Economic Analysis of a Hybrid Storage System Associated to PV Sources and Supervised by Fuzzy Logic Power Management

Xingyu Yan, Dhaker Abbes, Antoine Labrunie, Youssef Krim, and Benoit Robyns

Abstract This study concerns a grid-tied photovoltaic (PV) generator related to a hybrid storage system composed of lithium NCA battery (energy source) and Maxwell supercapacitor (power source). Two supervision algorithms have been proposed for energy management system (EMS): a Boolean and a fuzzy logic EMS. Moreover, a comparative study between both supervision algorithms based on levelized cost of energy (LCOE) and the lifespan of the storage system has been suggested. The economic analysis is done with two different planned PV power production profiles: one with a "clear sky" bell curve and a second with an ideal forecast. The supervisor based on Boolean method is simple and easy to understand, while the fuzzy logic method offers more flexibility in supervision. It improves the battery lifespan and system performance a little and reduces significantly the system penalties. The simulation results show for all scenarios the achievement of the planned aims in terms of respect of the production program taking into account the constraints of the electrical network manager with an LCOE below 130 €/MWh.

1 Introduction

Worldwide, renewable energy sources (RES) such as photovoltaic (PV) and wind generators are increasingly becoming significant sources for power and will consequently minimize the use of fossil fuels as energy production means. However, being highly meteorologically sensitive, RES face the challenges of large-scale using and

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W. Zamboni, G. Petrone (eds.), *ELECTRIMACS 2019*, Lecture Notes in Electrical Engineering 615, https://doi.org/10.1007/978-3-030-37161-6_52

are withdrawn by their intermittent form with uncertain availability. To maintain secured operation and system reliability with a high penetration level of RES, energy storage system (ESS) is required to mitigate uncertainties of RES power production in more and more grid codes to deal with their intermittent nature [1]. If suitably deployed, ESS can help operators to manage the fluctuation in generation and load.

However, batteries' energy storage faces limitations, such as high cost, lifespan limited by the number of charge/discharge cycles, and inverse proportionality between specific energy and specific power. Instead, several storage devices with different capacities will be required [2]. The combination of two storage technologies and development of an intelligent power management overcome the intermittences of the renewable PV generator, facilitate the integration of the RES into the grid, and increase the longevity of storage elements.

Despite the advanced installation of several large-capacity storage systems in various industrial applications, there is not yet a storage device characterized by both a high density of power and energy. These storage technologies are actually in exploration. Therefore, several research projects are actually established by the European Union and suggest ancillary services using hybrid storage systems, such as the GROW-DERS project [3], which combines Li-ion battery and flywheel energy storage. In [4], by inserting a supercapacitor power storage device with battery, ESS achieves the improvement of the battery lifespan and a good frequency adjustment [5, 6].

Management of electrical ESS is a significant research field, more precisely in association with renewable distributed generators, such as photovoltaic (PV) power systems. Indeed, besides energy management of power flow, many purposes (grid services, state of charge of storage systems, lifespan and aging, etc.) are considered altogether. In addition, integration of two storage systems with complementarity of energy and power characteristics can support system operators to reach energy management goals much easier while ensuring an improvement of lifespan to some sensitive components (such as supercapacitors and batteries, flywheel and batteries, etc.).

In this context, a supervision algorithm based on fuzzy logic is suggested to manage the power flow between different energy sources. The fuzzy logic supervision (FLS) methodology for energy management system (EMS) is now in development in many applications like EMS for polygeneration microgrids [7] and for islanded hybrid renewable generator [8] and EMS for DC microgrid systems [9]. Furthermore [10], depict an EMS where the FLS considers the variation of the energy demand, total cost in 1 day, and the production in order to ensure an accessible grid. In this concern, it can be marked that the respect of production schedule and participation in frequency control are not explored in these aforementioned studies as principal objectives of the EMS.

This study presents a PV generator that is associated with two storage systems (lithium NCA battery for energy needs and lithium NCA battery and Maxwell supercapacitor for power demands) to establish a hybrid storage system (HSS). To manage the powers in this hybrid PV and storage system, two supervision algorithms are developed. The first supervisor is with Boolean logic. The second is an FL EMS that manages the HSS and includes power demand forecasting and frequency regulation.

In this framework, a comparative analysis based on economic criteria is put forward. It is made between both supervision methods using LCOE and battery lifespan as comparison criteria. Generally, RES generation forecasting is needed for scheduling and system operation [11]. Therefore, two different PV production profiles are proposed. They are based on two extreme scenarios: the first one is planned PV power production with "clear sky" bell curve profile, while the other is with ideal forecast.

2 Hybrid Power System Description

Figure 1 depicts the architecture of the PV power generator combined with energy storages in a DC coupled structure. The HSS station is composed of two complementary storage technologies: SC for short-term storage power and battery for long-term storage energy.

Figure 2 illustrates the structure of the energy management supervisor to manage the power flow. It ensures many purposes at once (lifespan of storage system, auxiliary services, availability and levels of storage). In this study, the EMS aims to satisfy 1-day-ahead production planning and control of the state of charge (SoC) of each storage system and participate in frequency regulation.

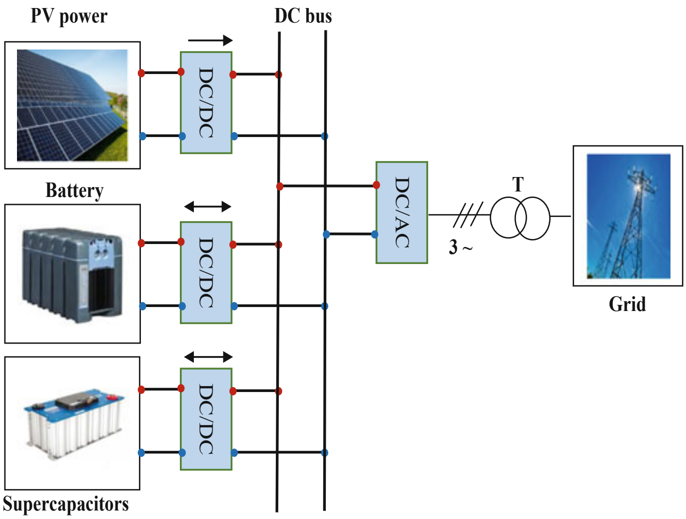


Fig. 1 Architecture of PV system with storages

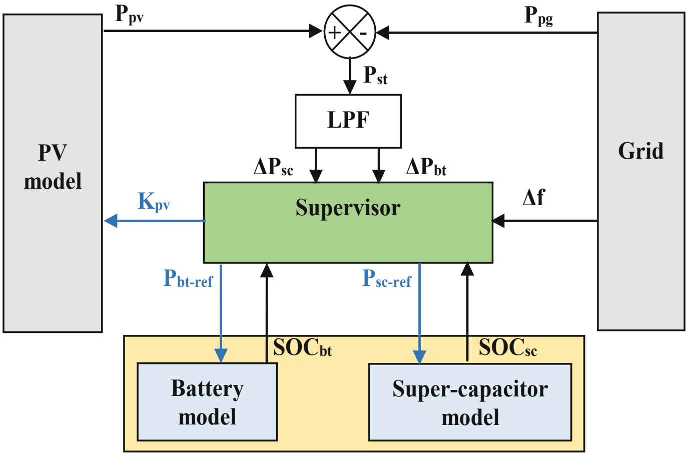


Fig. 2 Management structure of the studied system

The daily operation of the PV power plant should follow the scheduled production to maintain system reliability. It has to satisfy operational constraints and to respond to dynamic disturbances, such as frequency control with primary and secondary reserves [12]. Thus, as an innovative part of our application, the storage system must be able to provide active support power based on frequency deviation.

3 Hybrid Storage System Supervisor

3.1 Supervisor Methodology and Objectives

The supervisor is designed for energy management of the studied PV system associated with battery/supercapacitor hybrid storage system. The purpose of the EMS is to generate a reference power minimizing system cost and fulfilling the commitment to the grid. Table 1 outlines supervisor objectives, constraints, as well as means of actions for the supervision system shown in Fig. 2.

3.2 Supervisor with Boolean Method

Figure 3 depicts the supervisor algorithm with Boolean method for validating the models. The power difference (ΔP) between real-time produced power (P_{pv}) and day-ahead programmed power (P_{pg}) is covered by energy storages separated through a first-order low-pass filter: the high variation power in short time can be absorbed by supercapacitor (P_{sc}), while the other is captivated by battery.

Table 1 EMS operating specifications

Objectives	• Meeting a production program and smoothing the power injected to the grid • Optimizing storage energy management and improving storage lifespan
Constraints	• PV production intermittency • Storage lower/upper capacity and charge/discharge power limitations • Penalties will be applied if the programmed power is not respected
Means of actions	• Injecting to the electrical network the planned PV power with the help of the two storage systems • Degradation of the PV production • Power storage

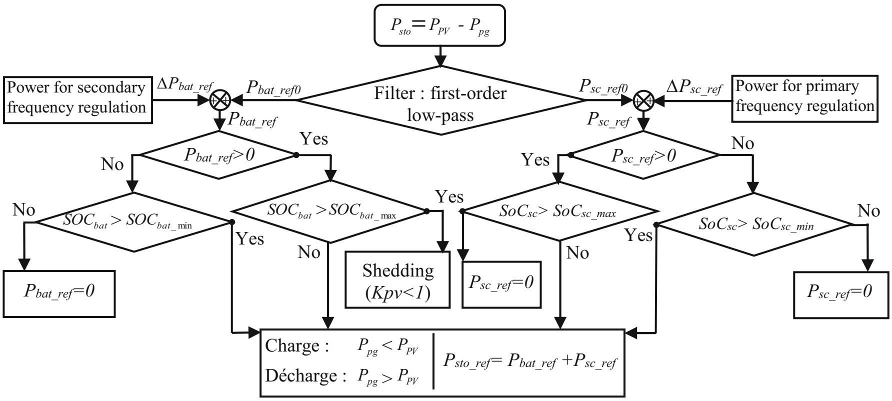


Fig. 3 Hybrid storage system supervisor with Boolean method

Supercapacitor power reference P_{sc_ref} is the sum between the initial reference P_{sc_ref0} and the power ΔP_{sc_ref} dedicated for primary frequency regulation.

Battery power reference P_{bat_ref} includes initial reference P_{bat_ref0} and frequency support power ΔP_{bat_ref}. In case of storage overcharge, a security function rapidly degrades photovoltaic production to protect the storage system.

The Boolean logic has limited performances, such as significant penalty. Thus, the purpose of the next part is to develop an intelligent approach based on fuzzy logic.

3.3 *Supervisor with Fuzzy Logic*

Instead of using the Boolean method, in this part, a supervisor with a fuzzy logic methodology is developed. Figure 4 presents the structure of the developed EMS.

Fuzzy logic approach is chosen since linguistic rules can simplify the control and management of such HSS, with many objectives and constraints.

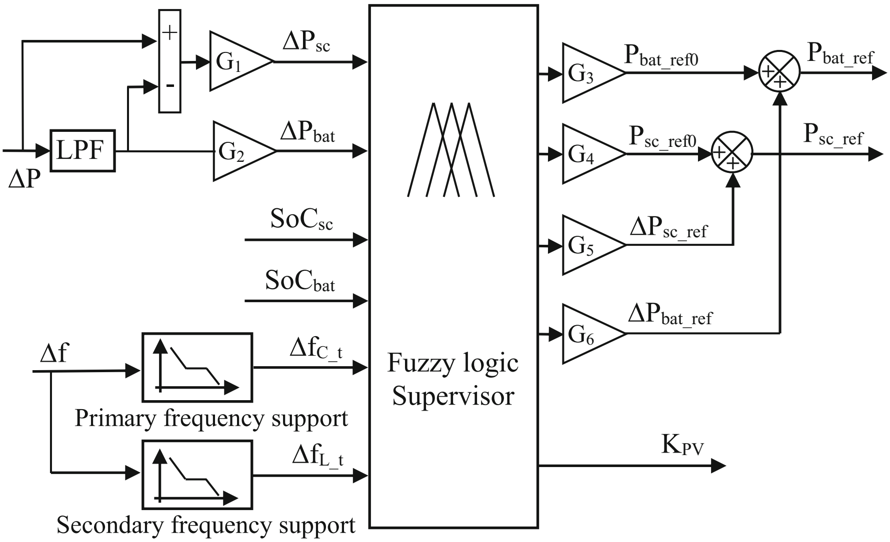


Fig. 4 Block diagram of the fuzzy logic supervisor

Normalization gains ($G_{i=1:6}$) are defined according to input and output membership functions as follows: $G_1 = 1/P_{sc\text{-}max}$, $G_2 = 1/P_{bat\text{-}max}$, $G_3 = P_{sc\text{-}max}$, $G_4 = P_{bat\text{-}max}$, $G_5 = 0.08 \times P_{sc\text{-}max}$, and $G_6 = 0.02 \times P_{bat\text{-}max}$. $P_{sc\text{-}max}$ is the maximum power of supercapacitor and $P_{bat\text{-}max}$ is the maximum power of battery.

Inputs are battery (ΔP_{bat}) and supercapacitor (ΔP_{sc}) powers from demand and production difference and battery SOC (SOC_{bat}) and supercapacitor SOC (SOC_{sc}) powers for first frequency regulation (Δf_{C_t}) and for secondary frequency regulation (Δf_{L_t}). Outputs are the references sent to the means of actions: battery power reference (P_{bat_ref}), supercapacitor power reference (P_{bat_ref}), and degradation factor K_{pv} used for safe operation of the battery.

According of the SOC of storage elements, three operation modes are considered [13].

The variation margin of battery SOC is chosen between 20% and 90% of its capacity. These limits offer a safety margin against possible overcharge and excess of discharge.

4 Financial Parameters of Production and Remuneration

4.1 Remuneration and Penalties

The economic indicators suggested in this paper are remunerations and penalties. Indeed, the remuneration of produced power is calculated every minute. In addition, if the production, for each minute, does not respect this announcement (commitment production in day 1) with a tolerance of ±5% of installed capacity, penalties will be applied. The calculation method of the penalties is detailed in [14] and the Annex 9 of the document [15].

4.2 Notion of LCOE

In this sub-section, we calculate the total cost LCOE. Parameters taken into account are the following:

Lifespan of the PV plant with 30 kW rated power: nb_years = 25 years.

Price of building the PV plant (including PV panels and the costs of installation): $C_{PV} = 1$ €/Wc.

Cost of lithium ion batteries (including the costs of transformer station, converter, installation, and transportation): $C_{bat} = 550$ €/kWh, with a replacement cost of 200 €/kWh after 12–15 years.

Price of Maxwell supercapacitor (including the costs of converter, transportation, installation, and transformer stations): $C_{sc} = 500$ €/kW (estimated lifespan is 14 years), with a replacement cost of 200 €/kW. In our case, the nominal power of the supercapacitor is 5 kW and its capacity is 52.8 Wh.

Costs of maintenance and operation (M&O) of PV system each year: $O\&M_{PV} = 20$ k€/MWc (taking into account a discount rate of $r = 2\%$).

Estimated costs of M&O of storage system each year: $M\&O_{sto} = 20$ k€/MWc.

The LCOE is calculated as total cost divided by total energy. $LCOE_p$ represents the cost with penalties, while LCOE represents the cost without penalties.

$$\mathrm{LCOE} = \mathrm{Cost} / \sum E_{\mathrm{Prod}} \tag{1}$$

with: $\mathrm{Cost} = (C_{PV} + C_{bat} + C_{sc} + M\&O_{PV\_total} + M\&O_{sto\_total})$

$$\mathrm{LCOE_p} = \mathrm{Cost_p} / \sum E_{\mathrm{Prod}} \tag{2}$$

with: $\mathrm{Cost_p} = (C_{PV} + C_{bat} + C_{sc} + M\&O_{PV\_total} + M\&O_{sto\_total} + \mathrm{Penalty})$

The total M&O cost of storages during 25 years (nb_years) is calculated as $M\&O_{sto\_total} = M\&O_{sto} \times (1 + r)^{nb\_years}$, and so as to the total costs of PV M&O.

The total energy production is calculated as $\Sigma E_{prod} = E_{prod} \times nb_{years} \times (d)^{nb\_years}$, with $d = 0.5\%$/year being the degradation rate of PV production per year.

5 Case Studies and Simulation Results

In this section, three detailed comparative studies based on economic criteria are presented. They aim to analyze:

- The influence of the filter constant on battery lifespan, penalties, and $LCOE_p$. We change the filter parameter.
- The influence of production schedule profiles, profile without forecast and profile with forecast, on battery lifespan.
- The performances of fuzzy logic method compared with Boolean method.

5.1 PV Production Profiles

A system with 30 kW rated PV power and an energy storage system are taken into consideration. For production programming, we studied two extreme configurations as shown in Fig. 5.

Real PV power production P_{PV} is on blue color, planned PV power P_{pg} without forecasting is on yellow, and broken black line is the ideal forecasted PV power production.

Absence of production forecast: the forecast corresponding to a reference irradiation ("clear sky," bell curve) multiplied by a gain equal to the ratio between the annual production and the annual reference irradiation.

Ideal production forecast: the committed production is produced on the assumption that there is a very good forecast. This planned profile is obtained based on the real production with a filter which follows the following rule: the difference between two successive values (in 1 min) must be below ±5% of installed power, which is 30 kW in this case, as described in Annex 10 of the document [15].

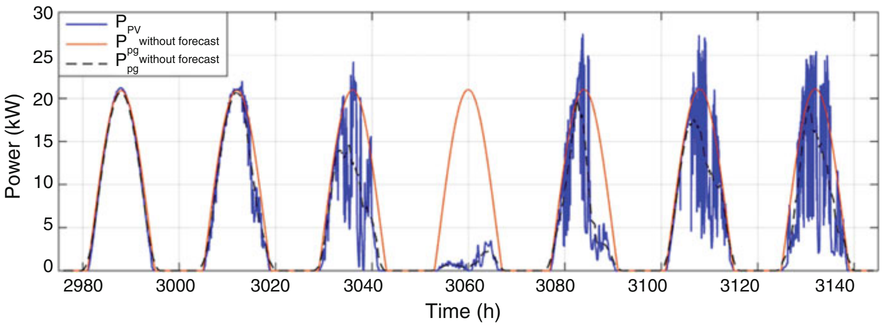


Fig. 5 PV power actual production (in blue), production without forecasting (in red), and ideal production forecast (in orange), example over 7 days

5.2 Filter Choosing

According to the two proposed methodologies for supervisor, there will be four scenarios. The acronyms for different scenarios are defined as follows:

FBC: Supervisor with fuzzy logic, planned PV with bell curve (without prediction)
BBC: Supervisor with Boolean, planned PV with bell curve (without prediction)
FIP: Supervisor with fuzzy logic, planned PV with ideal prediction
BIP: Supervisor with Boolean, planned PV with ideal prediction

In this case, different filter durations (from 60 to 180 s) are studied with the Boolean methodology. Table 2 shows the comparison results of two scenarios: without prevision (BBC) and with ideal prevision (BIP).

Compared with the BBC scenario, the total remuneration in 25 years of scenario BIP is larger because of the precise prediction of the PV power production. For the same reason, the penalty in 25 years is much less.

For lifespan of battery lithium NCA (18 kW), scenario BIP (14.89 years for filter time of 120 s) has a much better performance than scenario BBC (12.34 years for filter time of 120 s).

LCOE is the same for both scenario BIP and BBC, as 96.8 €/MWh. Nevertheless, since the penalty is bigger, the $LCOE_p$ is greater for scenario BBC (105.2 €/MWh for filter time 120 s) than the scenario BIP (98.3 €/MWh for the same filter) and batteries have more extreme situations and thus a shorter lifespan. However, to relativize, we have to include the extra cost for forecasting. In addition, the actual forecast will have a much worse performance than this ideal forecast scenario.

5.3 Comparison of Different Storage Configurations

In this part, the battery sizing effect is studied with Boolean method according to different battery power: from 9 to 31.5 kW. The filter time is chosen as 120 s. The capacity of the supercapacitor is 52.8 Wh and its nominal power is 5 kW.

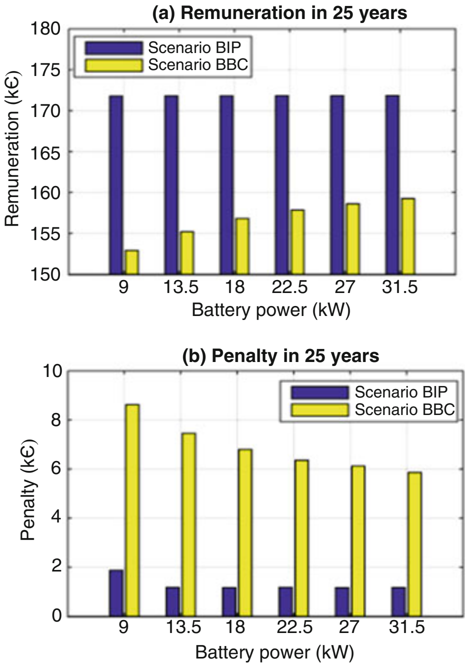
The comparative framework is between ideal and bell curve inputs for solar power production: it is a comparison based on economic criteria, which allows us to choose between paying penalties and buying good forecasts. For the scenario BBC, as the battery power is increasing, the remuneration increases slightly, while penalty has a significant decrease (Fig. 6). Without forecast, the errors between the planned PV production and real PV production could be much greater than the maximum energy storage (mainly battery) size and batteries will saturate more frequently. Therefore, this scenario could cause bigger penalties and shorter battery lifespan.

LCOE is the same for both scenarios, while $LCOE_p$ for the scenario BBC is bigger than the scenario BIP. It is not a surprise because the penalty in scenario BBC is bigger than in scenario BIP, as shown in Fig. 7.

Table 2 Studied results of different filter times with Boolean method

Filter (s)	BBC Rem. in 25 years (k€)	BBC Penalty in 25 years (k€)	BBC Lifespan (year)	BBC $LCOE_p$ (€/MWh)	BBC LCOE (€/MWh)	BIP Rem. in 25 years (k€)	BIP Penalty in 25 years (k€)	BIP Lifespan (year)	BIP $LCOE_p$(€/MWh)	BIP LCOE (€/MWh)
60	158	8.0	12.32	106.8	96.8	172	11	14.83	98.1	96.8
90	157	7.0	12.33	105.5	96.8	172	11	14.87	98.2	96.8
120	157	6.8	12.34	105.2	96.8	172	1.2	14.89	98.3	96.8
150	157	6.7	12.34	105.1	96.8	172	1.2	14.90	98.3	96.8
180	157	6.7	12.34	105.1	96.8	172	1.2	14.91	98.3	96.8

Fig. 6 (**a**, **b**) Remuneration and accumulated penalties over 25 years depending on battery sizing and production profile type



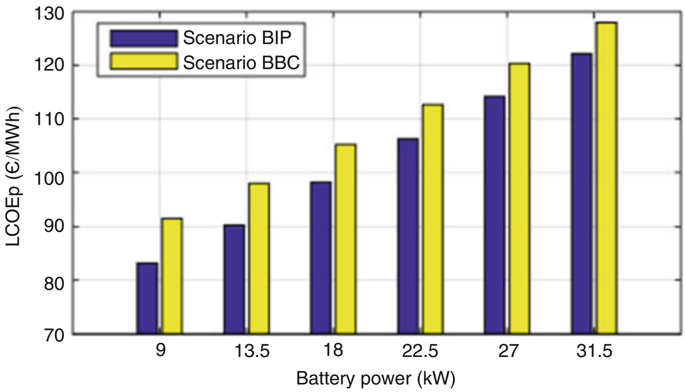


Fig. 7 LCOEp depending on the different battery sizing

5.4 Comparison of the Boolean method with the Fuzzy Logic Method

For the remuneration during 25 years, scenario BBC has a slightly better performance than scenario FBC, as shown in Fig. 8a. At the same time, the penalty during 25 years is less for scenario FBC than scenario BBC (Fig. 8b). As battery size increases, remuneration increases, while penalty decreases due to less extreme

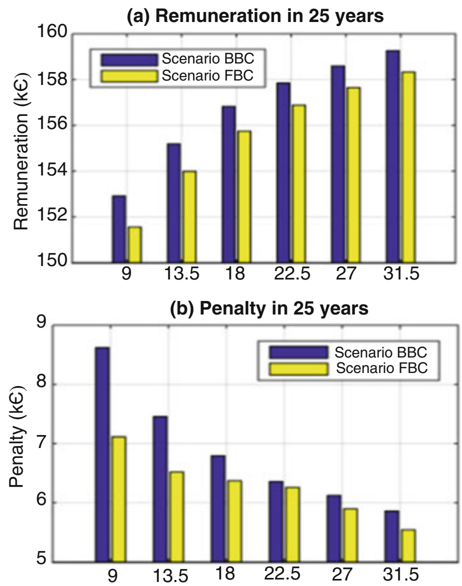


Fig. 8 (**a**, **b**) Remuneration and accumulated penalties over 25 years depending on the battery sizing

situations for battery charge and discharge. The remuneration gap between scenario BBC and scenario FBC is almost constant when the battery sizing increases, while penalty gap decreases for battery power from 9 to 22.5 kW and then increases a little at battery power of 31.5 kW. Therefore, we can conclude that increasing battery size decreases system penalty.

Figure 9 illustrates the battery lifespan in different scenarios. The lithium NCA battery lifespan with an ideal PV power forecasting (scenarios BIP and FIP) is longer than in scenarios without PV power forecasting (BBC and FBC). For the same planned PV power production (scenarios BIP and FIP or scenarios BBC and FBC), the battery lifespan is slightly longer for the fuzzy logic method than Boolean method.

Since LCOE has almost no difference for all the scenarios (from 81 €/MW h with a battery size of 9 kW to 121 €/MW h with a battery size of 31.5 kW), only $LCOE_p$ has been studied in Fig. 10. The same as the battery lifespan, scenarios with ideal prediction (BIP and FIP) have smaller $LCOE_p$ than scenarios without PV power forecasting (BBC and FBC). Moreover, even though $LCOE_p$ for scenarios BIP and FIP has no big difference, it is smaller for scenario FBC than scenario BBC.

Consequently, we could conclude that the supervisor based on the fuzzy logic method performs better than that based on Boolean method even though it is not much. In the future, the performance could be improved by applying optimizing fuzzy membership functions and thus rules.

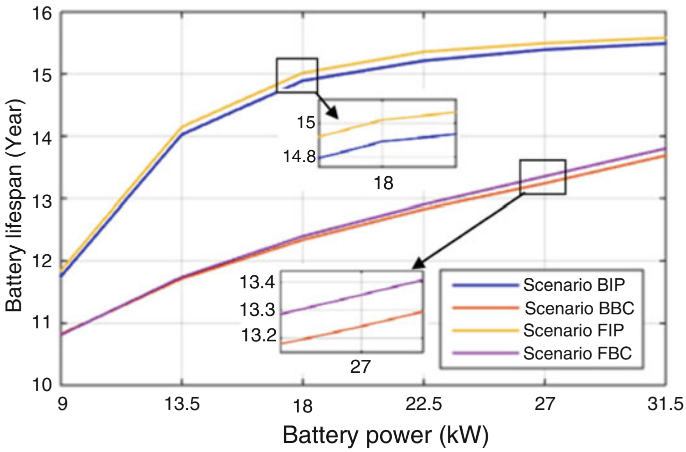


Fig. 9 Battery lifespan for different scenarios

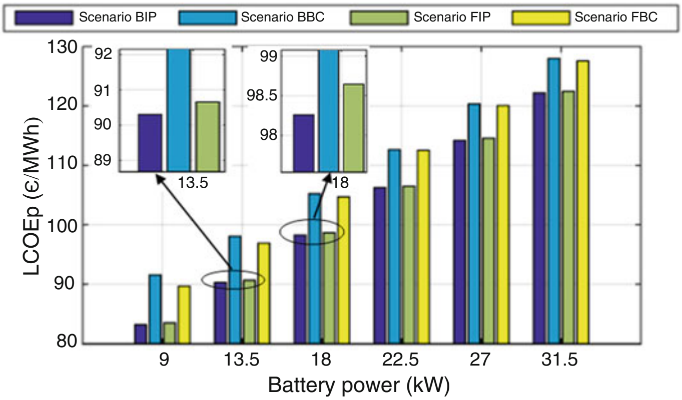


Fig. 10 $LCOE_p$ for different scenarios depending on battery sizing

6 Conclusions

This paper has proposed a detailed comparative study for a hybrid storage system associated to photovoltaic power with:

- Two complementary storage systems (lithium NCA battery for energy needs and lithium NCA battery and Maxwell supercapacitor for power needs).
- Two different PV production profiles proposed: the first one is planned PV power production with "clear sky" bell curve profile, while the other is with ideal forecast.
- Two supervision algorithms developed: one with Boolean logic and another with fuzzy logic.

- New criteria of comparison: battery lifespan, penalties, and LCOE.

The supervisor based on Boolean method is simple and easy to understand, while the fuzzy logic method offers more flexibility in supervision and improves battery lifespan and system performance a little. It also reduces significantly system penalties.

In BBC scenario, the errors between the planned PV production and real PV production are more important than the battery capacity, which causes a reduction of the battery lifespan and bigger penalties. However, to relativize, we have to include the extra cost for forecasting. In addition, the actual forecast will have a much worse performance than the ideal forecast used in this paper.

Finally, a perspective of this study is to explore a joint optimization method of the battery sizing and the membership functions of the fuzzy logic EMS to reduce the LCOE.

Acknowledgments This work was founded as a part of the CRE PV call of 2015 (research component) and also of the DEESSE Project founded by ADEME, France.

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