PHOTOVOLTAIC AND BATTERY ENERGY STORAGE SYSTEMS IN SHOPPING MALLS: ENERGY AND COST ANALYSIS OF AN ITALIAN CASE STUDY

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ABSTRACT: Nowadays, due to the high diffusion and the lower cost of photovoltaic (PV) systems, there is an increasing interest in combining PV generators with battery energy storage systems (BESS) to improve load match and grid interaction, giving more flexibility to the building. The aim of this work is twofold. First, considering a specific building energy demand (i.e. a supermarket), an energy evaluation of the PV-BESS system and grid exchange is performed though dynamic simulations. Then, a cost analysis is carried out with the evaluation of the return of investment (ROI) both with and without BESS. Finally, the achievable percentage of carbon dioxide reduction with the inclusion of PV-BESS system is also estimated. The main purpose of this work is to show when the BESS becomes cost effective for the Italian market. The described analysis is part of the CommONEnergy FP7 EU project.

Keywords: *Photovoltaic, Grid Integration, Storage, Energy efficiency*

1 INTRODUCTION

Commercial buildings have large electrical and thermal loads, offering interesting opportunities to improve the energy efficiency and to reduce CO_2 emissions. Over the last few years, multiple shops and services, previously decentralized in different locations of a city, are now usually concentrated in shopping malls. Shopping malls are a very peculiar kind of buildings, because of the specific final energy uses (mainly related to lighting, ventilation, cooling and refrigeration), the complexity of the overall system, mainly driven by the need to ensure a certain sales volume, and the state of constant renovation. This means a challenging energy efficient managing.

For this reason, the CommOnEnergy EU FP7 project regards shopping malls as a great opportunity to increase energy efficiency through deep retrofitting. CommONEnergy relies on a comprehensive systemic approach involving innovative technologies and solutions as well as methods and tools to support their implementation [1]. The ambitious objectives of the CommONEnergy project are: i) to reduce energy demand by 75%, ii) to shave the power peaks and iii) to increase the use of renewable energy resources by 50%. The use of energy storage systems (ESS) and energy management systems (EMS) can effectively contribute to such objectives [1].

Typically, shopping malls have large areas (e.g. on the roof or in the parking lot) where photovoltaic (PV) systems of considerable size could be installed.

The goal of the analysis described in this paper is to understand and to explore how the combination of PV systems and BESS can contribute to meet the targets of the CommONEnergy project, when an increasing amount of renewable energy resources is available.

Similar analyses about the combination of PV generators with ESS in commercial buildings or supermarkets are reported for instance in [2] and [3]. However, while in [3] the authors deal with the method based on fuzzy logic for EMS control, the focus of this paper is mainly on the economic impact of the PV and BESS coupling in the Italian context, assuming net-metering, absence of incentives and tariff variability.

A starting point to evaluate the economic and energy benefits of introducing PV systems and ESS in shopping malls is to consider the relative overall consumption. The PV-BESS model is developed in TRNSYS, a modelling environment used to simulate complex dynamic systems, e.g. buildings and energy systems [4].

The paper is structured as follows: in Section 2 the system model of PV-BESS is described and the analyzed indices are defined in Section 3. In section 4 the simulation results in three different cases are presented. Finally conclusions and future works are reported in Section 5.

2 SYSTEM MODEL OF PV-BESS

Methodological approach foresees a parametric analysis that is performed by varying the PV nominal power (P_n) and the BESS capacity (C_{BESS}). The PV production is calculated using the meteorological and radiation data from the Weather Analytics database [5], while the consumption data were collected in a supermarket located in the city of Genoa, Italy. The simulations are performed over one year, with one-hour time resolution.

The PV-BESS system is modeled in TRNSYS using the built-in types of the electrical library [4]. The main components are: the PV system, the inverter/regulator and the battery bank.

The main input data to the PV system are the meteorological information collected in the Genoa area in 2013 and extracted from the Weather Analytics database [5], assuming to have PV crystalline modules oriented towards south with a 30° slope. The output electrical quantities are instead power, voltage and current at the maximum power point (P_{MMP}, V_{MMP}, I_{MMP}), computed as described in [4]. Once the PV parameters and the voltage of the inverter (e.g. 500 V) are set, it is possible to vary the nominal power by changing the number of strings in parallel. PV efficiency is η_{PV}=15%.

The battery model allow us to define the cell capacity and the number of cells in series and in parallel. Moreover, the total charge and discharge efficiency can be set, as wanted (i.e. 90% in our case study). The PV system, the battery bank, and the load are connected through the inverter/regulator.

The energy management system (EMS) implements different control rules according to the specific objectives. In the following, it will be shown that the EMS is able to exploit mainly the power produced by the PV system and to store the surplus into the BESS.

In the case of PV overproduction the surplus is stored into the batteries till the maximum state of charge (SOC_{max}) is reached. Afterwards, if the PV production is not enough to fulfill the energy demand, some power is drawn firstly from the battery and then from the grid. When the demand is completely supplied and the battery is fully charged (i.e. $SOC=SOC_{max}$), the PV overproduction is injected into the grid.

3 ANALYZED PARAMETERS

One of the main reasons motivating the use of PV-BESS in shopping malls is the intention to increase the exploitation of renewable energies, while decreasing the amount of power taken from the grid. In this sense, the most important two parameters to evaluate are: the self-consumption and self-production defined according to the following expressions:

$$Sc_{\%} = \frac{\sum_{i=1}^{8760}(E_{PV\_onsite} + E_{BESS})}{\sum_{i=1}^{8760}(E_{PV})} \times 100 \qquad (1)$$

$$Sp_{\%} = \frac{\sum_{i=1}^{8760}(E_{PV\_onsite} + E_{BESS})}{\sum_{i=1}^{8760}(E_{load})} \times 100 \qquad (2)$$

where E_{PV_onsite}, E_{BESS}, E_{load} and E_{PV} are the total energy over the year of PV system consumed on-site, BESS, the load consumption and PV system production respectively. Moreover, since shopping malls are usually located in city districts, it is important to take into account also the possible interaction with the grid and the role played in the future by shopping malls as flexible buildings. For this reasons, the amount of green energy produced and consumed on site, as well as the energy exchanged from or to grid over the year, is also estimated.
The sustainability of the system is quantified in terms of reduction of CO_2 emissions. Stated k_{CO2}= 0.483 as the coefficient of conversion of the electricity mix in Italy from MWh into tons of CO_2 as reported in [6], the relative reduction of CO_2 emissions is given by:

$$CO_2\ reduction_{\%} = \left(1 - \frac{CO_2\ w\ PVBESS}{CO_2\ wo\ PVBESS}\right) \times 100, \qquad (3)$$

where "*CO_2 w PVBESS*" and "*CO_2 wo PVBESS*" are the CO_2 emission with and without the PV-BESS respectively.
From the economic point of view, it is interesting to compute the return of investment (ROI), taking into account the infrastructure costs (i.e. PV system, inverter, BESS) and the price of electricity. In our analysis the electricity price has been chosen on the basis of the 2013 Italian Unique National Price (PUN) available in [7] along with additional fixed costs. In particular, such fees are divided into three daily ranges, labelled as F1, F2 and F3, respectively. Moreover, in Italy the surplus of power generated by PV systems and injected into the grid is valorized through the net-billing scheme ("scambio sul posto", up to a maximum yearly amount equal to the electricity consumption) and is also included in the economic analysis. All considered costs are reported in Table 1.

Table 1 - Economic parameters

Items	Cost
PV system	2000 €/kWp
BESS	500 €/kWh
Price of electricity	PUN*+fixed costs
Net-metering scheme	100 €/MWh

4 SIMULATION RESULTS

Parametric simulations have been performed in order to analyze the energy-related and economic impact of PV-BESS systems considering three different shopping malls final energy uses:

- the total supermarket consumption (*Case A*);
- the supermarket lighting system consumption (*Case B*);
- the supermarket lighting system consumption, when this is shifted with the PV production (*Case C*).

In the following sub-sections the simulation results are presented.

4.1 Shopping mall energy consumption

Shopping malls usually comprise several shops (of various size and with different energy profiles) and at least one supermarket. Typically, a supermarket has a large area and dissipates a large amount of energy, due to the presence of constant loads, such as refrigeration cabinets, lighting, ventilation and air conditioning. The PV-BESS can match only partially the very large total demand, and this implies that a grid-connected system should be considered.
In the following, some results based on the measured consumption data in a supermarket located in Genoa, Italy, are presented. Starting from the measured data collected in 2013, the maximum and minimum values of active power demand are 257 kW and 67.6 kW, respectively. The nominal power of the PV system is 300 kWp, i.e. higher than the maximum peak consumption and achievable if all the available area is exploited. This scenario will be referred to as *Case A*.
Figure 1 shows the hourly power profiles (expressed in kW) of PV production (in red) and supermarket consumption (in blue), during a typical summer week (July in this case).
Assuming to install only the PV system or the PV system in combination with different storage capacity (C_{BESS} = {50, 100, 150, 200} kWh), the results of the simulations for the parameters described in Section 3 are summarized in Table 2.
By using the PV system only, self-production reaches a value of about 30%, and the self-consumption is near 100%, as expected. If the PV system is combined with the BESS, the self-production slightly increases.

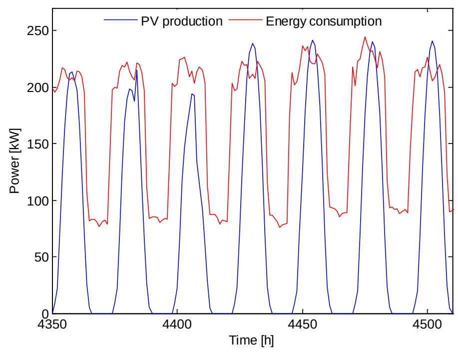

Figure 1 - Typical summer-week (July) profiles with generation (red) from a 300 kWp PV plant and supermarket consumption (blue).

Table 2 – Result values for 300 kWp of photovoltaic, different energy storage capacities and supermarket energy consumption.

Storage capacity [kWh]	**0**	**50**	**100**	**150**	**200**
Sp [%]	28.4	29	29.2	29.4	29.4
Sc [%]	93.0	93.5	94.5	94.8	95.0
Green-on-site [%]	28.40	28.80	29.04	29.16	29.22
To grid [%]	0.52	0.54	0.40	0.28	0.22
From Grid [%]	71.08	70.66	70.56	70.56	70.56
CO_2 reduction [%]	28.96	28.96	28.96	28.96	28.96
ROI [years]	7	7.52	8.18	8.55	8.92

Therefore, the largest part of the energy (around 70%) is drawn from the grid.
Since the fraction of energy taken from the grid is approximately the same in all the considered cases, the reduction of CO_2 emissions given by expression in (3) is on the same level (28.96%).
The last row of Table 2, shows the trend of the return of investment (ROI), which grows by about two years (from 7 to 8.92 years), when a 200 kWh BESS is installed.
Finally, in *Case A* the benefits of PV system in terms of self-production and CO_2 reduction are evident. On the contrary, simultaneous generation and demand as well as the net-billing scheme do not play in favor of storage systems.

4.2 Lighting energy consumption

The results in *Case A* show the advantages, but also the limitations of PV-BESS in a shopping mall, when the large energy demand of a supermarket is considered.
However, the shopping mall comprises several different loads, as mentioned in Section 4.1. One of the most significant is the lighting demand, which represents almost 40% of the total energy consumption.
In the rest of this section, the lighting system demand for the Genoa supermarket is considered to be simultaneous (*Case B*) and non-simultaneous (*Case C*) to PV production. The lighting profiles are simulated maximizing the use of natural lighting and dimmering the electrical lights, as described in [8]. The nominal power of the PV system in these cases is fixed to 100 kWp, since the maximum consumption is equal to 98.5 kW. A weekly example of *Case B* and *Case C* profiles are shown in Figure 1 and Figure 2, respectively.
Similar analyses are performed by varying the BESS capacity C_{BESS} = {25, 50, 75, 100} kWh. The results are reported in Table 3 and Table 4 for *Case B* and *Case C*, respectively.
As far as self-consumption is concerned, the benefit of the BESS is more evident than in the *Case A*. Indeed the *Sc* grows from 59% to 74% in *Case B* and from 31% to 45% in *Case C*. The reduction values of CO_2 emissions follow the same trend being strictly related to the on-site energy.
It is interesting to highlight the different, but consistent behavior of the renewable energy generated on-site and the amount of energy exchanged with the grid. In *Case B*, since the production and consumption are simultaneous, the increase of *Sc* corresponds to an increment of on-site renewable energy with a consequent decrease of the energy exchanged with the grid. On the contrary, *Case C* is favored by a higher interaction with the grid, because of the mismatch between the time when PV generation is active and the instant when the demand is satisfied. In this case, the deployment of BESS is more favorable. These results impact also on the ROI, which in *Case C* ranges from 11.7 to 13.7 years, while in *Case B* ranges from 9.3 to 11.3, as shown in the last rows of Table 4 and Table 3, respectively.
In practice, due to the presence of net-billing in Italy, the price of the storage is still too high, for having a positive effect on the payback time. Thus, the main question that arises is whether and when the cost of BESS becomes competitive.
Assuming that in the future the difference of the price between grid-in and grid-out (kWh produced by PV, virtually stored by the grid, used in a second moment) will become smaller, from Figure 4 and Figure 5 it is possible to have an idea (for *Case B* and *Case C* respectively) about how much the cost of the battery have

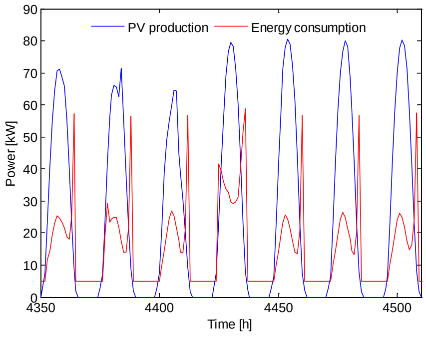

Figure 1 -Typical summer-week (July) profiles of generation from a 100 kWp PV system (red) and simulated lighting consumption (blue).

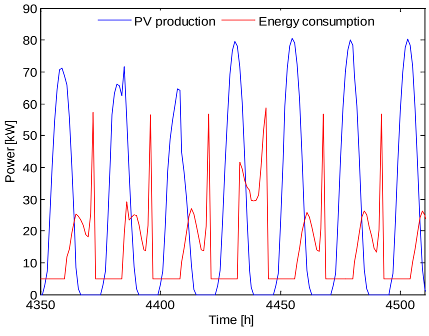

Figure 2 -Typical summer-week (July) profiles of generation from a 100 kWp PV plant (red) and simulated lighting consumption, not simultaneous with the PV production (blue).

Table 3 – Result values for 100 kWp of photovoltaic, different energy storage capacities and lighting energy consumption.

Storage capacity [kWh]	**25**	**50**	**75**	**100**
Sp [%]	44.0	46.2	49.3	55.2
Sp [%]	59.0	61.9	66.1	74.0
Green-on-site [%]	34.36	36.74	40.28	47.84
To grid [%]	21.90	20.47	18.24	13.38
From Grid [%]	43.74	42.80	41.48	38.78
CO_2 reduction [%]	44.00	46.19	49.27	55.23
ROI [years]	9.3	10.1	10.7	11.3

Table 4 – Result values for 100 kWp of photovoltaic, different energy storage capacities and lighting energy consumption.

Storage capacity [kWh]	**25**	**50**	**75**	**100**
Sc [%]	23.2	27.1	30.1	33.9
Sp [%]	31.0	36.3	40.3	45.5
Green-on-site [%]	15.45	18.64	21.17	24.67
To grid [%]	51.23	50.11	49.23	48.01
From Grid [%]	33.33	31.25	29.60	27.32
CO_2 reduction [%]	50.02	54.55	57.96	62.42
ROI [years]	11.7	12.2	12.8	13.7

to decrease. The trend of the ROI is given by changing the values of net-billing from 100 €/MWh to 0 €/MWh (blue lines), as the valorization of PV hourly surplus (up to a maximum PV electricity production equal to the consumption on an annual basis), when only the PV system is considered. Then, assuming to have for example 50 kWh of BESS, we calculated the relative suitable cost to have the same ROIs (green lines).

5 CONCLUSIONS

In conclusion, this paper presents some results about the possible use of PV-BESS in an Italian shopping mall. Three different scenarios, based on three different consumption profile are reported. The main consideration is that the PV-BESS system improves, accordingly to the analyzed cases, the self-consumption and reduce the energy exchanged with the grid. The ROI slightly increases from the scenario with only PV system and with significantly BESS capacity. However, currently the price of the BESS is still high and some consideration about the suitable cost, in case of simultaneous and non-simultaneous cost are also provided.

At the end the main consideration is that the PV-BESS system is and will be interesting also in Italy for commercial (e.g. shopping mall) buildings. This will be more advantageous if the PV-BESS will be associated to smaller load (e.g. EV-mobility) or if the cost of the BESS will decrease and/or the value of net-billing.

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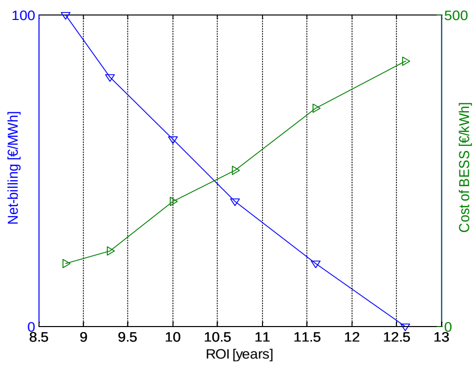

Figure 4 - Trend of the price of the BESS and net-billing over the ROI for 50 kWh of BESS, when the production is simultaneous with the consumption.

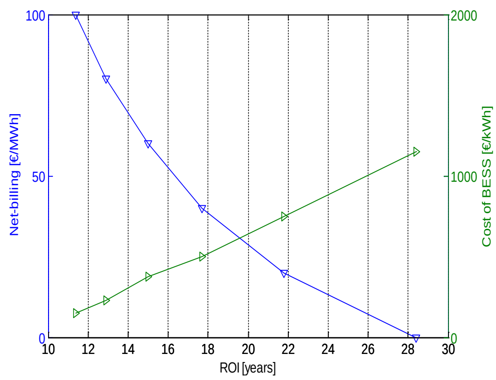

Figure 5 - Trend of the price of the BESS and net-billing over the ROI for 50 kWh of BESS, when the production is simultaneous with the consumption.

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