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Experimental tests to recover the photovoltaic power by battery system

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Abstract

The uncertainty and variability of the Renewable Energy Sources (RES) power plants within the power grid is an open issue. The present study focuses on the use of batteries to overcome the limitations associated with the photovoltaic inverter operation, trying to maximize the global energy produced. A set of switches, was placed between a few photovoltaic modules and a commercial inverter, capable to change configuration of the plant dynamically. Such system stores the power that the inverter is not able to let into the grid inside batteries. At the base of this optimization, there is the achievement of two main configurations in which the batteries and the photovoltaic modules are electrically connected in an appropriate manner as a function of inverter efficiency and thus solar radiation. A control board and the relative program, to change the configuration, was designed and implemented, based on the value of the measured radiation, current, batteries voltage, and calculated inverter efficiency. Finally from the cost and impact analysis we can say that, today the technology of lithium batteries, for this application, is still too expensive in comparison with lead-acid batteries.

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Keywords: Power plants, Renewable energy sources, Distributed generation, Photovoltaic, Energy storage.

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1. introduction

The small-medium size, uncertainty, and variability of the Renewable Energy Sources (RES) power plants within the power grid is an open issue as the networks currently in use are designed for the management of energy coming

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mostly of large, predictable, and fixed rated power plants (following a top-down load driven and not multiple points generation driven logic). Thus, the devices between systems that exploit renewable energy sources and distribution network represent a crucial point. In this direction, so many efforts have recently been carried out to optimize the inverter and control electronics [1–5]. These works have the disadvantage of not being focused on maximizing the global energy gained by the plants. On the other hand, yet interconnected, the efforts have been concentrated on analyzing different methods to storage the energy that cannot be supplied to the grid [6–15].

Electrochemical storage, in particular batteries, is the most cost effective energy storage solutions especially at small scale. The integration of a battery system is generally connected either to a stand-alone systems [16] or to the necessity to absorb peak power and stabilize the system protecting the grid from possible fluctuations [9]. The present study focuses is based on the possibility of using batteries for energy recovery not normally exploited by PV systems due to the limitations associated with the operation of the PV inverter. Indeed, in grid connected PV (Photovoltaic) systems, the inverter normally works using a MPPT (Maximum Power Point Tracker) system to maximize the power output. This system, however, in order to work, needs a minimum power input, which usually is around 5-10% of the rated power value, because the inverter has a minimum voltage of activation below which it does not work and does not deliver power to the grid, even if the photovoltaic system produces a certain amount of energy. This occurs many times during the day considering that the performance of the PV system can decrease due to several factors (e.g. low irradiance, i.e. at sunrise and sunset and in case of particular cloudiness conditions; temperature effect; reflection; dirt; shading; mismatch losses, that is non-uniformity in performance between strings). In literature there are simulations of similar system [17-19] but not so much experimental data are available. Therefore, the authors, that studied several kind of renewable energy systems and processes [20-35], in this paper focus the attention on the possibility to recover the energy produced by a photovoltaic systemthat,owing to inverter limitations, cannot be sent to the grid or it is sent with low efficiency.

2. Experimental layout and logic

The experimental layout is shown in Fig. 1, while the implemented control logic is shown in Fig. 2and itrepresents the algorithm of the software, which actually manages the overall system. The main geographical and components data are shown in Table 1.

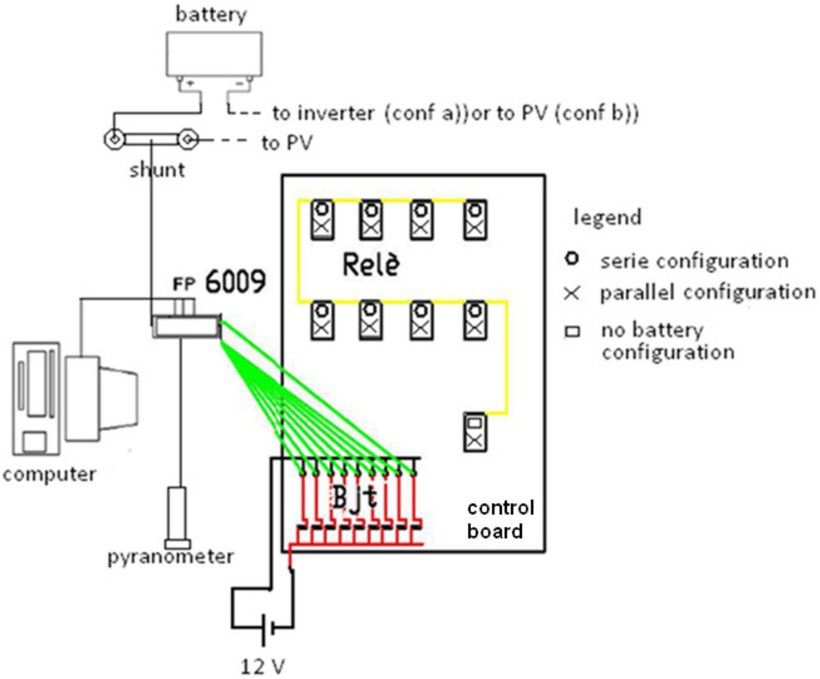

Fig. 1. Experimental layout

The batteries addition and use depends on the status of the radiation and the calculated inverter efficiency. Indeed, the system can switch in one of these three different configurations, as reported in Fig. 3:

a) Configuration "Batteries discharging - series with battery": When the inverter efficiency is very close to 93% and the battery units are charged, they are placed in series with the PV modules. Thus, the batteries are used as an additional module working with the maximum inverter efficiency (93%, see inverter sub-section).
b) Configuration "Energy recovery in batteries – parallel with battery": when the batteries are not completely charged and the string produces a power value below the one needed to operate the inverter at efficiency higher than the batteries plus inverter efficiency (i.e.83%, see batteries sub-section), the batteries are connected in parallel directly with the PV system.
c) Configuration "standard PV plant –series no battery": when the inverter efficiency is below 83%,but the batteries are completely charged and or when the string produces a power value sufficient that permit the inverter to operate at maximum efficiency of 93% but the batteries are completely discharged or when the inverter efficiency value is between 83% and 93%, the battery are not connected and the plant is a standard grid connected PV plant (with all the modules series connected). The maximum inverter efficiency corresponds to a PV modules power / inverter nominal power ratio between 50% and 70%, see inverter sub-section.

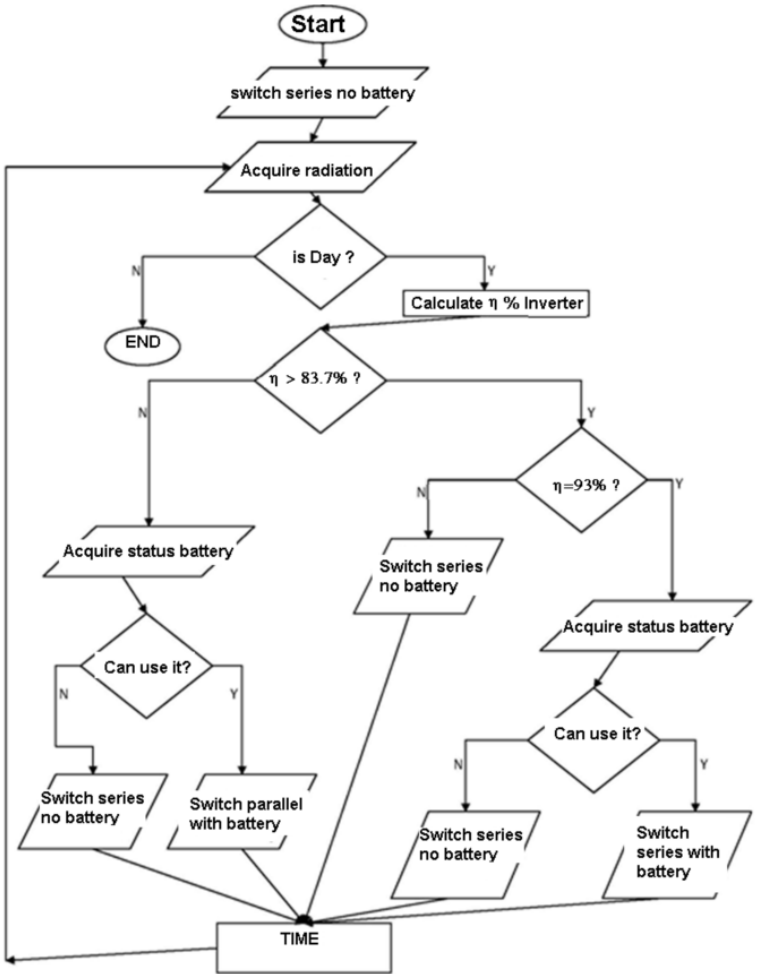

Fig. 2. Experimental logic and software algorithm

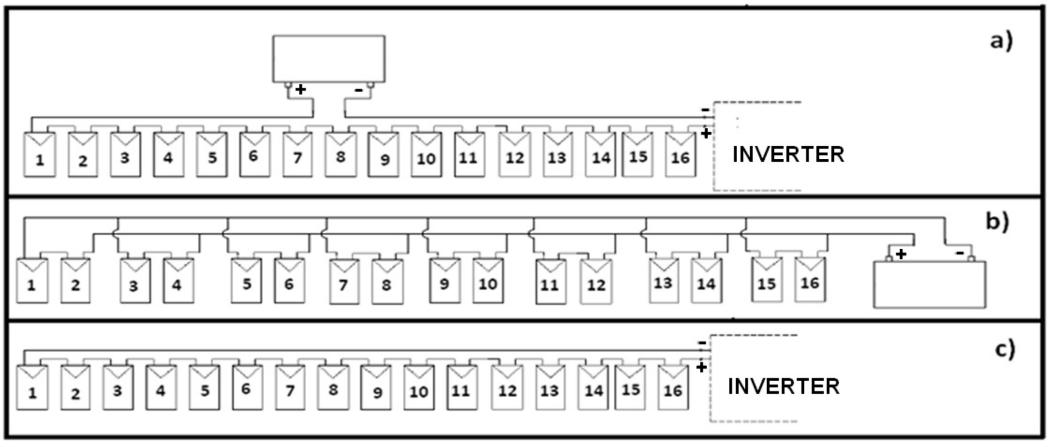

Fig. 3. System configurations: a) Battery discharging (series with battery), b) Battery charging (parallel with battery), c) Standard PV plant (series no battery)

2.1 PV

The PV system is a fixed single-phase grid-connected 790 W ground installation in Civitavecchia (near Rome) composed of one string of 16 monocrystalline silicon 49.2 W modules with a total surface of about 7 m^2. The PV frame has a tilt of 30° and an azimuth of -45°. With a radiation of 1100 W/m^2 , the PV system has been able to deliver about 3.5 A, as show in experimental data paragraph, with a voltage of about 300 V obtaining a total power of 1050 W. When the radiation is close to 300 W/m^2 the current obtainable is about 0.8 A with a power of about 240 W and in this condition the inverter works with an efficiency lower than 83%.

2.2 Inverter

As shown in the following Fig. 4, the maximum inverter efficiency equal to 93% occurs at a partial load variable between 50% and 70% of the nominal power. Therefore, the output of an inverter is not constant, but varies according to the power at which it works, which in turn depends on environmental conditions, especially solar radiation and temperature. It is to be observed that the yield is low for powers less than 15% of the nominal power, but grows very fast with the increase of solar radiation values stabilizing at approximately constant, and then decreased slightly at the end.

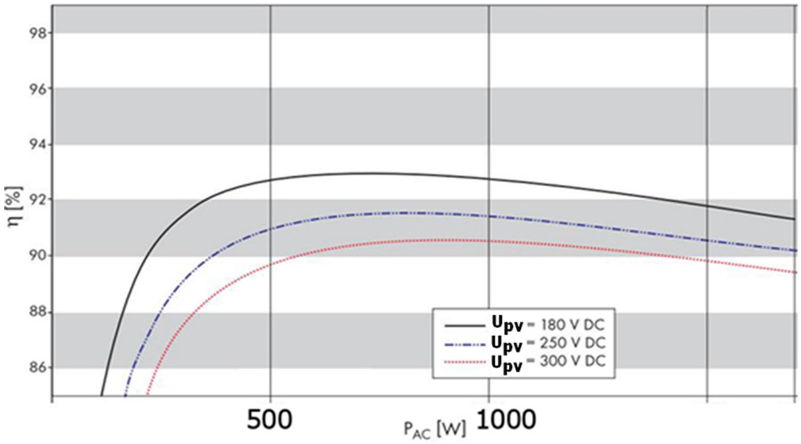

Fig. 4. Manufacturer inverter efficiencies

2.3 Batteries

Owing to the 3.45 V operation voltage of a single lithium ($LiFePO_4$) battery unit and 40 Ah capacity, seven batteries have been connected in series to form a battery pack able to have an operation voltage in a range of 20-28 V (thus chargable by two series connected modules) and a total capacity of about 960 Wh. The efficiency of the system using batteries is 83 % because the battery charging and discharging efficiency is 90% and the maximum inverter efficiency is 93%, (see inverter sub-section).The battery pack can be used in discharging mode until the batteries do not reach a depth of discharge of 80%. Under these conditions it is possible to guarantee about 3000 cycles of charge and discharge without any significant reduction of performance.The battery system could be also taken in consideration as a sort of bakup system to use the energy when it is unavailable from the grid and considering the PV nominal power it is able to deliver its energy for 1.2 hours.

Table 1. Experimental system data

Geographical Data	Value
Latitude, longitude	42°3'44" North, 11°49'7" East
Elevation	16m a.s.l
Annual average radiation	1530 kWh/m^2
Shadow coefficient	0.65
PV module data	
Nominal peak / Minimum guarantee power	49.2 W / 45 W
Peak power / Open circuit voltage	16.9 V / 21.8 V
Peak power /Short circuit current	2.91 A / 3.27 A
Nominal efficiency	11.3%
Inverter data	
DC side maximum power / voltage	1210 W / 400 V
Activation / MPPT voltage	139 V / 320 V
Nominal / maximum power AC side	1000 W / 1100 W
Maximum current AC side	5.6 A
Voltage / frequency AC side	220-240 V / 50-60 Hz
Maximum / European efficiency	93.0% / 91.6%
Battery unit data	
Battery model	WB-LYP40AHA
Nominal capacity	40 Ah
Operation voltage	2.8 – 4 V
Max charge current at constant current	3 C
Max charge current at impulsive current	20 C
Standard charge/discharge current	0.5 C
Cycle life 80% DOD	3000 cycle
Cycle life 70% DOD	5000 cycle

2.4 Control Board

A standard printed circuit board, equipped with relays and a transistor, has been used to manage the series/parallel transition of solar modules. It makes the control board. In particular, the relays have a double switching dual path contact. This means that they are equipped with two plates of iron completely separated one from the other. Thus, at the base of the relay, there are eight pin:

- 2 pin for 12V DC input power.
- 2 pin for the input signal (in our case the positive and negative of the eight modules pairs).
- 2 pin of the first switching
- 2 pin of the second switching

The selected relays are able to withstand up to 10A DC, have a range of 250VA and operate with a supply voltage of 12VDC. A BJT transistor controlled by a field point connected to the computer and interfaced with the LABVIEW software drives every single relay. A ninth relay manages the insertion of the battery pack within the circuit. This is very important since it prevents discharges/charges beyond limits, which, if exceeded, could affect proper operation of the battery itself.

2.5 National instrument units

The National Instrument units are composed of a field point 6009 and an SCX 1600. The field point on the analog side have inputs that arrive from Pyranometer(RG30 model of Silimet) and from the shunt used to measure the batteries current, both in charging and in discharging phases. On the digital side, the voltage outputs are connected to the bases of all nine used relays. Finally, the SCX 1600 provides in a continuous way the value of the voltage of each battery (fourteen cables from the positive and negative terminals of each battery).

3. Experimental data

The acquisition of the experimental data of the system, described in the previous section, covered a period of about six months, running from November to April. Fig. 5 depicts the radiation, (Fig 5a) and Fig 5 b)), and the corresponding battery current, (Fig 5c) and Fig 5d)), of almost five sunny and four cloudy days in March and December, respectively. Fig. 5 shows that, the system accumulates the energy supplied by the photovoltaic system for radiation values below about 300 W/m^2, and provided energy to the grid for higher values. In particular, during sunny days, the batteries, as indicated by the arrows, are charged almost exclusively at sunrise and sunset (i.e. sunset and sunrise are almost the only day time when radiation values are lower than about 300 W/m^2 and thus the system changes to configuration b) of Fig. 3). Whereas, for cloudy days (i.e. day 1 and 2 in Fig 5b)), the current fluctuates between negative (batteries discharged, configuration a) of Fig. 3) and positive (batteries charged, configuration b) of Fig. 3) values more frequently.Fig. 6 depicts the voltage of a battery of the stack, during the same sunny and cloudy days as in Fig. 5. Further, the Fig. 6 shows that during sunny days the battery is in discharge configuration during the day, while it is in charging configuration at sunset and sunrise. Because of the battery is in discharge mode more time than in charge mode, the voltage tends to go down day after day; whereas, during cloudy days, the opposite occurs. Obviously, the battery charge after one day can remain also the same, just like on the first cloudy day of figure 6 b).

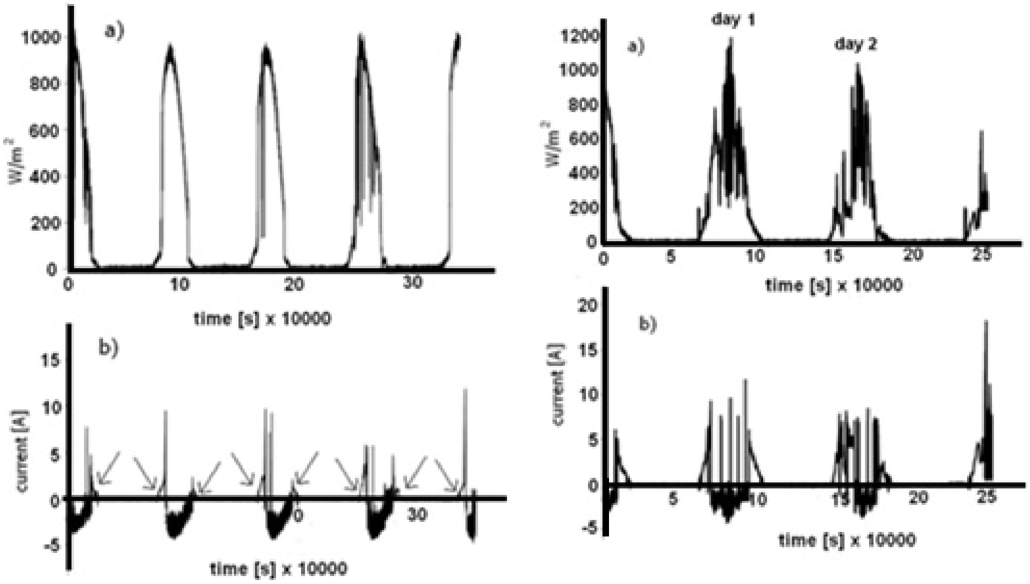

Fig. 5. Radiation and corresponding battery current value during sunny and cloudy days

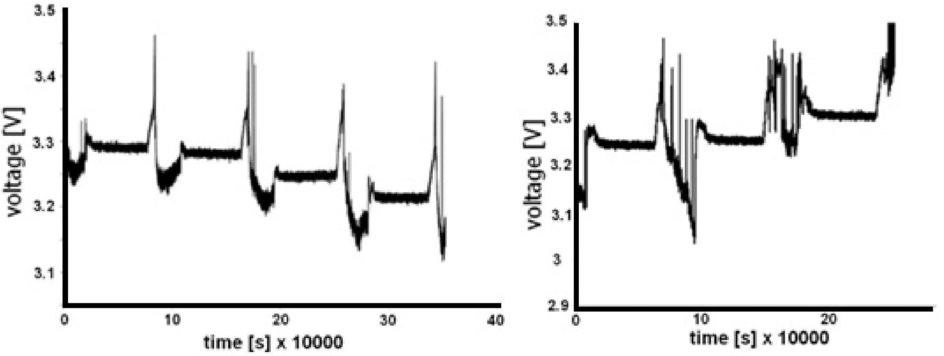

Fig. 6. Battery voltage value during a) sunny and b) cloudy days

Obviously, for very cloudy/rainy days, the batteries are only charged when possible and no electricity is fed into the grid. Fig. 7 shows the case of very rainy/cloudy days: a low constant radiation throughout a day (day 1 in Fig 7a)), the case of similar day but with higher radiation in the afternoon (day 2in Fig 7a)) and a variable day (day 3in Fig 7a) and other days in Fig 7c)). In Fig 7b) and 7d) the relative battery currents are shown.

Fig. 8 highlights the current value as a function of the radiation. When the radiation is below values of about 200 W/m^2, the current assumes low values of about 1 A, while above 200 W/m^2, it grows rapidly up to values of about 5.5 A and the batteries are in charging configuration (configuration b) of Fig. 3). When the radiation exceeds the value of 300 W/m^2, as explained above, current changes sign, increasing linearly with the radiation up to a maximum of 3.5 A and the batteries are in discharging configuration (Fig. 3 configuration a)).

For a six-month period, the system totted up about 640 kWh. More specifically, the cloudy days represented approximately 23% of the total. The energy accumulated during the period of radiation lower than 300 W/m^2 was 15%. In particular, the energy accumulated during radiation value below the ones needed to activate the inverter, was equal to about 3% during sunrise and sunset, while the remaining energy, equal to 12%,has been recovered during the rainy and cloudy days. Without batteries, 65% of this energy is generated at power above the inverter cut-in, and can be converted with an average inverter efficiency of 40%. The remaining 35% energy would be simply lost. It is deduced that there was an effective energy recovery of about 10 %.

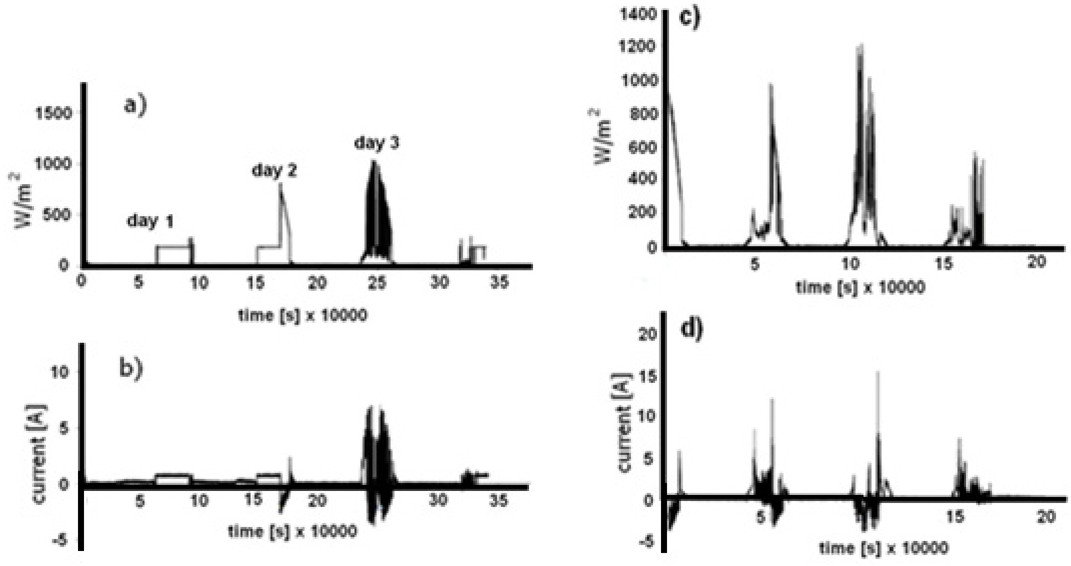

Fig. 7. Radiation and corresponding battery current value during a) and b) rainy and c) and d) cloudy days

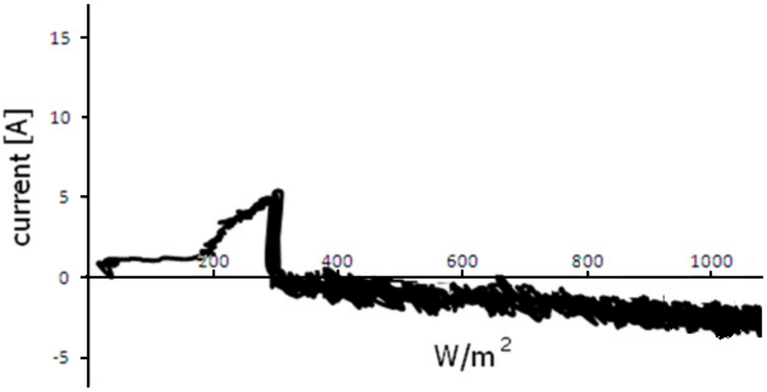

Fig. 8. Current versus solar radiation

4. Costs

The 40 Ah battery cost is about Eur.70, thus the total seven batteries cost is about Eur.490, while the card with the relays amounts to roughly Eur.50. Therefore, the total system cost is Eur.540. The battery pack is capable of storing approximately 966Wh:

$$E_b = [C \cdot N_b \cdot V_w] = 40 \cdot 7 \cdot 3.45 = 966 \quad [\text{Wh}] \qquad (1)$$

where:

- E_b is theenergy storable in battery pack [Wh],
- Nb is the number of the batteries,
- C is the amperometric capacity[Ah],
- Vw is the mean working voltage of a battery [V],

therefore the cost per kWh, in this case is about 570 €/kWh, slightly larger than those reported in the document Elemental Energy [36] and in McKenna [37].The estimated total energy produced by the plant in a year is approximately 1300 kWh and then the energy recovered is equal to about 130 kWh/year. The electricity cost for a small user in Italy isvariable (depending on the time, place, etc.). Anyway we can estimate an average value around 0.23 €/kWh and the annual savings therefore amounted to about 30€/year. Under these conditions, by using lithium batteries, the system pays itself off after about 18 years. On the other hand, using 2 lead-acid batteries of 13 V each with constant capacity of 40 Ah, it would cost a total of about Eur.200, including the control board, and the accumulation system in this case will be repaid after about 6.5years. The frequency with which it recovers energy during sunrise and sunset for one year is much greater than the rate at which energy is recovered during the cloudy days, so the batteries are frequently called to accumulate a daily energy of about 106 Wh (3% of 1300/365). This means about 1/10 of the total capacity. Under these conditions, lead-acid batteries can have a lifetime of about 4000 cycles or about 11 years, while the lithium batteries can easily last up to 20 years up until the end of the life of the PV system itself. The cost of lithium batteries is still too high; it is thus more convenient to consider the lead-acid system, but in the short run, it is expected to reach the values of lead-acid batteries, thus, the lithium batteries will definitely be the best possible choice. Finally, this analysis was carried out considering the released energy recovery system (batteries) from the production system (photovoltaic and inverter), assuming, therefore, that a user of the system may, on their own initiative, be pushed to find a system able in some way to recover energy.

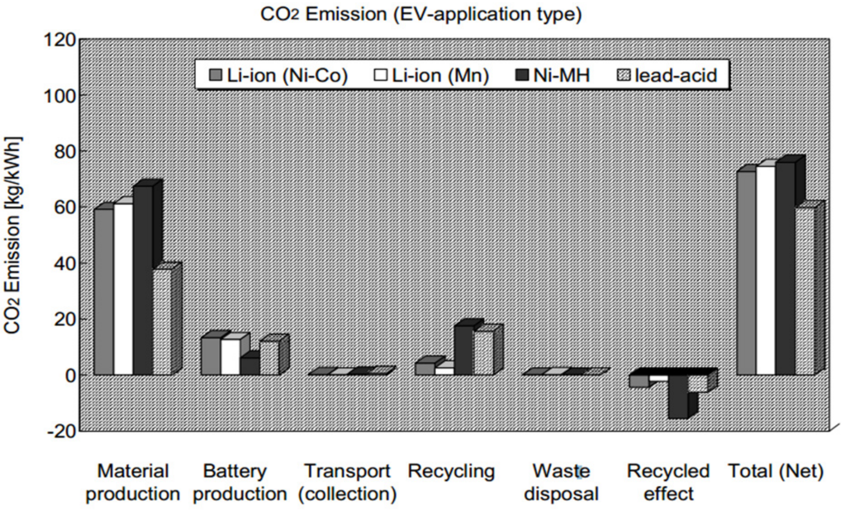

Fig. 9. Batteries impact in terms of CO2 emission [38]

Normally, it is the manufacturer or seller of the PV inverter who will integrate the system. Thus, this would lead to cost values that are definitely lower. Indeed, some manufacturers already integrate the MPPT in the single PV panel. To consider the environmental impact in the analysis, we refer to the quantity of CO_2 emissions emitted during the life cycle of batteries elaborated by the Central Research Institute of Electric Power Industry [38]. Fig. 9 shows the CO_2 emissions of different battery technologies during the life cycle, including recycling. It can be seen that lead-acid batteries have the least impact. As a conclusion then we can say that, both in terms of costs and in terms of environmental impact, the technology of lead batteries for this application is today more convenient.

5. Conclusions

The objective to overcome the limitations associated with the photovoltaic inverter operation, maximizing the use of the total energy produced,was reached usinga storage battery system able to capture the energy that the inverter cannot send to the grid. At the base of this concept, there is the achievement of two main configurations in which the batteries and the photovoltaic modules are electrically connected in an appropriate manner as a function of inverter efficiency and thus solar radiation. More specifically, a control board and the relative program, to change the configuration, was designed and implemented, based on the value of the measured radiation, current, batteries voltage, and inverter efficiency. In general, the system has recovered up to 10% more of the energy produced otherwise lost.Finally from the cost and impact analysis we can say that, today the technology of lithium batteries, for this application, is still too expensive in comparison with lead-acid batteries.

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