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Energy Management of a Hybrid Photovoltaic-Wind System with Battery Storage: A Case Report

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ABSTRACT

This work presents a case report related to the management and the monitoring of a hybrid photovoltaic-wind system with battery energy storage, installed at the administrative offices building of the municipality of Valderice (Italy) within the framework of the Italy-Tunisia ENPI cooperation project Le Développement Durable Dans la Production Energétique Dans le Territoire (DE.DU.ENER.T.). The paper describes the hybrid system and briefly reports the monitoring data for a whole year, comparing the real production with the expected one and evaluating some performance indexes of the system. The performance indexes are very simple and have been defined only with the purpose of showing the advantages of distributed generation. Then, two different control logics for the battery energy storage systems are compared in order to define the most suitable management of the local energy resources, in presence of different Time-of-Use electricity tariffs. In particular, the two logics are compared by varying the difference between the electricity prices in peak hours and in off-peak hours and the rate between the electricity consumption of the building and the battery energy storage's capacity.

KEYWORDS

Power systems, Photovoltaic systems, Battery energy storage system, Hybrid plants, Batteries, Control logics, Sustainability, Distributed generation.

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INTRODUCTION

The development of sustainable technologies for electrical systems and of new Renewable Energy Sources (RES) based generators, together with the deregulation of the electricity market, has led to a growing penetration of Distributed Generation (DG), Building Automation and Control (BAC) systems and Information and Telecommunication Technologies (ICT) applications and components, thus transforming the electrical distribution system. In this scenario, the issue of the optimal management of the available electrical [1] and thermal [2] energy resources and loads [3] also at end-user level is getting more and more attention.

At the same time, in the last few years, Li-ion batteries have become common components of commercial Photovoltaic (PV) systems [4], opening the way to new possibilities for the optimal exploitation of the energy produced by such systems, in particular, in the presence of net-metering policies or residential time-of-use tariffs [5]. As an example of the works in literature on this topic, in [6], the behavior and efficiency of a low-cost isolated photovoltaic system for typical rural houses near Luena in Angola are examined, while in [7] the authors present an economic optimization of battery operation for two different applications in residential buildings under different dynamic tariff structures. In [8], the performance of a household battery energy storage system with a Li-ion battery pack and a single-phase converter are studied. In [9], a new methodology to enable high penetration of PV systems in Low Voltage (LV) grids by using shared battery storage and variable tariffs is proposed. In [10], a technical economical analysis is performed for determining the cost optimal configuration for a PV plant with batteries considering the share of self-consumption, the degree of autarky, grid feed-in and supply as well as various battery system parameters.

Moreover, thanks to Li-ion batteries, Demand Response (DR) policies [11] can experience new possibilities. In [12], the authors describe a distributed control method for residential Battery Energy Storage System (BESS) coupled with PV plants for using customer owned storage units for solving the over-voltage issues caused by high PV penetration. In [13], an overview of some recent initiatives for exploitation of local storage systems and DR as a solution for achieving a stable operation of renewable energy sources-based microgrids. In [14], the issue of voltage quality improvements using PV systems is discussed.

For exploring the opportunities given by RES generators coupled with innovative storage systems, two different hybrid Photovoltaic-Wind systems with storage were built in Valderice (Italy) and in Borj-Cédria (Tunisia) within the framework of the international cooperation project Le Développement Durable Dans la Production Energétique Dans le Territoire (DE.DU.ENER.T) [15]. The systems comprise:

- A PV generator;
- A micro-wind generator;
- BESS.

In literature some works deal with hybrid RES systems and are mainly focused on autonomous power supply in case of grid shortage [16], operation of grid-off systems [17], applications related to rural electrification and remote community [18] or power quality improvements [19].

The current work, starting from the data obtained from one year of monitoring of the Valderice installation, analyzes the behavior of the hybrid system evaluating some performance indexes and shows a comparison between two different algorithms for the management of the BESS. The two BESS management algorithms have been presented in [20] and are tested here, taking into account various electricity tariffs, suitable for the considered end-user. In the following, the comparison between the algorithms is done considering only the daily economic savings, having assumed that the system is already in operation. Therefore, no considerations on the capital investment cost or on the economical viability of the investment are provided.

The rest of the paper is structured as follows:

- The two BESS management algorithms are described and four performance indexes are defined for comparing them;
- The hybrid system is introduced and the production data in the period March 2016-February 2017 are shown;
- A comparison of the algorithms in various cases is presented changing the electricity tariff;
- Finally, the conclusion of the work are given.

METHODS

In this section, the BESS management control logics are presented together with three indexes for their comparison.

Battery Energy Storage System management control logics

Two different management control logics, named System Led and Market Led, for combined RES-BESS generators connected to the LV utility grid are described in the following. The control logics have been implemented with the aim of:

- Increasing the self-consumption quota in order to minimize the exchange of energy between the end-user and the grid;
- Reducing the yearly energy bill, fully exploiting the advantages of Time of Use (ToU) tariffs.

System Led

According to the System Led control logic, the Energy Management System (EMS) installed at the end-user's facility acquires:

- The energy generated by the PV system (E_{p1});
- The energy generated by the wind system (E_{p2});
- The energy consumption of the building (E_c);
- The BESS State of Charge (SoC) (E_{st}).

On the basis of these data, the EMS command the combined RES-BESS system according to the flow chart represented in Figure 1.

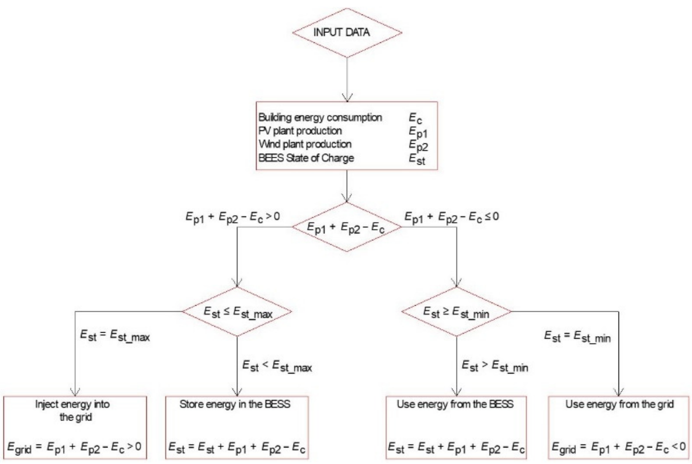

Figure 1. Block diagram representing the System Led control logic

In the case that the total production exceeds the building's energy consumption and SoC of the batteries is lower than the maximum SoC (E_{st_max}), the energy in excess is stored in the batteries, otherwise is injected into the grid.

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On the contrary, in the case that the energy production is lower than the energy consumption of the building, if the SoC is higher than the minimum SoC (E_{st_min}) the batteries supply the building, otherwise, the required energy is taken from the grid.

Market Led

As formulated, the System Led algorithm is not able to take into account the effect of ToU tariffs and consequently, it cannot be used for an optimal economic exploitation of the BESS.

For this reason, a second control logic has been defined, named Market Led algorithm. This control logic is based on the variations of the electricity price during the day (and the week). The Market Led control logic has been defined considering the three pricing periods for Italian end-users [21, 22] reported in Table 1.

The end-users' EMS, equipped with an internal clock and calendar, is set for recognizing the pricing period at every moment of the day.

In this case, the Market Led control logic operates according to the flow chart in Figure 2. When the building's electricity consumption is lower than the electricity production from the generating unit, different situations can happen:

Table 1. Italian pricing periods

F1	F2	F3
Peak price period: from Monday to Friday from 8:00 to 19:00	Medium price period: from Monday to Friday from 7:00 to 8:00 and from 19:00 to 23:00 and Saturday from 7:00 to 23:00	Off-peak price period: all remainder hours of the week and holidays

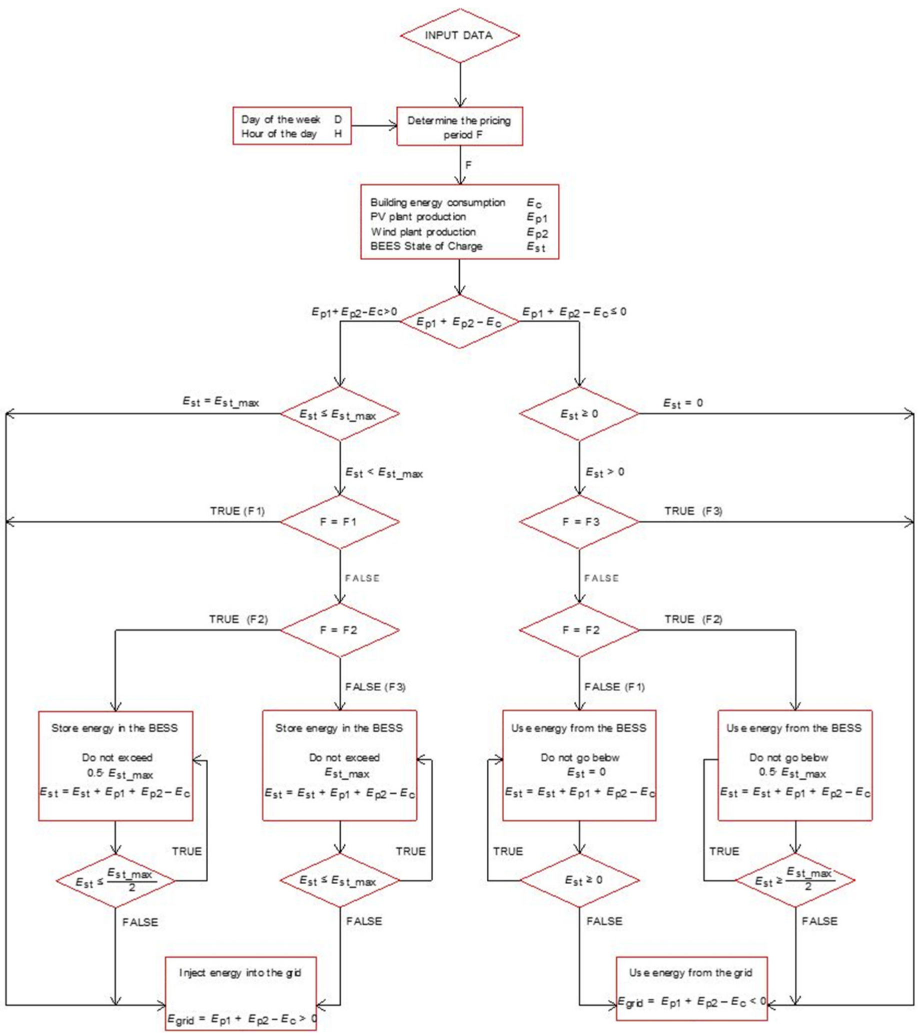

Figure 2. Block diagram representing the Market Led control logic

- During pricing period F1, the energy in excess is injected into the grid because the selling price is the highest and the end-user can achieve the maximum revenue;
- During pricing period F2, the production in excess is stored in the batteries. In this case, the charge of the batteries rises till $E_{st\_max}/2$. When this limit is exceeded, the production in excess is injected into the grid;
- During pricing period F3, the energy in excess is stored in the batteries again. In this case the charge of the batteries rises till E_{st_max}. When this limit is reached, the energy in excess is injected into the grid.

On the contrary, when the building's consumptions exceed the generated electricity:

- During pricing period F3, the grid supplies the building because the electricity price is the lowest and the cost for the end-user is minimum;
- During pricing period F2, the energy is taken from the batteries till the SoC is over $E_{st\_max}/2$ and when the SoC gets below this value, the energy is taken from the grid;
- During pricing period F1, the energy is taken from the batteries till the SoC is over E_{st_max}, when the SoC gets below this value the energy is taken from the grid.

Performance indexes

Three simple performance indexes have been defined for comparing the System and Market Led strategies. Indeed, their definition has been led by the purpose of providing a clear and simple set of indicators that can be easily understood even by non-technicians, in order to promote the diffusion of the culture of RES-based system among a broader public.

The three indexes are:

- Energy saving index (*EnS*);
- Economic saving index (*EcS*);
- Carbon dioxide (CO_2) reduction index (CO_2R).

Energy saving index. The energy saving index is defined as:

$$EnS = 1 - \frac{E_b}{E_a} \tag{1}$$

where E_a is the electric energy demand of the building in a month and E_b is the energy produced by the hybrid system in the same month.

Economic saving index. The economic saving index is defined as:

$$EcS = 1 - \frac{E_{b1} \times c_1 + E_{b2} \times c_2 + E_{b3} \times c_3}{E_{a1} \times c_1 + E_{a2} \times c_2 + E_{a3} \times c_3} \tag{2}$$

where E_{a1}, E_{a2} and E_{a3} are the electric energy demand of the building in the three price periods F1, F2 and F3 in a month, E_{b1}, E_{b2} and E_{b3} are the energy produced by the hybrid system in the same month for the three price periods and c_1, c_2 and c_3 are the electricity prices in the three price periods.

CO_2 reduction index. The CO_2 reduction index is defined as:

$$CO_2R = E_b \times C_e \tag{3}$$

where E_b is the total energy produced by the hybrid system in one year and C_e is the conversion coefficient from electric energy to tons of CO_2.

RESULTS

In this section, the two algorithms are applied to the management of the BESS of the hybrid PV-Wind system built in Valderice. Before presenting the results of the comparison, the system is described.

System description

The hybrid system is installed at the administrative offices building of the Municipality of Valderice, located close to Trapani (geographical coordinates: 38.02 N 12.36 E) in Italy (Figure 3).

The building is characterized by four floors and has a flat roof and external fixtures made of anodised aluminium and single glass without shutters. The covering of the building has a sufficiently regular shape and has a useful surface of about 400 m^2, with parapet walls and an elevator fence (Figure 4).

The building is supplied by the LV utility grid through a three-phase connection with available power of 20 kW, is equipped with a centralized gas boiler and has single air-conditioning units only in some rooms.

Figure 3. The administrative offices buildings of the Municipality of Valderice

Figure 4. Rooftop of the building

The study of the solar radiation map and wind speed allows the characterization of the site chosen. The building insists on a geographic area characterized by solar PV productivity of about 1,650 kWh/kWp per year and wind productivity of about 2,000 kWh/kW per year.

After performing the energy characterization of the building, the rationalization and energy efficiency measures and the areas available for the installation of the plants have been identified and, on the basis of the available budget, the optimal size of the systems micro-generation and electrical storage system have been calculated and the necessary components and devices have been chosen.

Thus, the prototype is composed of:

- A 8 kWp PV system in polycrystalline silicon, consisting of 32 × 250 Wp modules divided into two strings;
- A 1 kW Vertical-Axis Wind Turbine (VAWT);
- An electrical storage with capacity of 2 kWh (Li-ion batteries) integrated into one of the two inverters of the PV system;
- A solar-thermal system with flat collectors and a 250 liters tank for hot water storage serving 4 bathrooms and replacing electric water heaters;
- An indoor lighting controller for the offices, in order to contain the relative electrical consumption.

The following Figures 5-8 show the main components of the prototype.

Figure 5. PV field

Figure 6. 1 kW wind turbine

Figure 7. Thermal solar collectors with tank

Figure 8. Technical room

The hybrid power plant benefits from a net-metering contract.
Tables from 2 to 4 report the technical data of the PV and wind generators.

Table 2. Technical data of the PV modules

Electrical data (STC)	
Maximum power (P_{max}) [Wp]	250
Voltage at maximum power (V_{mpp}) [V]	29.89
Current at maximum power (I_{mpp}) [A]	8.36
Open circuit voltage (V_{oc}) [V]	37.62
Short circuit current (I_{sc}) [A]	9.01
Panel efficiency [%]	15.27
Powertolerance [%]	+2
Electrical data at Normal Operating Cell Temperature (NOCT)	
Maximum power (P_{max}) [Wp]	194.68
Voltage at maximum power (V_{mpp}) [V]	29.37
Current at maximum power (I_{mpp}) [A]	6.63
Open circuit voltage (V_{oc}) [V]	35.2
Short circuit current (I_{sc}) [A]	7.28
Temperature [°C]	45 ±2
Thermal rating	
Operating temperature range [°C]	−40 ~90
Temperature coefficient of P_{max} [%/°C]	−0.44
Temperature coefficient of V_{oc} [%/°C]	−0.32
Temperature coefficient of I_{sc} [%/°C]	0.059
Maximum ratings	
Maximum System voltage [V]	1,000
Material data	
Panel dimension [mm]	1,650 × 992 × 38
Weight [kg]	18
Cell type	Polycrystalline
Cell size [mm]	156 × 156
Cell number	60

Table 3. Technical data of the PV inverters

Data	Inverter 1	Inverter 2
Maximum DC power at cos φ = 1 (P_{max}) [W]	4,200	5,200
Maximum input voltage [V]	750	750
Rated input voltage [V]	400	350
Minimum input voltage [V]	125	125
Maximum input current [A]	15	15
Maximum short-circuit current [A]	20	20
Rated power at 230 V, 50 Hz [W]	4,000	3,680
Maximum apparent AC power [VA]	4,000	3,680
Ratedgrid voltage [V]	230	230
Nominal AC current at 230 V [A]	17.4	16
Maximum output current [A]	22	20.2
Maximum output current under fault conditions [A]	34	31.3
Maximum efficiency [%]	97	97.1
Storage	-	Li-ion
Capacity [kWh]	-	2
Maximum voltage [V]	-	150
Charging current [A]	-	12.5

Table 4. Technical data of the wind generator

Wind turbine	
Generator type	4 – Full converter
Rated power [W]	1,000
Maximum power [W]	1,200
Rated output voltage [V]	230
Rotation speed [rpm]	50÷250
Cut-in speed [m/s]	2
Cut-off speed [m/s]	16
Inverter	
Maximum input voltage [V]	520
Rated input voltage [V]	360
Rated power [W]	1,100
Maximum input current [A]	12.5
Maximum short-circuit current [A]	15
AC Rated Power at 230 V, 50 Hz [W]	2,200
Ratedgrid voltage [V]	230
Maximum AC output current [A]	10.5
Maximum efficiency [%]	96.3

As shown in Table 3, the PV system comprises two 4 kW inverters instead of only one 8 kW device. This choice has been made with the aim of comparing the performance of the two inverters in the presence and in the absence of storage.

Results of the measurement campaign

Figure 9 shows the actual daily energy produced by the PV system compared with the expected values calculated by simulations.

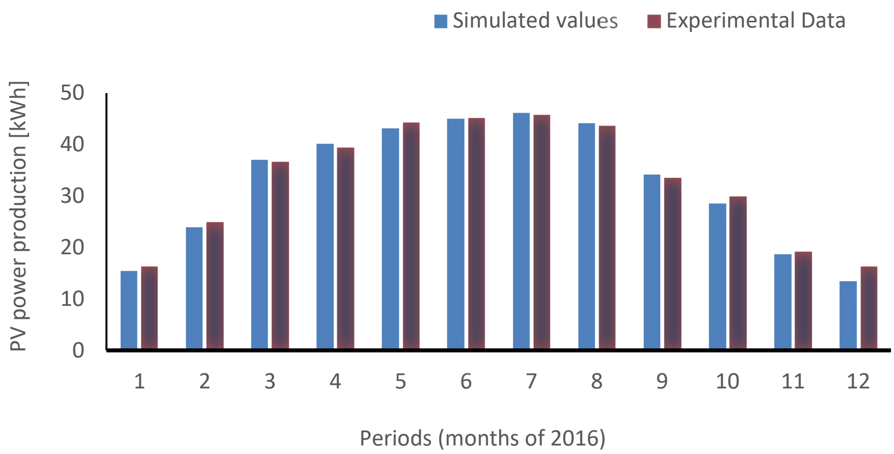

Figure 9. Average daily electricity production profile from PV: experimental and simulated data

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Thanks to the energy meters installed at the point of common coupling with the distribution grid and at the output terminals of the hybrid generators, both the energy produced by the hybrid system and the energy demand of the building have been measured for one year. By using these data, the four indexes defined above are calculated. Table 5 reports the results of the calculation of *EnS* and *EcS*.

Table 5. Calculation of *EnS* and *EcS* indexes

Month	E_{a1} [kWh]	E_{a2} [kWh]	E_{a3} [kWh]	E_a [kWh]	E_{b1} [kWh]	E_{b2} [kWh]	E_{b3} [kWh]	E_b [kWh]	c_1 [€/kWh]	c_2 [EUR/kWh]	c_3 [EUR/kWh]	*EnS*	*EcS*
March	1,207	912	1,141	3,260	652	24	23	699	0.11	0.0969	0.0765	0.79	0.75
April	1,167	884	1,105	3,156	1,157	47	34	1,238	0.11	0.0969	0.0765	0.61	0.55
May	1,206	916	1,141	3,263	1,359	50	24	1,433	0.11	0.0969	0.0765	0.56	0.49
June	1,169	893	1,104	3,166	1,254	50	6	1,310	0.11	0.0969	0.0765	0.59	0.52
July	1,206	913	1,141	3,260	1,457	42	4.5	1,503	0.11	0.0969	0.0765	0.54	0.47
August	1,191	904	1,126	3,221	1,191	43	18	1,252	0.11	0.0969	0.0765	0.61	0.55
September	1,241	910	1,001	3,152	985	35	14	1,035	0.11	0.0969	0.0765	0.67	0.63
October	1,214	859	1,120	3,193	885	31	13	930	0.11	0.0969	0.0765	0.71	0.66
November	1,222	925	1,089	3,236	701	25	10	737	0.11	0.0969	0.0765	0.77	0.74
December	1,180	936	1,250	3,366	598	21	9	628	0.11	0.0969	0.0765	0.81	0.78
January	1,250	879	1,074	3,203	645	23	10	678	0.11	0.0969	0.0765	0.79	0.76
February	1,133	859	1,077	3,069	710	25	11	746	0.11	0.0969	0.0765	0.76	0.72
Total	14,386	10,790	13,369	38,545	11,594	416	172	12,189	0.11	0.0969	0.0765	0.68	0.64

The values in Table 5 show that due to the installation of the hybrid system the building has yearly energy savings of about 68% and yearly economic savings of about 64%.

Finally, considering the Italian energy mix, the coefficient for converting the electricity consumptions into avoided emissions of CO_2 gas is equal to 494.30 g CO_2/kWh [23]. This implies that CO_2R = 1.97 t CO_2/year.

Comparison of the control logics

A MATLAB code has been written for simulating the behaviour of the RES-BESS system of Valderice, receiving as input the real monitored production data reported above.

With regard to the consumption of the building, the following occupancy schedule has been assumed for calculating it: from 8:00 to 14:00 from Monday to Friday, from 16:00 to 18:00 on Tuesday and Thursday. The offices have been assumed closed on Saturday and Sunday with no electricity consumption on these days. Starting from the real average yearly consumption of the building of about 32,000 kWh, and from the occupancy schedule above, the following daily consumptions have been assumed for the simulations: 124 kWh for Mon., Wed., Fri., 170 kWh for Tue., Thu., and 0 kWh for Sat., Sun.

The daily load profiles built starting from the above assumptions and used in the simulations are reported in Figure 10.

The comparison between the two control logics has been done considering one week as an example. Figure 11 reports the daily production of the hybrid system in a week of May 2016. The red curve has been obtained as average of the real consumptions from Monday to Friday.

The comparison is done considering only the power produced by the PV system given that the wind system does not supply the batteries. Nevertheless, the control logics are also applicable to the case of wind turbine connected to the BESS and the results of the study are not influenced by the actual configuration of the system under examination.

Six cases are considered:

- CASE 1: the electricity price is equal to 0.11 EUR/kWh, 0.0969 EUR/kWh and 0.077 EUR/kW in the three pricing periods and the daily consumptions are derived by Figure 10;

- CASE 2: the electricity price is equal to 0.11 EUR/kWh, 0.0969 EUR/kWh and 0.077 EUR/kW in the three pricing periods and the daily consumptions are 50% of those considered in CASE 1;
- CASE 3: the electricity price is equal to 0.22 EUR/kWh, 0.0969 EUR/kWh and 0.077 EUR/kW in the three pricing periods and the daily consumptions are derived by Figure 10;
- CASE 4: the electricity price is equal to 0.22 EUR/kWh, 0.0969 EUR/kWh and 0.077 EUR/kW in the three pricing periods and the daily consumptions are 50% of those considered in CASE 3;
- CASE 5: the electricity price is equal to 0.39 EUR/kWh, 0.0969 EUR/kWh and 0.077 EUR/kW in the three pricing periods and the daily consumptions are derived by Figure 10;
- CASE 6: the electricity price is equal to 0.39 EUR/kWh, 0.0969 EUR/kWh and 0.077 EUR/kW in the three pricing periods and the daily consumptions are 50% of those considered in CASE 6.

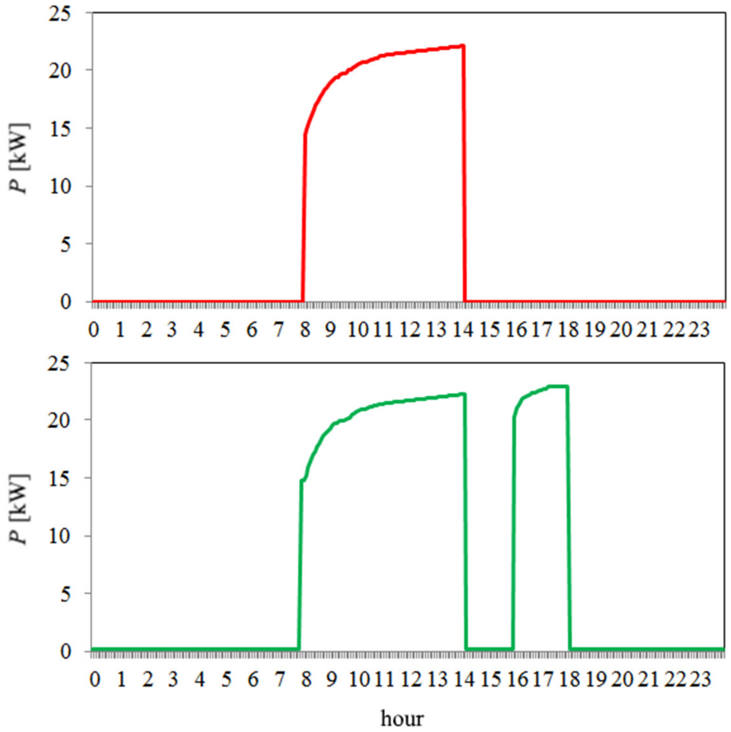

Figure 10. Daily load profiles of the building (red line for Mon., Wed., Fri., green line for Tue., Thu.)

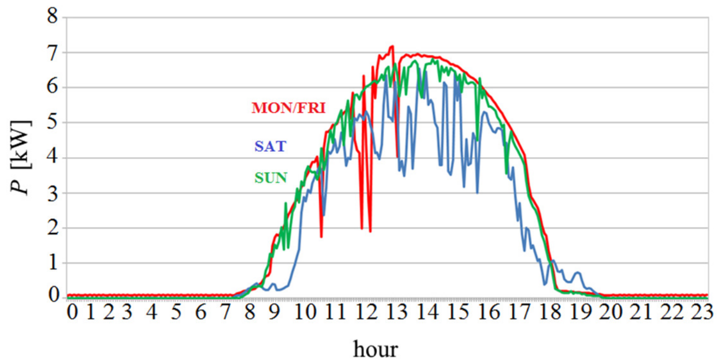

Figure 11. Daily production profile of the hybrid system (weekdays: red line, Saturday: blue line, Sunday: green line)

Table 6 reports the revenues and the costs due to the sale of electricity between the building and the utility, evaluated for the System Led and the Market Led algorithms. The electricity price has been assumed equal to 0.11 EUR/kWh, 0.0969 EUR/kWh and 0.077 EUR/kWh for pricing periods F1, F2 and F3, respectively (CASE 1).

The percentage economic saving of the Market Led algorithm with respect to the System Led algorithm is 0.56%. Therefore, in the considered case the new algorithm is not able to give a significant advantage with respect to the classical one.

Nevertheless, the performance of the Market Led algorithm depends on the rate between the production and the demand of the building. Considering the same system with consumptions equal to 50% of those represented in Figure 10, the results in Table 7 are obtained (CASE 2).

Table 6. Daily revenues and costs (Case 1)

	System Led		Market Led	
	Cost [EUR]	Revenue [EUR]	Cost [EUR]	Revenue [EUR]
Mon.	−9.71	2.53	−9.71	2.63
Tue.	−13.43	1.57	−13.65	1.82
Wed.	−9.71	2.69	−9.71	2.73
Thu.	−13.43	1.57	−13.65	1.82
Fri.	−9.71	2.69	−9.71	2.73
Sat.	0.00	4.63	0.00	4.58
Sun.	0.00	4.55	0.00	4.55
Mon.	−9.71	2.69	−9.71	2.78
Tot.	−35.61		−35.41	

Table 7. Daily revenues and costs (Case 2)

	System Led		Market Led	
	Cost [EUR]	Revenue [EUR]	Cost [EUR]	Revenue [EUR]
Mon.	−6.41	4.24	−6.54	4.70
Tue.	−9.02	2.61	−9.63	3.04
Wed.	−6.32	4.34	−6.50	4.76
Thu.	−9.02	2.61	−9.63	3.04
Fri.	−6.32	4.34	−6.50	4.76
Sat.	0.00	8.14	0.00	8.01
Sun.	0.00	8.16	0.00	8.06
Mon.	−6.32	4.52	−6.32	4.87
Tot.	−2.26		−2.03	

The percentage economic saving of the Market Led algorithm with respect to the System Led algorithm is about 10%.

It is important also to investigate how the Market Led algorithm behaves in presence of high differences between F1 and F23 electricity prices. Therefore, simulations have been carried out with the two different consumption profiles considered above and imposing the following electricity prices: 0.22 EUR/kWh, 0.0969 EUR/kWh and 0.077 EUR/kWh for pricing periods F1, F2 and F3, respectively. The elaboration gives the results reported in Table 8 (CASE 3) and Table 9 (CASE 4).

The percentage economic saving of the Market Led algorithm with respect to the System Led algorithm is about 1.2% and 18% for the third and fourth considered cases, respectively.

Table 8. Daily revenues and costs (Case 3)

	System Led		Market Led	
	Cost [EUR]	Revenue [EUR]	Cost [EUR]	Revenue [EUR]
Mon.	−19.41	4.74	−19.41	5.06
Tue.	−26.85	2.79	−27.29	3.33
Wed.	−19.41	4.90	−19.41	5.16
Thu.	−26.85	2.79	−27.29	3.33
Fri.	−19.41	4.90	−19.41	5.16
Sat.	0	4.62	0	4.57
Sun.	0	4.55	0	4.55
Mon.	−19.41	4.90	−19.41	5.21
Tot.	−82.48		−81.48	

Table 9. Daily revenues and costs (Case 4)

	System Led		Market Led	
	Cost [EUR]	Revenue [EUR]	Cost [EUR]	Revenue [EUR]
Mon.	−11.96	9.49	−11.96	10.12
Tue.	−17.12	5.58	−18.00	6.67
Wed.	−11.96	9.80	−11.96	10.33
Thu.	−17.12	5.58	−18.00	6.67
Fri.	−11.96	9.80	−11.96	10.33
Sat.	0	9.25	0	9.15
Sun.	0	9.10	0	9.10
Mon.	−11.96	9.80	−11.96	10.43
Tot.	−11.18		−9.17	

Finally, other two extreme cases are presented (CASE 5 and CASE 6 reported in Table 10 and Table 11). The following prices are considered: F1 0.39 EUR/kWh, F2 0.0969 EUR/kWh, F3 0.077 EUR/kWh. Finally, Table 12 reports the comparison of the results for the six examined cases.

In particular, Table 12 shows that:

- In case of low difference between peak and off-peak prices, the Market Led algorithm does not provide any significant benefit for the end-user with respect to the System Led algorithms. Moreover, increasing the size of the storage with respect to the electricity consumptions, poorly increase producer's revenue;
- In case of high difference between peak and off-peak prices, the Market Led algorithm assures higher revenues to the producer and the benefits increase when consumptions are lower (or, alternatively, if the storage capacity increases).

Table 10. Daily revenues and costs (Case 5)

	System Led		Market Led	
	Cost [EUR]	Revenue [EUR]	Cost [EUR]	Revenue [EUR]
Mon.	−34.42	8.17	−34.42	8.83
Tue.	−47.60	4.68	−48.38	5.68
Wed.	−34.42	8.32	−34.42	8.93
Thu.	−47.60	4.68	−48.38	5.68
Fri.	−34.42	8.32	−34.42	8.93
Sat.	0	4.62	0	4.57
Sun.	0	4.58	0	4.58
Mon.	−34.42	8.32	−34.42	8.98
Tot.	−154.90		−152.64	

Table 11. Daily revenues and costs (Case 6)

	System Led		Market Led	
	Cost [EUR]	Revenue [EUR]	Cost [EUR]	Revenue [EUR]
Mon.	−21,20	16.34	−21.20	17.65
Tue.	−30,35	9.37	−31.91	11.37
Wed.	−21,20	16.65	−21.20	17.86
Thu.	−30,35	9.37	−31.91	11.37
Fri.	−21,20	16.65	−21.20	17.86
Sat.	0	9.26	0	9.15
Sun.	0	9.17	0	9.16
Mon.	−21,20	16.65	−21.20	17.96
Tot.	−37.17		−32.66	

Table 12. Comparison of the results

Case	Benefits [EUR]	
	1 week	1 year
1	0.20	212
2	0.23	244
3	1.00	1,060
4	2.01	2,131
5	2.36	2,502
6	4.52	4,791

CONCLUSIONS

The paper has presented the management of a hybrid PV-wind system with batteries installed at the administrative office of Valderice in the framework of the ENPI DE.DU.ENER.T research project. Four indexes have been presented for evaluating the performance of the system. Moreover, three different algorithms for managing the BESS's integrated with the hybrid generator have been proposed and discussed.

Simulations show that, in particular, the Market Led algorithm in certain specific condition but not always is able to generate economic saving for the owner of the hybrid system with respect of the System Led algorithm. It has been shown that the savings depend on the rate between production and building electricity consumption and on the difference between the electricity prices in the peak price period and in the other pricing periods.

Market Led algorithm is particularly suitable for public administration office buildings, characterized by reduced electricity consumptions in the weekend. Indeed, this allows completely recharging the BESS and restarting the work cycle at the beginning of every week.

It is worth nothing that the results of the comparison between the System and the Market Led algorithm are valid in the case that the peak price period corresponds to the highest production period of the PV system (daylight hours). In some countries, for example in islands not supplied by the mainland with high values of generation from PV systems, electricity prices are structured so as to encourage the consumption during day hours, presenting higher values during the evening and in the night.

Therefore, the results of this study must be carefully evaluated and limited to the situations that can be assumed similar to those considered in the simulations.

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NOMENCLATURE

c_1	electricity price in F1	[EUR/kWh]
c_2	electricity price in F2	[EUR/kWh]
c_3	electricity price in F3	[EUR/kWh]
C_e	conversion coefficient	[g CO_2/kWh]
CO_2R	CO_2 reduction index	[t CO_2]
E_a	monthly electricity demand	[kWh]
E_{a1}	monthly electricity demand in F1	[kWh]
E_{a2}	monthly electricity demand in F2	[kWh]
E_{a3}	monthly electricity demand in F3	[kWh]
E_b	monthly generated electricity	[kWh]
E_{b1}	monthly generated electricity in F1	[kWh]
E_{b2}	monthly generated electricity in F2	[kWh]
E_{b3}	monthly generated electricity in F3	[kWh]
EcS	economic saving index	
EnS	energy saving index	
E_{p1}	electricity generated by photovoltaic	[kWh]
E_{p2}	electricity generated by wind	[kWh]
E_c	building's energy consumption	[kWh]
E_{st}	battery energy storage system state of charge	[kWh]
E_{st_max}	maximum state of charge	[kWh]
E_{st_min}	minimum state of charge	[kWh]
I_{mpp}	current at maximum power	[A]
I_{sc}	short circuit current	[A]
P_a	power peak without generator	[kW]
$P_{a'}$	power peak with generator	[kW]
P_{max}	maximum power	[W]
PPR	power peak reduction index	
V_{mpp}	voltage at maximum power	[V]
V_{oc}	open circuit voltage	[V]

Acronyms

AC	Alternating Current
BAC	Building Automation and Control
BESS	Battery Energy Storage System
DG	Distributed Generation
DSO	Distribution System Operator
EMS	Energy Management System
LV	Low Voltage
NOCT	Normal Operating Cell Temperature
PV	Photovoltaic
RES	Renewable Energy Source
SoC	State of Charge
STC	Standard Conditions
ToU	Time of Use
VAWT	Vertical-Axis Wind Turbine

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