# A Small-scale Prototype for the Optimization of PV Generation and Battery Storage through the use of a Building Energy Management System

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***Abstract*—The use of renewable energy sources to cover, at least partially, the energy demand of residential, industrial and commercial buildings is fundamental for sustainability and $CO_2$ emission reduction. In this respect, the so-called energy management systems play a key role to maximize the amount of energy produced by local, renewable-based generators that are consumed by the same buildings where such generators are installed. In this paper, we present a prototype consisting of a photovoltaic (PV) generator and a battery energy storage system (BESS), properly coordinated by a building energy management system (BEMS), designed to handle the power flows of a shopping mall, while taking into account the BESS state of charge and the actual power demand. The control strategy implemented in the BEMS is one key point of the work. Some preliminary experimental results confirm the validity of the proposed approach.**

***Keywords*—*Building Managment System, photovoltaic, battery storage system, energy efficiency***

## I. Introduction

The reduction of energy consumption is one of the key challenges of the $21^{th}$ century. Currently, residential, industrial and commercial buildings are responsible for about 40% of the worldwide energy consumption [1]. For this reason, several European projects and initiatives aim at reducing the building energy demand through effective retrofitting actions or ad-hoc design practices. In this respect, natural ventilation or lighting strategies and thermal comfort management play a central role [2], [3]. According to [4], in the near future, the electricity demand is expected to increase considerably due not only to a larger number of electrical appliances and electronic devices, but also to the diffusion of electrical vehicles and to the heating/cooling sector.In this context, the use of renewable energy sources is essential to reduce $CO_2$ emissions and electrical energy import. Among possible sources, the photovoltaic (PV) technology is largely deployed in both rural and urban areas due to its modularity and capability to be easily installed on roofs, on building façades or in courtyards. Recently, the installed PV capacity has rapidly increased and the majority of PV installations are grid-connected and located close to the final users with interesting benefits in terms of losses and power quality [5]. The main purpose of PV at building level is to meet the local electricity demand, thus limiting the amount of energy based on non-renewable sources drawn from the distribution grid. In practice, this means maximizing self-consumption. Typically, shopping malls have large areas (e.g. on the roof or in the parking lot) where PV systems of considerable size can be deployed. The management strategies of PV local generators have been widely studied in the literature. For instance, the key role of building energy management systems (BEMS) to properly optimize generation and consumption is described in [5]. To maximize the exploitation and self-consumption of power generated by a PV system, this should be combined with a battery energy storage system (BESS). The advantages of PV-BESS depend considerably on energy tariffs, local or national regulations and the actual energy demand. For example, it is shown in [6] that in Italy the net-metering scheme considering only the PV production is particularly advantageous for residential buildings. On the contrary, in commercial buildings (e.g. shopping mall where the electricity demand is much larger) the current net-metering scheme does not encourage the diffusion of BESS to increase the self-consumption [7]. The main benefits of the combination of PV and BESS are carefully analyzed in [8], where the PV-based electricity overproduction in a residential building is stored into a battery to be used later on. Neglecting economic aspects and specific regulations, the objective of this paper is to present how the optimization strategies implemented in a BEMS can handle PV generation and BESS. The system has been developed within an European research project on shopping mall retrofitting, with the goal of reducing energy consumption by about 75%, while encouraging the use of renewable energy and storage technologies [9]. The specific solution described in this paper is a small-scale prototype (i.e. able to handle a limited amount of power flows), installed at the Advanced Energy Systems Lab of Eurac Research, Bolzano, Italy. This small-scale system has been developed to test the proper operation and the interoperability of different components of a big-scale system currently installed in a shopping mall in Grosseto, central Italy [10]. Several experiments have been conducted for some months to evaluate if and to what extent different retrofitting actions make the PV-BESS solution profitable from the energetic point of view in the context of shopping malls. The rest of the paper is structured as follows. In Section II the main elements of the PV-BESS prototype are described. Section III will be focused on the control strategies implemented in the BEMS as well as on the monitoring configuration. Finally, Section IV will report some experimental results for different energy demand profiles.

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## II. Prototype system description

The PV-BESS prototype is a single-phase system. Its block diagram is shown in Fig. 1. It consists of four main components: the PV generator, the BESS, AC or DC loads and an intelligent BEMS. Globally, the system is able to emulate and to manage the power demand of a shopping mall. However, it could be used also in different kinds of buildings due to its inherent reconfigurability or to emulate different load profiles.

The PV system is able to generate up to 1.5 kW and it is based on six monocrystalline modules connected in series. Each module is able to generate 250 kW of peak power. In order to maximize production, modules are south-oriented with an inclination of about 30°. A pyranometer and a thermocouple are installed on the PV module plane to monitor solar radiation and module temperature, respectively, in different environmental conditions. The PV system is connected to the main AC grid through a 3-kVA grid-tie string inverter

A container located next to the PV system encloses the BESS cabinet, the intelligent BEMS, a DC electronic load emulating the energy consumption of the building, and a link to a charge station for electric vehicles (EV).

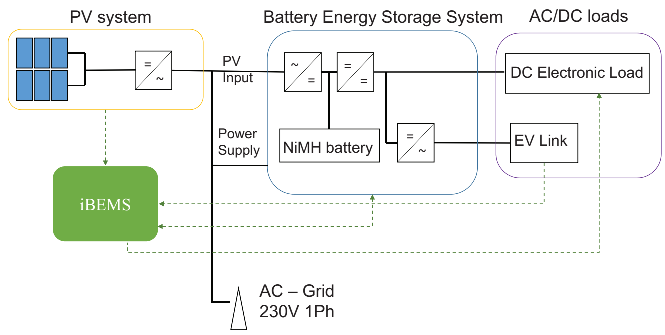


Fig. 1. Block diagram of the PV-BES prototype system.

The BESS consists of three nickel-metal-hydride (NiMH) batteries providing up to 3.24 kWh of storage capacity, where the technical characteristics can be found in [11]. The NiMH is a mature technology for several kinds of applications such as consumer products and EV battery. However, the use of NiMH batteries in buildings is not so common as lithium accumulators. Therefore, their use in shopping malls is highly innovative. Indeed, NiMH batteries for buildings are interesting for various reasons: they are recyclable, less flammable and cheaper since they require simpler battery management systems. The input of the BESS is linked to a unidirectional charger connected both to the PV system and to the main grid. At the output of the BESS, one inverter and one DC-DC converter are used to supply the AC and DC load, respectively. For safety reasons, all low-level charge/discharge operations are handled directly by the battery management system (BMS) and battery state of charge and state of health can be remotely monitored or through a Human Machine Interface (HMI). The DC electronic load can draw at most 2.4 kW and it is remotely configured by the BEMS with customizable power consumption profiles [12]. The AC output of the BESS is instead connected to an EV-link where it is possible either to recharge a real EV or to connect an EV emulator.


Fig. 2. From left to right, the pictures shows: the PV system with the EV-link, the EV tester, the BESS cabinet and the DC electronic load in the container. The rightmost picture displays the BEMS along with two energy meters.

As shortly introduced before, the high-level monitoring and management functions are implemented in the BEMS [13]. Usually, each subsystem of a building (e.g. lighting or BESS) is provided by its own management system. As it is well described in [14], the chosen BEMS has the peculiarity to exchange information in real-time with such local management systems in order to coordinate multiple actions, while taking into account the status of the entire building. Moreover, the BEMS is able to interact with several active devices (such as the one reported in [14]) through different communication protocols (i.e. Modbus, BACner, ZigBee, SMI). In the system presented in this paper, the communication between the BEMS and the other subsystems is shown in Fig.1, where the dashed green lines and the arrows direction indicate if the BEMS has only a monitoring function or also a control role.

## III. Monitoring and control functions

As mentioned above, the PV system, the BES system and the AC and DC loads are manitored/controlled by the BEMS through various communication protocols (i.e. RTU ModBUS,TCP/IP ) to collect both measured data of physical quantities (e.g. power, voltage, current) and the values of different boolean variables (e.g. charge/discharge enable, load connected/disconnected flag). All monitored data are collected every five minutes and are used by the BEMS implementing the control strategy. Also, data are stored in a server for possible further off-line analyses. In order to set the control strategy, we need to take into account two aspects, i.e. the

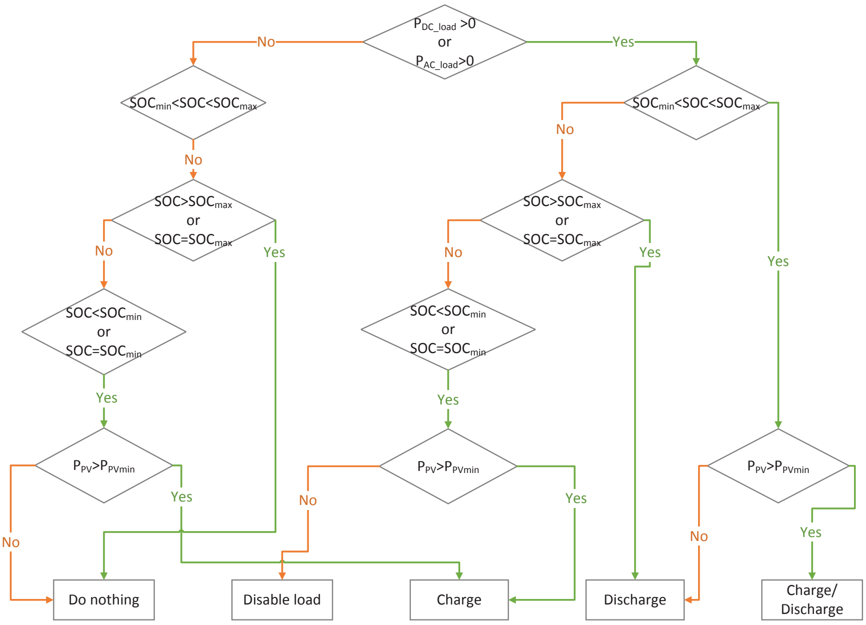


Fig. 3. Flowchart of the control algorithm implemented into the BEMS to maximize PV generation for BES charging.

target function to optimize and the physical infrastructure. In the case at hand, the main objective is to maximize the energy produced by the PV system to charge the battery and to limit the power drain from the distribution grid. It is worth recalling that this peculiar BES system can work in three different modes: charge, discharge or mixed charge/discharge. The mixed operating mode allows the battery to supply the load while it is charged from the grid or by the PV generator. The charge/discharge mode can be enabled only when the state of charge (SOC) of the battery is between $\text{SOC}_{max} = 74\%$ and $\text{SOC}_{min} = 35\%$, respectively. Since the BESS charging current $I_{ch}$ is fixed, in order to use only the PV energy for charging, it is necessary that $I_{PV} \geq I_{ch}$, where $I_{PV}$ is the current generated by the PV system. Therefore, the minimum amount of PV power $P_{PVmin}$ able to charge the BESS is achieved when $I_{PV} = I_{ch}$. The flow-chart of the whole control algorithm implemented in the iBEMS is shown in Fig. 3.

The BEMS collects the DC or AC load active power values (denoted as $P_{DC-load}$ and $P_{AC-load}$, respectively), the power generated by the PV system and the BESS SOC. If the load power is different from zero, the SOC is between $\text{SOC}_{max}$ and $\text{SOC}_{min}$ and the power generated by PV is greater than $P_{PVmin}$, then the BEMS drives the BESS into charge/discharge mode. On the contrary, if SOC$\geq$ $\text{SOC}_{max}$, the BESS is driven into discharge mode. Finally, if SOC$\leq$ $\text{SOC}_{min}$ the load is disconnected and the recharge is possible only if the power generated by the PV system is larger than a minimum value. For the sake of completeness, the flowchart in Fig. 3 shows also the case when no energy demand is present. In this case, depending on the SOC and PV production, the BES system can be charged only. Otherwise, no actions are taken.

It is relevant to mention that the proposed control strategy can work with multiple load profiles, e.g. due to different buildings or to changeable conditions of the same building. In the next section, some experimental results will show the effectiveness of the control strategy and behavior of the prototype system.

## IV. Experimental Results

Before running the system for a long period, some preliminary experiments have been conducted for some days to check the proper operation of the control algorithm, communication interoperability and correct data transfer. To this purpose, the DC load emulator has been configured with the active power profiles measured in the common area of a shopping mall located in Catania, Italy, and reduced by 50%. An example of daily power profiles is shown in Fig. 4. Note that the

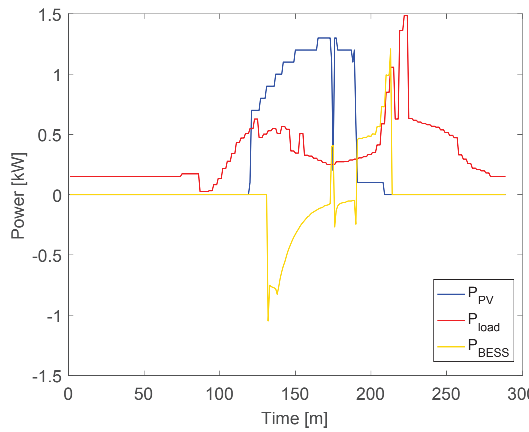


Fig. 4. Daily profile examples of PV power generation (in blue), DC load (in red) and BES (in yellow).

load power profile denotes a significant consumption even at nighttime due to the lighting and refrigerating systems of the shopping mall. The profile shows consistent behavior with the control algorithm in Fig. 3. In particular in the considered spring day, we can note that at daytime the BESS is set in

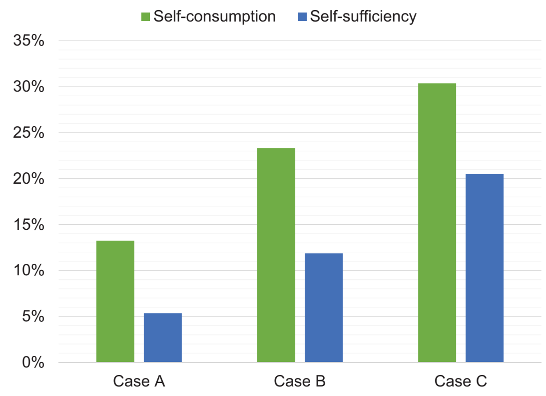


Fig. 5. Monthly self-consumption and self-production for two different load profiles.

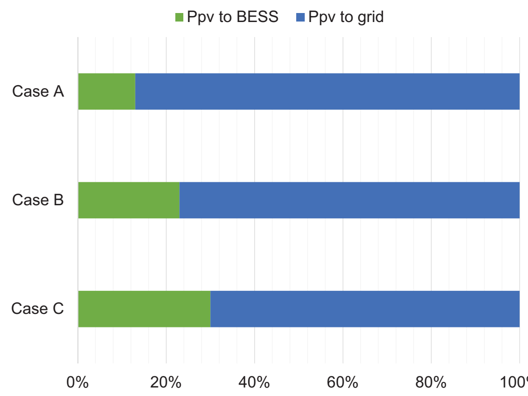


Fig. 6. Percentage of energy produced by PV generation which is stored into the battery (in green) and injected into the grid (in blue).

mixed mode due to the presence of PV generation. Indeed the system is able both to meet the power demand and to charge the storage system. Afterwards, when the PV power is lower than a given threshold, according to the rules defined in Fig. 3, the load is supplied by discharging the BESS. Observe that when the power flows into the BESS (i.e. for charging) this is conventionally regarded as negative. On the contrary, when the power is drawn from the battery, this is positive.

After the preliminary tests described above, the prototype system has worked for several weeks with different power load profiles in order to evaluate *self-consumption*, *self-production* and the reduction in $CO_2$ emissions. The *self-consumption* was computed as the percentage of energy consumed on site over the all PV production, while the *self-production* is given by the energy consumed on-site over all energy demand.
Three series of experiments with different kinds of profiles have been conducted. The demand profiles are based on the consumption measured in 2014 in the common area of a shopping center located in Catania, Southern Italy. Further details on load profiles and building configurations can be found in [15]. Since the prototype has been designed and developed under the CommONEnergy project [9], the main objective of the experimental campaign is to evaluate the impact of PV-BESS on the reduction of shopping mall energy consumption through the retrofitting solutions developed in the project itself. In particular, considering the same reference building (i.e. the shopping mall in Catania) the three tests will be denoted with:

- *Case A*: when the electricity profiles are properly scaled, but no retrofitting solutions are used;
- *Case B*: when the energy demand is reduced by 50% through basic retrofitting;
- *Case C*: when the energy demand is reduced by 75% by using the retrofitting solutions able to meet the targets of the project.

Every test was performed over 20 days during summer 2017, since in that period PV production was maximum. It is evident from Fig.5 that when demand decreases, the percentage of *self-consumption* and *self-production* increase considerably from *Case A* to *Case C* (i.e. from 13% - 5% to 30% - 21%, respectively). It is interesting noticing that even in the case of 75% demand reduction, 70% of the electrical energy is supplied by the grid. This result suggests that the prototype system emulates a real scenario. Indeed, the large loads that characterize a shopping mall can be just partially covered by a PV (or PV-BESS) system, as reported also in [7]. Fig. 6 reports the percentage of PV production injected into the grid or stored into the battery in *Cases A, B and C*. Of course, the reduction of energy demand increases the fraction of available energy based on sustainable sources. In order to give an idea of the environmental impact of the proposed system, the available energy consumption data have been also used to evaluate the $CO_2$ emission reductions. The conversion coefficient for Italy is $k_{CO_2} = 0.483$ [16]. The values obtained in *Cases A, B and C* are shown in Tab. I. These results confirm that the energy benefits of the joint use of PV and BESS depend not only on the management strategy implemented on the BEMS, but also on the actual energy demand. Therefore, a strong correlation exists between the need for energy efficiency in buildings and the impact of PV-BES systems.

TABLE I. $CO_2$ EMISSION REDUCTION

| | **$CO_2$ emission reduction** |
|---|---|
| **Case A** | 5% |
| **Case B** | 12% |
| **Case C** | 20% |

## V. CONCLUSION

The need to meet the efficiency and sustainability requirements imposed by both national governments and the EU require energy management systems able to optimize local power generation based on renewable sources and actual electricity demand of buildings. The prototype energy management system presented in this paper and coordinating PV generation and battery storage systems (BESS) is conceived to address this issue in shopping malls. The experimental results performed using real power profiles uploaded into a load emulator confirm and quantify the benefits of PV-BESS system even in prsence of large energy consumption like in shopping mall context, especially if proper smart control startegy is implemented and the energy consumption are reduced thanks to retrofitting actions. The small-scale prototype described in this paper has been useful to optimize and test the interoperability of different components under different operation mode in order to pave the way for a pilot system installed in a real shopping mall.

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