Optimal Size of Photovoltaic Systems with Storage for Office and Residential Loads in the Italian Net-Billing Scheme

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***Abstract*— This paper deals with energy and economic analysis of grid-connected photovoltaic (PV) systems with storage. According to the current Italian market rules, the first goal is to calculate the capacities of PV systems and batteries corresponding to the cost-optimal solution. Then, cost-effective solutions are investigated to maximize self-consumption, minimizing grid injections. Simulations are performed for one year, starting from irradiance data and load profiles from office and dwelling house users in Italy.**

***Index Terms*-- Photovoltaic systems; Lithium batteries; Optimization; Simulation; Cost.**

NOMENCLATURE

C_{ssp}	Contribution paid by GSE to prosumers (€/year)
C_{abs}	Economic value of annual absorbed energy (€/year)
$C_{bat,r}$	Battery rated capacity (Ah, kWh)
C_{cons}	Cost of energy in electricity bill (€/year)
C_{inj}	Economic value of annual injected energy (€/year)
C_{fix}	Fixed cost in electricity bill (€/year)
C_{grid}	Economic value of grid use, related to E_{exc} (€/year)
C_{power}	Cost of contracted power in electricity bill (€/year)
c_{abs}	Specific cost of abs. energy in Net-Billing scheme (c€/kWh)
c_{cons}	Specific cost of absorbed energy in electricity bill (c€/kWh)
c_{inj}	Specific cost of injected energy (c€/kWh)
c_{grid}	Specific cost of grid use (c€/kWh)
c_Q	Quadratic loss coefficient (kW)
Δt	Time step simulation (min)
E_{abs}	Annual absorbed energy (kWh)
E_{bat_life}	Energy supplied by batteries in their total life (kWh)
E_{PV}	Annual energy production from the PV plant (kWh)
E_{inj}	Annual energy injection in the grid (kWh)
E_{exc}	Annual energy exchanged with the grid (kWh)
E_{sc}	Annual self-consumed energy (kWh)
i	Interest rate
η_{bat}	Charge/discharge batteries efficiency
N_{cycles}	Batteries cycles in their total life
P_{bat}	Batteries active power (kW)
P_{bat_max}	Maximum battery power (kW)
P_{cont}	Contracted power (kW)
P_{dc}	Inverter power at DC side (kW)
P_{grid}	Grid active power (kW)
P_{PV}	PV active power (kW)
$P_{PV,r}$	PV rated power (kW)

P_{load}	Load active power (kW)
R_t	annual net cash flow (€)
SOC	State of charge (p.u.)
$V_{bat,r}$	Battery rated voltage (V)

I. INTRODUCTION

In recent years, PV systems with storage are rapidly increasing, due to the reduction of installation costs and the increase of efficiencies [1]. According to the load to serve (in the present paper offices and residential loads), users generally decide the plant size in order to find the cost-optimal solution.

An oversized grid-connected plant has lower specific installation cost and permits to reach a high self-consumption with respect to the consumption. Nevertheless, a too large generator could inject excessive power into the grid. Some existing billing schemes discourage the installation of generators not designed to well match the users' loads. The reason is that these generators can create bidirectional power flows not easy to manage in traditional grids [2].

The cost-optimal solution strongly depends on the initial investment and on the compromise between cost-effectiveness of self-consumption and low price for grid injection. For a correct sizing, it becomes necessary to simulate the energy production, the storage operation and the interaction with the grid.

The next sections of this paper are organized as follows. Section II presents an overview on promotion methods for self-consumption, with details on the Net-billing Scheme in the Italian Electricity Market. The power flow management of the Photovoltaic (PV) system with storage is described in Section III. The simulation procedure is discussed in Section IV. Section V presents the simulation results. The last section contains the conclusions.

II. COST ANALYSIS

A. *Promotion of self-consumption in European Electricity Markets*

The promotion of self-consumption of PV energy is generally based on the idea that electricity should be mainly used for local loads and not injected into the grid. The compensation is performed in different ways depending on used options and countries [3]. A first distinction is based on compensation time. The mechanisms created to compensate for production and consumption of energy in real time (or up to 15 minutes) are named "self-consumption schemes". If the compensation occurs in a larger time frame, they are "net-metering schemes". Another methodology is the compensation on cash-flow basis (rather than on an energy basis): in this situation, the mechanism is called "net-billing scheme". In some cases, the promotion programs are hybrids of the abovementioned main schemes. In most European countries, self-consumption is permitted, with different rules and cost-effectiveness. For example, in France, self-consumption of PV energy is less convenient than in other EU countries, because retail prices are low. The diffusion of PV systems is mainly driven by feed in tariffs (with a maximum duration of 20 years) rather than self-consumption. There are no limits for the size of the PV plants that may access to incentives, nevertheless the energy compensation is only made in real-time and it is not possible to sell PV energy to other users. In Germany, the injection of PV energy is paid with a feed-in tariff scheme and a *self-consumption scheme* works. The energy compensation is performed in real time and it is not possible to sell PV energy to other users. Furthermore, an energy storage incentive program supports new systems up to 30 kW. On the contrary, in Italy, a net billing system (based on compensation during the whole year) is currently working for PV systems up to 500 kW. There are no feed-in tariffs for new PV plants, but there are new rules that allow, in certain situations, selling energy by private distribution lines. More details about the Italian electricity bills and net billing system are presented in next subsection.

B. *Electricity Bill in the Italian Electricity Market*

The Italian electric bill includes many items: in addition to energy costs, there are those associated with the usage of the network, commercialization costs and taxes. One of them depends on the consumption, others are calculated on the basis of different parameters. For the sake of simplicity, the bill cost C_{bill} can be evaluated considering only four parameters.

$$C_{bill} = C_{fix} + C_{cons} + C_{power} + C_{taxes} \qquad (1)$$

The first quota C_{fix} is fixed, the second item is proportional to energy consumption $C_{cons}=c_{cons}\cdot E_{abs}$ and the third depends on contracted power $C_{power}=c_{power}\cdot P_{cont}$. The last parameter is taxation C_{taxes}.

For a residential user with contracted power ≤3kW and a consumption of ≈3500 kWh (typical for a family composed of 4-5 persons), the percentages (with respect to C_{bill}) are the following: the greatest quota is C_{cons}≈ 70%, the fixed cost C_{fix} ≈5% and the cost of contracted power C_{power} is ≈4%. Taxes correspond to ≈20% of the bill.

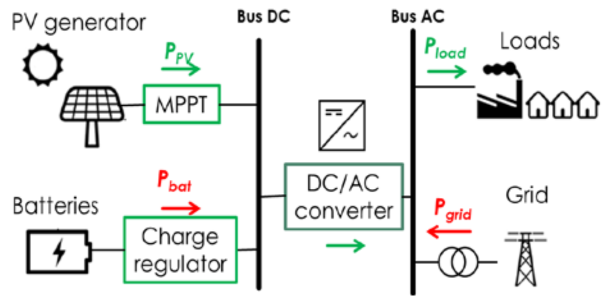

Fig. 3. Scheme of the PV-storage system with its power flows.

C. Net-billing Scheme in the Italian Electricity Market

In Italy, the Energy Services Operator (GSE) is the state-owned company promoting RES [4]. It encourages users to install systems producing an amount of electricity lower than the electricity consumed during the year, with specific rates and rules, depending on the capacity installed.

PV plants with a capacity <500 kW can access to a simplified net billing service called *On-site exchange* ("*Scambio sul posto*"). Under this service, the electricity generated by a prosumer and injected into the grid can be used to offset the annual electricity absorption from the grid.

Like the traditional users, the prosumer pays the absorption from the grid every two months. At the end of the year, GSE pays a contribution (C_{ssp}) to the prosumer based on injections (E_{inj}) and withdrawals (E_{abs}) of electrical energy. The economic values (respectively C_{inj} and C_{abs}) of annual absorbed and injected energy are calculated as:

$$C_{inj} = E_{inj} \cdot c_{inj} \tag{2}$$

$$C_{abs} = E_{abs} \cdot c_{abs} \tag{3}$$

where c_{abs} is the specific cost (c€/kWh) of absorbed energy and c_{inj} is the specific price (c€/kWh) of injected energy. The value of c_{abs} is calculated as the average of national market prices occurred each month in every region during the previous year. The current value is c_{abs}=5.2 c€/kWh [4] and it is independent on E_{abs}. The value c_{inj} (c€/kWh) of injected energy depends on the average sale price in the day-ahead market in the geographical areas. In Italy, it ranges from 4.9 to 5.7 c€/kWh (the highest prices occur in the islands) [4]. GSE refunds the user with the lower value between C_{inj} and C_{abs}. In addition, GSE returns the costs for network use C_{grid}, related to the minimum energy between absorption and injection:

$$C_{grid} = E_{exc} \cdot c_{grid} = \min\{E_{abs}, E_{inj}\} \cdot c_{grid} \tag{4}$$

where c_{grid} is the specific cost (c€/kWh) of the use of the grid. In particular, it includes transmission, dispatch and distribution cost and most of the other charges normally present in the electric bill. It strongly depends on the quantity of energy exchanged with grid and on the user type (c_{grid} ranges from 6.0 c€/kWh to 22.4 for residential users) [5]. Taxes are not returned. The final formula used to determine C_{ssp} is:

$$C_{ssp} = \min\{C_{inj}, C_{abs}\} + C_{grid} \tag{5}$$

The users who maximize self-consumption and minimize the injection into the grid by appropriate RES and storage have the highest economic profit. For example, a residential user consuming 3000 kWh/year decides to install a new PV generator to reduce grid absorption. The plant produces E_{PV}=2700 kWh/year: one third is self-consumed (E_{sc}=900 kWh) and the remaining part is injected in the grid. As described in Fig. 1, at the end of the year, the energy balance has E_{inj}=1800 kWh and E_{abs}=2100 kWh. The additional net absorption from the grid is equal to 300 kWh. If c_{inj} =5.1 c€/kWh, the economic values of energy flows are respectively C_{inj} ≈92 € and C_{abs}≈107 €. The GSE pays the minimum (≈92 €) and also refunds the grid cost C_{grid}≈120 €, related to exchanged energy E_{exc}=1800 kWh (c_{grid} ≈6.7 c€/kWh). In this case, the total refund C_{ssp} is equal to ≈212 €.

Since the specific costs of injection and absorption are similar for residential users, the energy exchange with the grid is mainly affected by the missing refund of taxes. Infact, taxes are paid by the user for purchased energy (C_{taxes}), but C_{ssp} does not include them.

When calculating the Net Present Value (NPV), C_{ssp} is not the only positive cash flow, because also the saving due to self-consumption must be considered. Fig. 2 shows the annual cash flows of the prosumer (described above) with respect to a traditional consumer with the same electricity demand. The consumer pays ≈600 € (≈19 c€/kWh). The prosumer, thanks to self-consumption, reduces the bill down to ≈420 € and receives by GSE ≈200 €. The total saving for the prosumer corresponds to ≈380 €, (more than 60% of the bill of the traditional consumer).

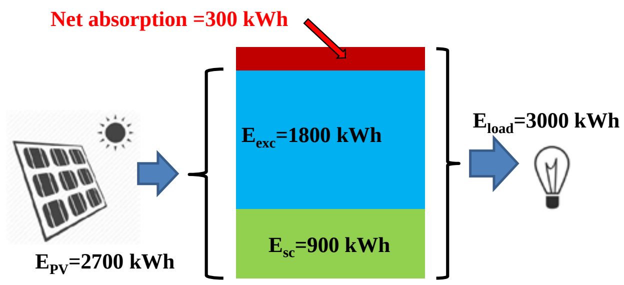

Fig.1. Example of annual energy balance for a residential prosumer

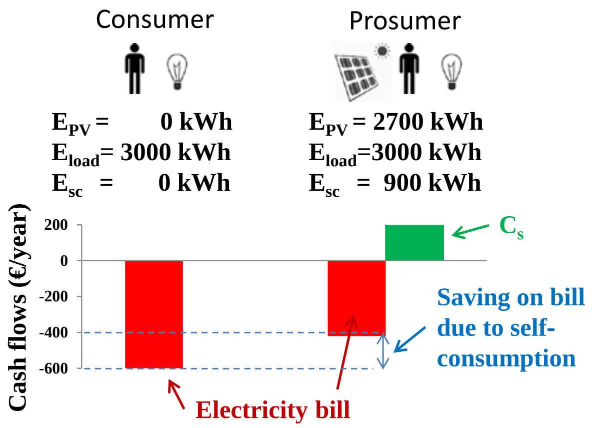

Fig. 2. Consumer vs. prosumer: economic annual balance

D. Other incentives to encourage PV system installations

The Decree-Law N° 83, 22 June 2012 and extensions defined an additional incentive for small PV plants [6]. Plants with a capacity <20 kW can currently take advantage of a tax credit that can be claimed on income taxes for 5% of the cost of a PV system for a total of 10 years. The conditions to access to the tax credit are the followings: the PV system must be used to feed residential loads and the maximum amount that can be claimed is 96 k€. The tax credit is consistent with the *On-site exchange* net metering service.

As mentioned before, only plants with a capacity <500 kW can access to the net metering service. The other plants can access to a simplified purchase and resale arrangement called *Dedicated withdrawal* (“*Ritiro dedicato*”). In this case, the price paid to the user for the electricity injection into the grid [7], is ≈4 c€/kWh, while the average cost of electricity, for the tertiary sector, is ≈20 c€/kWh.

III. System Architecture

A. Presentation of the System

The main components of the simulated system are shown in Fig. 3: the PV generator, batteries, power electronic converters, user loads and distribution grid. The core of the system is the DC bus, which connects the PV output at the voltage imposed by the batteries. An uni-directional inverter provides AC energy to supply the user loads, or to sells energy to the grid if the production from PV exceeds the local loads. The batteries are discharged only when the renewable power production is lower than the loads. A DC/DC converter works to track the Maximum Power Point (MPP) for the PV System.

B. Power Flow Calculation

The power balance in the PV system with batteries is written neglecting the conversion losses into the DC/AC converter, in which losses are generally lower than 3% of the rated power.

The arrows indicate the direction of the power flows: the PV active power (P_{PV}) is always positive, while the active powers of batteries and grid (P_{bat} and P_{grid}) may be negative when they absorb.

Only the active power balance is discussed here. The power-flow calculation is performed every minute (Δt=1 min) with the procedure shown in Fig. 4, including five main steps:

- Step #1: comparison between PV production and load, with overproduction ($P_{PV}(t)>P_{load}(t)$) or deficit ($P_{PV}(t)<P_{load}(t)$).
- Step #2: calculation of the maximum energy flows from or to the storage according with its State Of Charge ($SOC(t)$). In order to extend the battery life, SOC must be maintained within appropriate limits as in (6). If the battery is full, the difference between limits corresponds to the energy available in the discharge phase, calculated as the product of rated voltage $V_{bat,r}$ and rated capacity $C_{bat,r}$ in ampere-hours.

$$SOC_{\min} \le SOC(t) \le SOC_{\max}$$

  Another limit in batteries operation is the maximum power P_{bat_max} that can be extracted: according to manufacturer’s specification, it is never exceeded.
- Step #3: if the PV generation does not match the load and $SOC(t)$ is within the limits, the batteries can be discharged to help to feed the load (P_{bat}>0) or can be charged (P_{bat}<0) in case of overproduction from PV. If local storage does not work, because its SOC is outside limits, this step is skipped (P_{bat}=0).
- Step #4: the local storage alone cannot balance PV and loads energy flows. Grid injection (P_{grid}<0) or absorption (P_{grid}<0) is calculated.
- Step #5: $SOC(t+1)$ of storage is calculated by (7) taking into account only the charge/discharge efficiency η_{bat}:

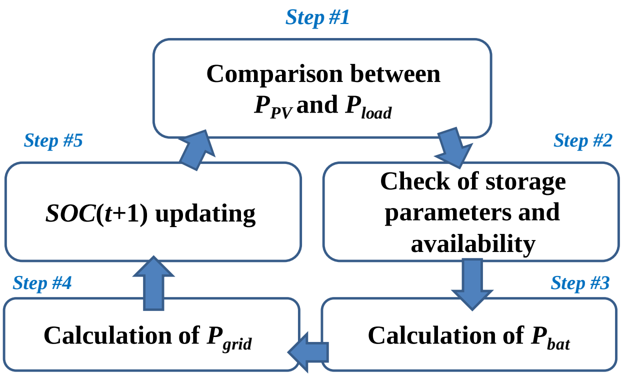

Fig.4. Scheme of the PV-storage system with its power flows.

$$SOC(t+1) = SOC(t) - \frac{\eta_{bat} \cdot P_{bat} \cdot \Delta t}{\left(V_{bat,r} \cdot C_{bat,r}\right)}$$

then the procedure restarts.

In summary, following the above described procedure:

- the PV system always feeds first the load, then, if possible, the storage and at the end the grid;
- batteries cannot be used to feed the grid.

For example, a user installs a PV system with storage ($C_{bat,r}$=7 kWh) to increase self-consumption. For the sake of simplicity, power flows are supposed constant for 1 hour: P_{PV} is 2 kWh, P_{load} is 3.3 kWh and batteries are quite empty (SOC=0.34). The load requires more power than the production; the deficit (1.3 kWh) must be fed by the storage or the grid. The *SOC* of storage can decrease down to 0.2: neglecting losses, as a first approximation batteries (with slow discharge to preserve life) can provide up to ≈1 kWh. The rest of the load is fed by the grid (P_{grid}=0.3 kWh). In this example, all the components of the system are working in the same time: as described in (8), both grid and batteries act like generators and help the PV system to feed the load:

$$P_{PV}(t) + P_{bat}(t) + P_{grid}(t) = P_{load}(t) \tag{8}$$

IV. Simulation Procedure

PV and storage systems are modular: as written in [9], it is possible to simulate the power profiles of the PV generator with respect to its power rating and the number of batteries define the quantity of energy that can be stored. First, the optimization procedure calculates the PV production of 1 kW of installed power. Then, the size of the PV generator and the number of batteries are defined. After that, the number of DC/AC converters is calculated (the rated power of a single device is 1.5 kW for residential load and 55 kW for offices). As a first approximation, the power flow is equally distributed in each device and they work in the same way.

A. Modelling of PV Generators

The production from PV power plants is evaluated according to the model in [8][9], in which a complete description of the system is also reported. In the present paper, the PV modules are supposed South oriented and 30° tilted. The PV production profile (an example is shown in Fig. 5), is calculated starting from irradiation data from PVGIS database. The DC power in the MPP of the current–voltage (*I–V*) characteristic is supposed proportional to the irradiance. The most important losses in PV conversion are included in the model: electrical losses (*I-V* mismatch, Joule effect in wires and thermal losses) and other losses (e.g., dirt and reflection on the front glass of the modules).

B. Modelling of the Storage System

The performance of batteries is described by the *SOC* estimation [10], [11]. The behaviour of batteries is modelled with instantaneous *SOC*, which is a function of *SOC* at the previous instant, self-discharge rate and charge/discharge efficiency [12].

As previously discussed, the procedure stops the use of batteries to avoid deep discharges and limits the maximum charging and discharging currents to reduce the batteries' degradation and ageing. The specifications of the commercial storage for PV applications, simulated in this work are reported in Table I [13].

TABLE I Specifications of a Li-ion Battery

Battery rated capacity	$C_{bat,r}$	100 Ah
Battery rated voltage	$V_{bat,r}$	12 V
Lifetime [1] (cycles)	N_{cycles}	3500 cycles, 1 per day, *DOD*=80%
Lifetime [1] (years)		8
Maximum power	P_{bat_max}	≈2.4 kW
Charge-discharge efficiency	η_{bat}	0.88

[1.] Warranty, real lifetime most likely higher. *DOD* is Depth of Discharge.

As a first approximation, the energy supplied by lithium-ion batteries in their total life can be calculated by (9):

$$E_{bat\_life} = V_{bat,r} \cdot C_{bat,r} \cdot DOD \cdot N_{cycles}$$

During every step of the simulation, the amount of discharged power is integrated. When it reaches the limit E_{bat_life}, batteries are replaced. Thus, the usage of batteries and their replacement affect the economic analysis.

C. *Modelling of the unidirectional DC/AC converter*

As previously stated, PV and batteries are connected to AC grid and loads by a unidirectional DC/AC converter, whose size is defined according to the capacity of PV. The quadratic model described in [14] is used; the efficiency at rated power is 95% for small inverters and 98% for devices with nominal power above 6 kW.

D. *Electric Loads of Residential Users and Offices*

In this paper, two case studies are presented in details to achieve the optimal sharing between PV and storage capacities with different profiles of residential and office loads. Irradiance, temperature and load profiles refer to a location in Northern Italy (latitude ≈45° N). The energy meters measure minute by minute the whole residential load and hour by hour the whole office load.

In case #1, the residential user is a family consisting of four persons with a 3 kW contract power. Loads are the typical household appliances, either active during the whole year (e.g., lights, fridge, oven) or mainly used in summer (air conditioning system and fans). The family consumes ≈3700 kWh/year and the yearly average and maximum power consumption are ≈0.4 kW and ≈3.2 kW, respectively. Fig. 5 shows grid absorption in case #1 in a winter weekday: it is reduced thanks to self-consumption. The production is low in winter days, nevertheless there is grid injection, when PV production exceeds the loads (low during light hours and high in the evening). Consumption peaks can be attributed to household appliances converting electricity into heat (e.g. hairdryer, iron or boiler).

In case #2 loads are located in a big office building. The power consumption of the offices is prevailing in the middle of the day in the whole year. In this case, employees come in mainly at 8 - 9 am and leave between 4 and 6 pm. The peak consumption occurs in the afternoon and is due to the merge of work activities and server air-conditioning in the summer.

Consumption highly increases (up to 460% of the yearly average) during the summer, due to cooling systems made with electric heat pumps: the electricity demand rises with increasing temperature and the peak consumption in the day is approximately at 3 pm. The annual energy consumption is ≈365 MWh/year and the yearly average and maximum power consumption are ≈41 kW and ≈190 kW, respectively.

E. *Simulation Constraints*

To find the cost-effective capacities of generation and storage, the procedure examines all the possible combinations, subject to the following constraints:

- for residential load: PV capacity may be up to 6 kW, with 0.25 kW steps (corresponding to a PV module) and storage capacity ranges from 0 to 10.8 kWh, with steps of 1.2 kWh (corresponding to a battery element). The number of solutions calculated by the procedure is 240, corresponding the product of all considered PV sizes and storage sizes.
- for office load: PV capacity may be up to 600 kW, with 20 kW steps and storage capacity ranges from 0 to 1.5 MWh, with steps of 50 kWh. In this case, the steps are higher than in residential case to limit the total simulation time: the number of solutions calculated by the procedure is ≈1000.

Maximum installable capacities are very high with respect to the load and the best solutions are not close to boundaries.

V. SIMULATION RESULTS

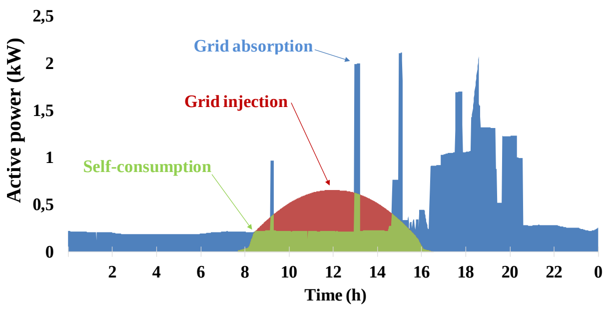

Fig.5. Load profile vs. PV production in case #1 in a winter weekday.

A. Cost-optimal solutions

The first step is the analysis of cost-optimal solutions, based on the NPV within 25 years. The NPV of a time series of cash flows is calculated as the sum of the present values of each annual net cash flow R_t with a supposed interest rate i=3% [15]:

$$NPV = \sum_{t=0}^{N=25} \frac{R_t}{(1+i)^t}$$

The internal rate of return (IRR) is also calculated to compare profitability of investments with different initial investments. The IRR of an investment is the discount rate i at which the negative cash flows equals positive cash flows during the whole investment period (NPV=0).

The procedure searches for maximizing the NPV of the investment, calculating all the energy and cash flows (Section II). The installation costs of a PV generator is 2000 €/kW for small plants ($P_{PV,r}$<6 kW) and decreases down to ≈1200 €/kW for big plants ($P_{PV,r}$>400 kW). The cost of batteries is 300 €/kWh and operation and maintenance (O&M) costs for PV are 0.8% of the installation cost. The cost-optimal solutions, for both tertiary sector users, do not include the installation of storage, because battery cost is high. Thanks to the actual net-billing scheme, it is more convenient to exchange energy with the grid than using a local private storage. GSE refunds most of the money paid for exchanged energy, in this case, from the user point of view, the grid works like a cheap virtual storage without high installation and maintenance cost. In case #1 the optimum is obtained with a PV generator $P_{PV,r}$=3.5 kW. The initial investment is 7 k€ and the NPV is ≈6.6 k€: the profit is 94% and the Internal Rate of Return (IRR) is 8%. The NPV is positive starting from the 9th year. After the first year of operation, the self-consumption is ≈1350 kWh (corresponding to 35% of the load). The bill decreases (from ≈800 € paid for 3800 kWh, before the installation of the PV plant) to 440 € paid for 2250 kWh. The tax credit is 5% of the cost of a PV system (350 €) and GSE refunds the prosumer with C_{ssp}≈290 € for exchanged energy. The PV system produces ≈3900 kWh/year (about the energy consumption): the positive cash flow due to the small overproduction is negligible. Table II shows the cash flows after the first year. After the 10th year the tax credit is null and the total cash flow rises down to ≈590 €.

In case #2 the optimum is obtained with $P_{PV,r}$ = 340 kW. The PV system produces ≈380 MWh/year (≈1100 kWh/kWp) corresponding to 104% of the load. The initial investment is 440 k€ and NPV is ≈554 k€: the profit is 125% and IRR is 9%. As in case #1, the NPV is positive starting from the 9th year. After the first year of operation, the self-consumption corresponds to 53% of the load (≈195 MWh). The electricity bill reduction is ≈34 k€ and GSE refunds the prosumer with C_{ssp}≈26 k€ for exchanged energy.

TABLE II. CASE #1: CASH FLOWS DURING FIRST YEAR OF OPERATION

Bill reduction due to self-consumption	≈360 €
Tax credit	≈350 €
Contribution paid by GSE	≈290 €
Operation and Maintenance	≈ - 60 €
Total cash flow	≈940 €

The PV system produces 15 MWh more than required by the load: the positive cash flow due to the overproduction is ≈600 €. The tax credit is not applicable, because the size of the generator is higher than the limit (20 kW).

B. Cost-effective solutions

Fig. 6 shows the variation of the NPV in function of the sizes of PV generator and batteries, while Fig. 7 shows the corresponding levels of self-consumption. In Fig. 6 every curve (with constant storage size) shows a peak. If the PV plant is small, all the produced energy is directly self-consumed or injected into the grid, but later compensated by the energy absorbed from the grid. Nevertheless, in this case, the total production is not sufficient for the loads and both investment cost and NPV are low. The NPV becomes maximum when the PV plant produces all the energy required by the loads and the grid works only like a virtual storage. This situation may happen, because the exchange with the grid is cheaper than the use of a local storage. If the PV plant is oversized, the surplus is sold to the grid at low price. In this case the installation cost increases more than the higher profit due to the sale of the energy surplus and the NPV decreases from the maximum.

Starting from the maximum NPV, in Fig. 6 (NPV≈6.6 k€, without storage), it decreases linearly, with battery capacity. For example, if $P_{PV,r}$=3.75 kW and $C_{bat,r}$=7.2 kWh, the NPV≈1.7 k€ and self-consumption is ≈75%. It can rise up to ≈78% of the load, if the storage is =9.6 kWh: in this last case the NPV is null.

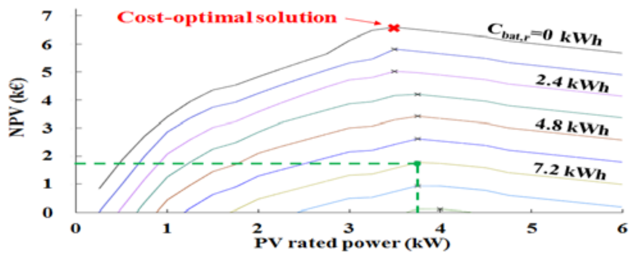

Fig.6. Case #1: Cost-optimal and cost-effective solutions.

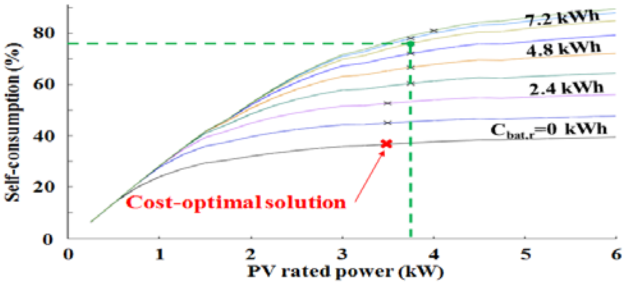

Fig.7. Case #1: Self-consumption vs. PV and storage sizes

VI. CONCLUSIONS

In this paper, the yearly energy and economic balances of a PV system with Li-ion batteries are determined to supply two different kinds of loads (residential and offices). Due to high cost of batteries, the cost-optimal solution is achieved avoiding the installation of storage. If storage is not installed, the self-consumption reaches 35% of the residential load. On the other hand, office consumption occurs mainly during light hours and the self-consumption in cost-optimal solution is higher (≈53%). Lower specific installation costs and higher self-consumption permit to obtain higher returns for offices (IRR=9%) that for residential loads (IRR=8%). The integration of storage systems is expensive for both users, but it is possible to strongly decrease the use of the grid keeping a positive NPV. The main findings are that the use of storage increases the self-consumption up to ≈80% for the residential load and >90% for the typical office.

REFERENCES

[1] International Energy Agency, Photovoltaic Power Systems Programme - Annual report 2014, 2015.

[2] H. Hatta, M. Asari and H. Kobayashi, "Study of energy management for decreasing reverse power flow from photovoltaic power systems," 2009 IEEE PES/IAS Conference on Sustainable Alternative Energy (SAE), Valencia, 2009, pp. 1-5

[3] IEA International Energy Agency, "Review and analysis of PV self-consumption policies," Report IEA-PVPS T1-28:2016.

[4] Italian Energy Services Operator, “Gestore servizi energetici (GSE)”, http://www.gse.it/

[5] Italian Energy Market Operator, “Gestore mercati energetici (GME)”, http://www.mercatoelettrico.org/It/default.aspx

[6] Italian Law, Decree-Law 22 June 2012, n. 83, http://www.gazzettaufficiale.it/eli/id/2012/08/11/12A08941/sg

[7] Italian Regulatory Authority for Electricity Gas and Water, Testo integrato delle modalità e delle condizioni tecnico-economiche per lo scambio, ARG/elt 74/08 (in Italian), http://www.autorita.energia.it/

[8] G. Chicco, V. Cocina, P. Di Leo, and F. Spertino, “Weather forecast-based power predictions and experimental results from photovoltaic systems,” IEEE International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2014.

[9] F. Spertino, A. Ciocia, V. Cocina, P. Di Leo, “Renewable Sources with Storage for Cost-Effective Solutions to Supply Commercial Loads”, IEEE International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2016

[10] S. Diaf, D. Diaf, M. Belhamel, M. Haddadi, A. Louche, “A methodology for optimal sizing of autonomous hybrid PV/wind system”, Energy Policy, vol. 35, no. 11, 2007, pp. 5708–5718.

[11] Y. Hongxing, W. Zhou, C. Lou, “Optimal design and techno- economic analysis of a hybrid solar wind power generation system”, Applied Energy, vol. 86, no. 2, 2009, pp.163–169.

[12] D. Guasch, S. Silvestre, “Dynamic battery model for photovoltaic applications”, Prog PVs: Res Appl, vol. 11, 2003, pp. 193–206.

[13] Alexandre Oudalov, ABB Switzerland, Corporate Research, Energy Storage in Electric Power Systems, Integration of Renewable Energy Sources, 2015

[14] F. Spertino, F. Corona, P. Di Leo, “Limits of advisability for master-slave configuration of DC-AC converters in photovoltaic systems,” *IEEE Journal of Photovoltaics*, Vol. 2, 2012, pp. 547-554.

[15] F. Spertino, P. Di Leo, V. Cocina, “Economic analysis of investment in the rooftop photovoltaic systems: A long-term research in the two main markets”, Renewable and Sustainable Energy Reviews, vol. 28, 2013, pp. 531–540.