trend up to the beginning of 2013, when the consolidated reality of peak-load prices higher than off-load prices experienced a crunch, and the peak-load price falls below the price of the F2 range. Just a year later, the peak-load price falls below the off-peak price, and it maintains a decreasing trend for all of 2015 until December, when the peak-load price is just 32.57€/MWh, whereas the off-peak price is 48.42€/MWh. Such large movements in the electricity prices caused a sort of distortion in the Italian electricity market with serious repercussions both inside and outside the market itself.

3.6 Electric load profiles: measurement harvest and selection of the representative profiles in the long period

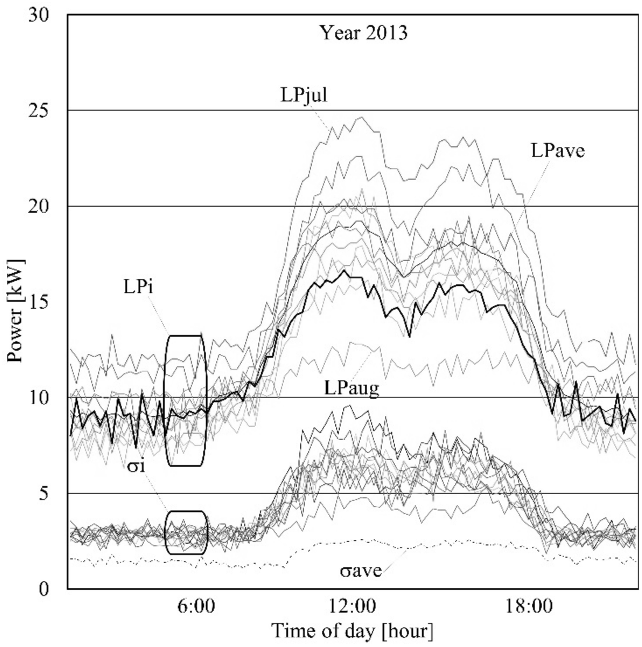
The electricity consumption in the case study was measured every 15 minutes from 2011 to 2015. As a result of this measurement harvest, it can be concluded that data measured in 2011 are representative of the habits in the long run of the case study. Therefore, the 35,040 values measured in 2011 are used as input for numerical simulations. The representativeness of the data measured in 2011 in the long run is now illustrated by showing, for sake of brevity, only a comparison compared to the data measured in 2013 and 2015.

Figure 4a shows the average daily profiles for the twelve months of 2011. Such profiles are indicated with the letter LP_i, with i = January and December; these months are clearly very similar, with the exception of the LP_{aug} profile of August when the electricity consumption is much lower than the consumption measured in the remaining months. Fig. 4a also shows the standard deviation σ_i to quantify the dispersion of the 96 daily measured values; for all months in 2011, the standard deviation is approximately 2.5 kW during the night and approximately 7 kW during the daytime. The black line LP_{ave} of Fig. 4a is the average value of the LP_i profiles, while the dotted black line of σ_{ave} is the corresponding standard deviation; the latter line is clearly close to zero.

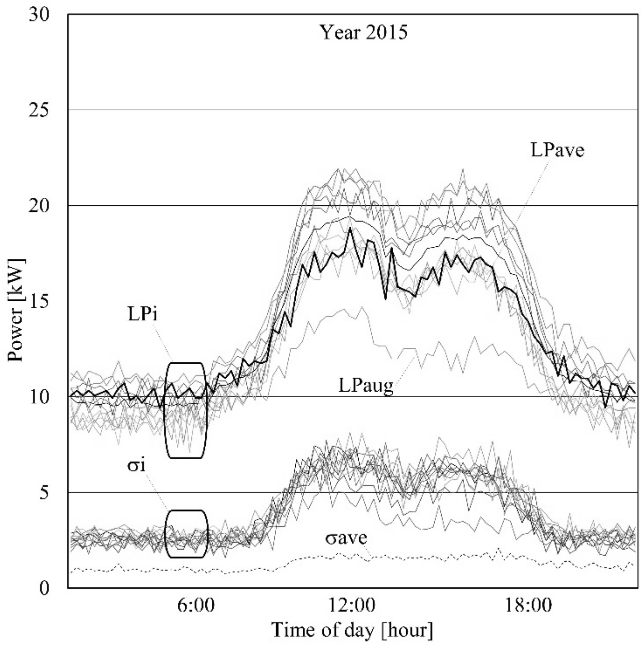
Figure 4b relates to the data measured in 2013. The average profile for July stands out because the electric power consumption is greater than in all other months; on the contrary, the average profile of August stands out because the electric power consumption is the lowest of all months, exactly as in 2011. Fig. 4c relates to the data measured in 2015. The August profile still stands out because it is the lowest of all months. When observing Figs. 4a, 4b and 4c together, it is clear that the average profiles and the standard deviation values are repeated by year in a strongly similar way, thus confirming that the 2011 data are representative of the long term.



a)



b)



c)

Fig. 4 Daily average load profiles and standard deviation in a) 2011, b) 2013 and c) 2015

At the end of this section, the authors calculate the distribution of the consumption of electrical energy between the three time-ranges F1, F2 and F3. As reported in the first row of Tab. 2, in 2011 from Monday to Saturday, 36.66% of the electricity consumption is in the F1 range, while 19.13% and 29.17% are in the ranges of F2 and F3, respectively. Sundays and holidays account for approximately 15% of the annual consumption. The remaining rows of Tab. 2 show the distribution of energy consumption from 2012 to 2015; such distributions are very similar to the distribution calculated in 2011. The values of Tab. 2 clearly confirm the necessity of investigating the impact of the movement of electricity prices in the economic evaluation of the integrated PV-BES system, as 37.60% and 38.15% of the energy consumption during the 2014 and 2015 were measured during the peak-load and, precisely during 2014-2015, the peak-load price collapsed below the off-peak price.

Table II – Distribution of electric energy consumption

	From Monday to Saturday			On Sunday and Holidays		
	F1	F2	F3	F1	F2	F3
2011	36.66	19.13	29.17	8.55	2.50	3.97
2012	31.44	21.82	34.87	5.95	2.27	3.63
2013	33.92	21.99	32.05	6.20	2.13	3.69
2014	37.60	17.95	28.61	9.36	2.61	3.84
2015	38.15	18.29	28.45	8.88	2.33	3.88

4. Numerical Results

In this section, the authors present the optimal solution returned by the optimization problem that was presented in section 2 for the case study described in section 3.1. It is worth noting that this solution is calculated using the measurements of energy consumption and electricity prices of 2011. Later, this solution is applied to the case study but uses data from 2012 to 2015.

This section ends with an assessment of the productivity of the battery energy storage system and the different contributions of the batteries during the months of the year. Finally, the 25% electricity self-sufficiency that is achieved by the end-user due to the integrated PV-BES system is discussed, along with a brief insight on the impact of the optimal solution on the user profile from the grid point of view.

4.1 The optimal sizing of the S-FIT incentive and the PV-BES system using data measured in 2011 and its application over four years, 2012-2015

The optimal solution returned by the optimization problem using 2011 data is as follows: an incentive equal to S-FIT=0.117c€/kWh, a photovoltaic plant with peak power equal to PV=45.90 kW, and a battery storage system with a storage capacity equal to BES=41.56 kWh. The authors approximate the optimal solution as follows: PV=50 kWp and BES 50 kWh. Consequently, the incentive is recalculated to comply with the constraints of the model and is S-FIT=0.126c€/kWh.

It is worth remembering that the rated power of the battery storage system is not a decision variable; the authors pragmatically set the rated power of the batteries equal to 50 kW because this value is the peak power of the PV system and is also a value that is close to the maximum power required by the user in 2011.

Table III – Economic and operational results from 2011 to 2015

			2011	2012	2013	2014	2015
Economic	$Bill_{w/out\ PV\text{-}BES}$	[€]	18560.92	19084.25	17005.60	15109.81	13571.97
	$Bill_{with\ PV\text{-}BES}$	[€]	9381.10	8957.72	9189.72	10007.35	8315.31
	Saving	[€]	9179.82	10126.53	7815.88	5102.46	5256.66
	Saving	[%]	49.46	53.06	45.96	33.77	38.73
	Inst(PV)	[€]	11655.41	11655.41	11655.41	11655.41	11655.41
	Inst(BES)	[€]	5180.18	5180.18	5180.18	5180.18	5180.18
	Subsidy	[€]	7655.77	7700.80	7211.96	7237.40	7017.23
	Balance	[€]	0.00	991.73	-1807.75	-4495.74	-4561.70
Operation	E_{load}	[MWh]	133.95	120.69	113.97	117.96	115.30
	E_{PV}	[MWh]	72.95	74.06	73.37	71.16	75.20
	E_{BES}	[MWh]	9.71	12.34	12.65	12.10	9.31
	E_a	[MWh]	73.48	59.86	57.00	60.79	64.76
	E_d	[MWh]	12.52	13.29	16.45	14.04	12.01
	Generation/demand	[%]	54.46	61.37	64.38	60.33	65.22
	Self-consumption	[%]	82.83	82.06	77.58	80.27	84.03

The economic and the operation results from 2011 to 2015 when the solution (PV; BES; S-FIT) = (50; 50; 0126) is adopted are reported in Tab. III. As shown in the first column, in 2011, the electric bill without the PV-BES system is equal to €18,560.92 while it decreases to €9,381.10 in the presence of the PV-BES system. Savings of €9,179.82 or 49.46% is thus achieved. Given these savings, the end user pays two instalments, one for the photovoltaic system and one for the battery storage system; the instalments amounted to €11,655.41 and €5,180.18, respectively. Since the user receives a subsidy equal to €7,655.77, a balance of €0.00 is achieved as desired and requested. Because the variable *Balance* is the sum of the expected cash flows from operations, the end user is not exposed to any economic risk or benefit; therefore, the net present value of the investment equals zero.

The last seven rows of Tab. III report the operation results for the case study.

The electricity demand in 2011 is 133.95 MWh, the photovoltaic system produces 72.95 kWh, while the batteries store 73.48 MWh; as a result, the energy absorbed by the distribution grid is 73.48 MWh, while the energy delivered to the distribution grid is 12.52 MWh. At the end of 2011, self-generation and the self-consumption amounted to 54.46% and 82.83%, respectively.

The remaining four columns of Table III report the economic and the operation results from 2012 to 2015 when the solution (PV; BES; S-FIT) = (50; 50; 0126) is adopted.

Therefore, upon scrolling through the values of the first row, it can be seen that as a consequence of the progressive fall in peak-load electricity prices — as discussed in section 3.5 and as shown in Fig. 3 — the electric bill without the PV-BES system decreases considerably from €18,560.92 in 2011 to €13,571.97 in 2015. In particular, assuming the 2011 bill as a base unit quantity, the bills from 2012 to 2015 are 1.2, 0.91, 0.81 and 0.73. Therefore, in five years, the electric bill decreases almost linearly by 27%.

Even the electric bill with the PV-BES system decreases in the period 2011-2015. Assuming the 2011 bill as a base unit quantity, the bills from 2012 to 2015 are 0.95, 0.97, 6.1 and 0.88; therefore, in five years, the electric bill decreases almost linearly by 22%.

The final conclusion of this section relates to the balance, which is the algebraic sum of the savings, the subsidy and the instalments. In 2011, the balance is zero because the optimal solution was calculated using 2011 data, and Eq. (2) of the optimization problem requires that the balance equal zero. In 2012, the balance is a positive number and amounts to €991.73. On the contrary, in later years, the balance becomes negative, indicating that the subsidy and savings do not pay for the instalments of the PV-BES system. By year, the user contracts a debt of €1807.75 in 2013, €4495.74 in 2014 and €4341.53 in 2015. The total debt amounted to €9,653.29, which is 26.21% of the subsidy that the end user receives in the period 2011-2015.

4.2 Storage productivity, profitable storage.

To evaluate the productivity of the battery energy storage system and its profitability, the economic and operational results of the case study are calculated again, but in the absence of the battery storage system because only the photovoltaic system is adopted. The incentive is also calculated again, and it is 0.077€/ kWh instead of 0.126€/kWh.

Table IV - Economic and operational results with and without the battery storage system

			2011-2015	
			with PV	with PV and BES
	PV	[kWp]	50.00	50.00
	BES	[kWh]	0.00	50.00
	S-FIT	[€/kWh]	0.077	0.126
Economic	Bill *w/out PV-BES*	[€]	83332.55	83332.55
	Bill *with PV-BES*	[€]	55289.28	45851.20
	Saving	[€]	28043.27	37481.35
	Saving	[%]	33.65	44.98
	Inst(PV)	[€]	58277.06	58277.06
	Inst(BES)	[€]	0.00	25900.91
	Subsidy	[€]	17934.18	37043.34
	Balance	[€]	-12299.66	-9653.29
Operation	E_{load}	[MWh]	601.87	601.87
	E_{PV}	[MWh]	348.75	348.75
	E_{BES}	[MWh]	0.00	56.11
	E_a	[MWh]	362.70	315.90
	E_d	[MWh]	109.58	62.96
	Generation/demand	[%]	57.94	57.94
	Self-consumption	[%]	68.58	81.95

Table IV reports the sum of the economic and operational results of the case study for all the five years, from 2011 to 2015; more precisely, the third column reports the numerical results when the solution (PV; BES; S-FIT) = (50; 50; 0.126) is adopted, while the fourth column reports the numerical results when the solution (PV; BES; S-FIT) = (50; 0; 0.077) is adopted.

The sum of the electric bills without the PV-BES system for the years 2011-2015 is €83,332.55. This amount decreases to €55,289.28 when only the PV system is adopted, while it further decreases to €45,851.20 when even the batteries are adopted. This latter decrease demonstrates that the installation of batteries generates value; in fact, the percentage saving increases from 33.65% to 44.98%. Furthermore, the subsidy granted to the user increases from €17,934.18 when the PV system is adopted to more than double that figure when the batteries integrate the photovoltaic system.

Moreover, the balance is €-12299.66 in the presence of the photovoltaic system, while it decreases to €-9653.29 in the presence of the integrated PV-BES system.

With regard to the operational results, the battery storage system allows the user to achieve an important goal: the energy generated by the photovoltaic system that is fed into the grid is 62.96 MWh instead 109.58 MWh; therefore, self-consumption amounts to 81.95% in the presence of storage instead of 68.58%, which is in the presence of the PV system only.

4.3 Battery usage and impact of the integrated system from the grid point of view

This article ends with an assessment of the impact of the integrated PV-BES system on the load profile from the grid point of view; in particular, this assessment illustrates how the contribution of the batteries varies over the months of the year and highlights the satisfactory 25% self-sufficiency achieved by the end user.

As a result of the adoption of the integrated PV-BES system, the load profile of the end user from the point of view of the grid necessarily changes as a function of the size of the photovoltaic system and the battery energy storage system. For example, the average daily load profiles of January, March, July and October in 2011 are plotted in Fig. 5; these profiles are obtained by calculating the arithmetic mean of the daily energy consumption that is measured every 15 minutes. The dashed black line is the load profile in the absence of an integrated PV-BES system, the grey solid line is the load profile as amended by the adoption of a 50 kWp PV system, while the black solid line is the load profile as amended by the adoption of the storage battery system 50 kWh, in addition to the photovoltaic system.

The area between the black line and the grey line is the renewable electric energy stored in the batteries; this area provides an idea of the contribution of the batteries to self-consumption; therefore, the larger this area is, the more relevant the use of the batteries is and vice versa. For example, regarding the average load profiles illustrated in Fig. 5, the use of the batteries is of limited relevance in January since the batteries accumulate 9.58 kWh/day or a value that is approximately equal to 20% of the battery storage capacity. In March and October, the use of the batteries increases when compared to January; in fact, the stored energy is equal to 21.42 kWh/day and 24.51 kWh/day, respectively. In

July, the contribution to self-consumption provided by the use of the batteries is certainly significant because they accumulate 35.02 kWh/day or a value close to 70% of the battery storage capacity.

In summary, the monthly stored and self-consumed energy equals 296.98 kWh in January, 664.02 kWh in March, 755.81 in October and 1085.62 in July. If the same calculation is executed using data measured every 15 minutes instead of the average profiles of Fig. 5, the monthly stored and self-consumed energy increases slightly and amounts to 385.71 kWh in January, 735.30 kWh in March, 773.27 in October and 1220.17 in July.

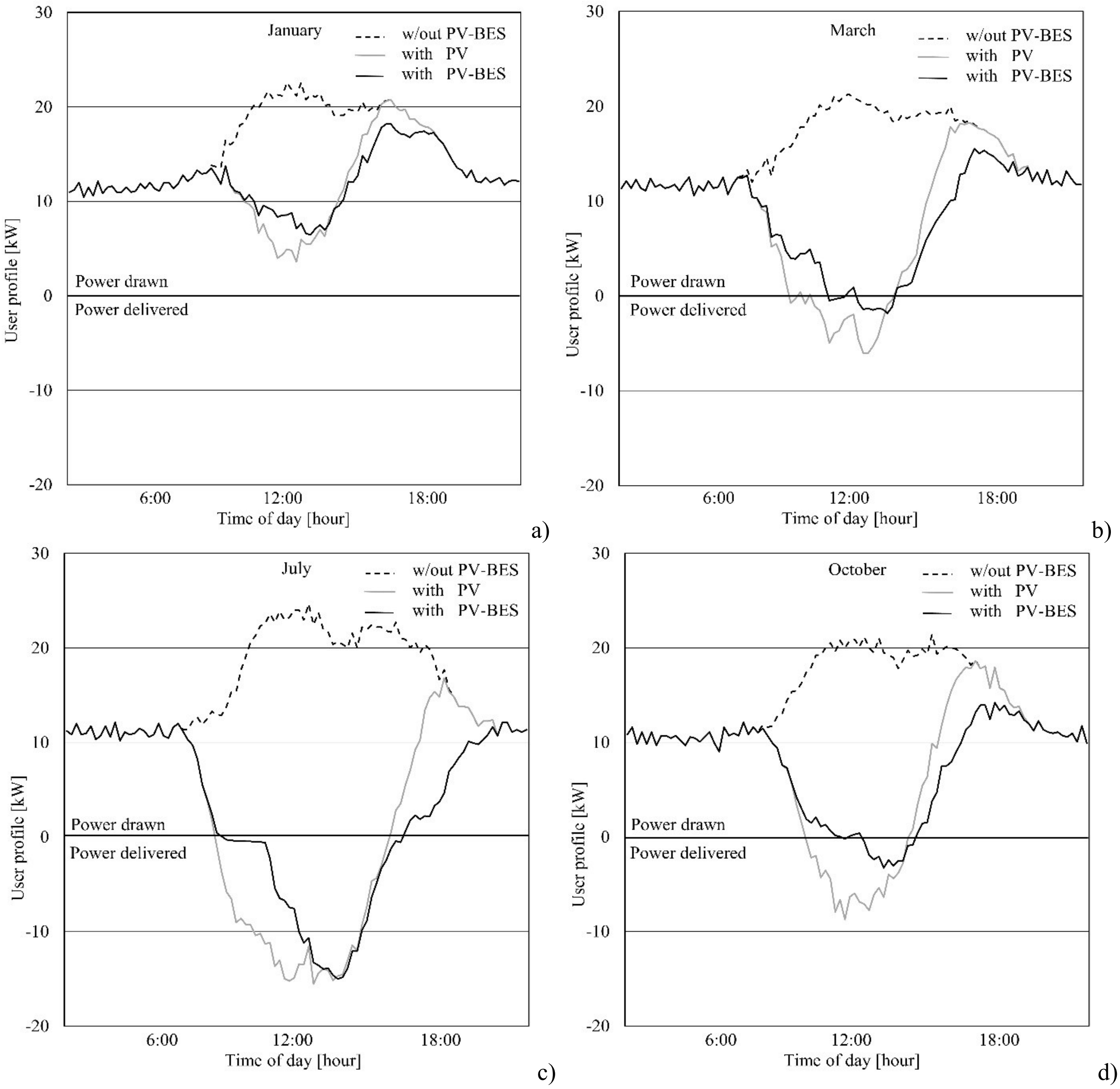


Fig. 5 Average load profiles in January, March, July and October

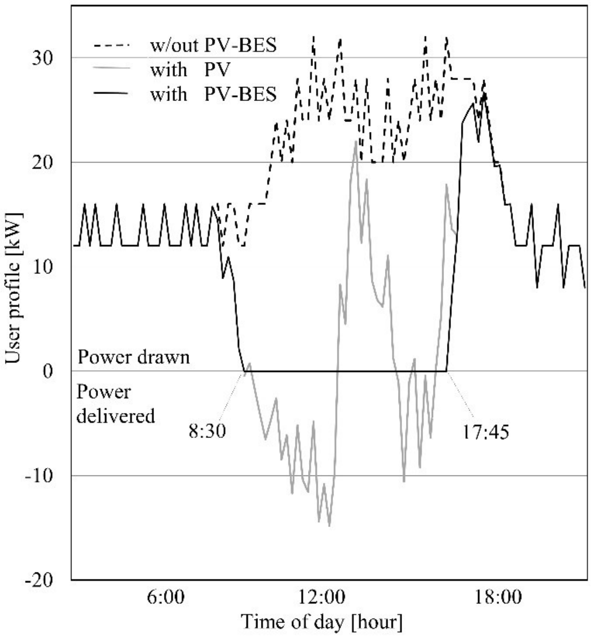


Fig. 6 Load profiles of 8th July 2011

To further investigate the impact of the integrated PV-BES system on the load profile from the grid point of view, the recurrences of the measurements of the energy absorbed from the grid every 15 minutes are now assessed. Fig. 6 illustrates the load profile of 8th July 2011 when, due to the adoption of the integrated PV-BES system, the load profile is zero from 8:30 to approximately 17:45, thus indicating that the user is energy self-sufficient for almost all daylight hours. On that day, the measurement of 0 kWh recurs 40%, while it never recurs in the absence of the integrated system. Recurrences of measurements for the five years from 2011 to 2015 are shown in Tab. V, distinguishing between the absence (w/out) and the presence (with) of the PV-BES system.

Table V - Recurrences of measurements of the energy absorbed from the grid

			Energy measurement [kWh]										
			0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Recurrences [%]	2011	w/out	0.00	0.13	18.50	34.25	18.78	10.87	10.98	5.06	1.26	0.16	0.01
		with	23.05	0.12	13.95	22.66	9.27	2.45	1.47	0.38	0.03	0.00	0.00
	2012	w/out	0.00	3.82	24.37	33.80	15.33	11.49	7.63	2.69	0.67	0.17	0.01
		with	27.11	2.63	15.87	20.51	5.59	1.52	0.67	0.14	0.03	0.00	0.00
	2013	w/out	0.00	8.27	28.14	29.81	12.57	10.78	6.99	2.45	0.80	0.17	0.01
		with	26.17	5.65	18.01	17.89	3.81	1.15	0.56	0.10	0.04	0.01	0.00
	2014	w/out	0.01	5.05	24.00	37.72	9.67	12.53	8.28	2.56	0.18	0.01	0.00
		with	25.75	3.61	15.97	22.91	2.98	1.56	0.77	0.26	0.01	0.00	0.00
	2015	w/out	0.00	4.32	23.75	33.90	14.09	11.42	8.47	3.19	0.73	0.13	0.01
		with	25.52	3.00	15.95	20.99	5.41	1.67	0.87	0.22	0.03	0.00	0.00

As reported in the first row of Tab. V, the measurements that occur most frequently in 2011 are 3 kWh (34.25%), 2 kWh (18.50%) and 4 kWh (18.78%), whereas the measurement of 0 kWh never occurs. The adoption of the integrated PV-BES system reduces all instances of the first row with the exception of 0 kWh, which, as in the second row, is the most common measurement (23.05%). Similarly, 0 kWh is the measurement that occurs most frequently even in the four years from 2012 to 2015, when the integrated PV-BES is adopted. On average, the end user shows complete electric energy self-sufficiency for about a quarter of the time.

In addition to the significant self-sufficiency described above, the adoption of the combined PV-BES system also provides benefits to the local distributor because the PV-BES system provides renewable energy, especially during peak hours. Additionally, it reduces power losses, and the voltage drops along the electric lines; consequently, it reduces the operating costs of the electrical system.

5. CONCLUSION

A feed-in tariff scheme for promoting the integrated photovoltaic battery (PV-BES) systems for grid-connected end users has been discussed. This scheme, S-FIT, solely rewards self-consumption, which is calculated as the difference between the energy produced by the photovoltaic system and the energy delivered to the grid over a short time interval, e.g., 15 minutes. Zero is the generation price; zero is the export price; the net-metering service is excluded; and the grid does not recharge or discharge the batteries.

An optimization problem was used to determine the incentive and optimal sizes of the photovoltaic and battery energy storage systems. The incentive was calculated so that the yearly subsidy equals the difference between the instalments paid for the integrated PV-BES and the savings obtained from the electricity bill. The sizes of the photovoltaic 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%.

The S-FIT scheme, together with the integrated PV-BES system, was applied to the case of an Italian Public Administration building from 2011 to 2015. Real values of temperature, irradiation, energy consumption and electricity prices were considered.

The numerical results demonstrated that the S-FIT scheme for an integrated PV-BES system is feasible and advantageous because the electricity bill in 2011 was reduced by 49.56%. Moreover, the yearly subsidy received by the end user is lower than the instalments paid for the integrated PV-BES system; therefore, the adoption of the S-FIT scheme has a positive socio-economic impact.

The optimal solution calculated using the 2011 data was applied to the years 2012 to 2015 to evaluate the scheme response to a radical change in electricity prices — namely, the collapse of the electricity peak-load price. The numerical results showed that the S-FIT scheme and the integrated PV-BES system also allow a reduction of the electricity bill in the presence of this radical change in electricity prices. The reduction equals 44.98% when the PV-BES system is adopted, whereas it equals 33.65% when only the photovoltaic system is adopted.

This article ends with an assessment of the impact of the integrated PV-BES system on the load profile from the grid point of view; in particular, this assessment illustrates how the contribution of the batteries varies over the months of the year and highlights the 25% self-sufficiency achieved by the end user.

ACKNOWLEDGEMENTS

This work was financed by the Italian Ministry of Economic Development (MISE) and the Ministry of Education, University and Research (MIUR) through the National Operational Program for Development and Competitiveness 2007-2013, Project DOMUS PON 03PE_00050_2.

REFERENCES

[1] McKenna E, McManus M, Cooper S, Thomson M. Economic and environmental impact of lead-acid batteries in grid-connected domestic PV systems. Appl Energy 2013;104:239–49. doi:10.1016/j.apenergy.2012.11.016.

[2] Braun M, Büdenbender K, Magnor D JA. Photovoltaic Self-Consumption in Germany - Using Lithium-Ion Storage to Increase Self-Consumed Photovoltaic Energy. 24th Eur. Photovolt. Sol. Energy Conf. Exhib. Hamburg, 21.-25.09.2009, 2009. doi:10.1017/CBO9781107415324.004.

[3] Hoppmann J, Volland J, Schmidt TS, Hoffmann VH. The economic viability of battery storage for residential solar photovoltaic systems - A review and a simulation model. Renew Sustain Energy Rev 2014;39:1101–18. doi:10.1016/j.rser.2014.07.068.

[4] J. Weniger, J. Bergner, T. Tjaden VQ. Economics of Residential PV Battery Systems in the Self-Consumption Age. 29th EU-PVSEC 2014:3871–7. doi:10.4229/EUPVSEC20142014-7DO.14.3.

[5] Linssen J, Stenzel P, Fleer J. Techno-economic analysis of photovoltaic battery systems and the influence of different consumer load profiles. Appl Energy 2015. doi:10.1016/j.apenergy.2015.11.088.

[6] Merei G, Moshövel J, Magnor D, Sauer DU. Optimization of self-consumption and techno-economic analysis of PV-battery systems in commercial applications. Appl Energy 2016;168:171–8. doi:10.1016/j.apenergy.2016.01.083.

[7] Mulder G, Six D, Claessens B, Broes T, Omar N, Mierlo J Van. The dimensioning of PV-battery systems depending on the incentive and selling price conditions. Appl Energy 2013;111:1126–35. doi:10.1016/j.apenergy.2013.03.059.

[8] ANIE R. I sistemi di accumulo nel settore elettrico 2015.

[9] Krajačić G, Duić N, Tsikalakis A, Zoulias M, Caralis G, Panteri E, et al. Feed-in tariffs for promotion of energy storage technologies. Energy Policy 2011;39:1410–25. doi:10.1016/j.enpol.2010.12.013.

[10] Ratnam EL, Weller SR, Kellett CM. An optimization-based approach to scheduling residential battery storage with solar PV: Assessing customer benefit. Renew Energy 2015;75:123–34. doi:10.1016/j.renene.2014.09.008.

[11] Ratnam EL, Weller SR, Kellett CM. Scheduling residential battery storage with solar PV: Assessing the benefits of net metering. Appl Energy 2015;155:881–91. doi:10.1016/j.apenergy.2015.06.061.

[12] Santos JM, Moura PS, Almeida AT de. Technical and economic impact of residential electricity storage at local and grid level for Portugal. Appl Energy 2014;128:254–64. doi:10.1016/j.apenergy.2014.04.054.
[13] Couture T, Gagnon Y. An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. Energy Policy 2010;38:955–65. doi:10.1016/j.enpol.2009.10.047.
[14] Sun P, Nie P yan. A comparative study of feed-in tariff and renewable portfolio standard policy in renewable energy industry. Renew Energy 2015;74:255–62. doi:10.1016/j.renene.2014.08.027.
[15] Ritzenhofen I, Spinler S. Optimal design of feed-in-tariffs to stimulate renewable energy investments under regulatory uncertainty - A real options analysis. Energy Econ 2016;53:76–89. doi:10.1016/j.eneco.2014.12.008.
[16] International Energy Agency. World Energy Outlook. 2015. doi:10.1787/weo-2014-en.
[17] Sioshansi FP. Menlo Energy Economics - EEnergy Informer 2016:1–28.
[18] Ru Y, Kleissl J, Martinez S. Storage Size Determination for Grid-Connected Photovoltaic Systems. IEEE Trans Sustain Energy 2013;4:68–81. doi:10.1109/TSTE.2012.2199339.
[19] Divya KC, Ostergaard J. Battery energy storage technology for power systems-An overview. Electr Power Syst Res 2009;79:511–20. doi:10.1016/j.epsr.2008.09.017.