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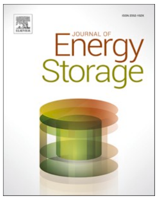

Research papers

Efficiency evaluation of photovoltaic systems with batteries considering different voltage levels

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ABSTRACT

The incorporation of batteries into photovoltaic (PV) self-consumption systems in buildings has a high potential to improve the degree of decarbonization and consumer benefits. However, very few studies have addressed the evaluation and comparison of the energy performance of PV systems with storage for self-consumption in buildings. Furthermore, studies have omitted the influence of energy storage at different voltage levels, which is an important parameter in the development of High Voltage (HV) lithium batteries.

Thus, a load control system was designed and connected to the output of two self-consumption PV systems with batteries operating at different voltages, to compare the energy efficiency under the same energy demand conditions and with identical solar irradiation levels.

The results show the importance of considering the voltage level parameter, as the average energy efficiency of High Voltage Installation (HVI) was higher than that of Low Voltage Installation (LVI) by 3 % to 10 % over the range of load powers analysed. Furthermore, it is shown that the most significant energy losses were influenced by the inverter's energy conversion process. Therefore, to achieve good system optimization, manufacturers should decrease the losses in this process and ensure high energy efficiency in the operating voltage and power ranges.

1. Introduction

Concerns about pollution, climate change, and the scarcity of fossil resources have driven the global transition to a “green economy” underpinned by a sustainable energy model [1]. Currently, fossil fuels dominate the global energy system, accounting for more than 80 % of the total energy supply [2]. Because of the large volume of CO_2 emissions, the global average temperature increased by about 1 °C above pre-industrial levels [3,4] and may increase by up to 1.5 °C in the coming decades [5]. The challenge is to avoid the steady increase in greenhouse gas (GHG) emissions and thus comply with the Paris Agreement, which aims to combat climate change and intensify the actions needed for a sustainable low-carbon future [6].

In 2021, the global installed capacity of new renewable energy installations was approximately 290 GW, surpassing the record 280 GW installed in 2020. The Renewables Market Report stated that growth will accelerate to an average of 305 GW per year from 2021 to 2026, where global renewable energy capacity will reach 4800 GW, i.e., 60 % more than at the end of 2020 [7]. Moreover, given the current global geopolitical and energy situation, the promotion of renewable energies will be substantially intensified in the coming years in the European Union (EU). However, according to the International Energy Agency (IEA), this rate of growth will not be sufficient to meet the global carbon emissions target for 2050 [7].

Along these lines, decarbonization of the building sector is key to reducing GHG emissions, as energy demand in buildings exceeds one-third of global final energy consumption and is responsible for around 40 % of total global CO_2 emissions [8]. The main policy measure should be the use of indigenous and clean energy sources in energy production [9]. In this regard, energy production through solar resources has been widely considered one of the most effective and efficient solutions to address the problems of fossil fuel depletion, GHG emissions, and increasing demand for energy consumption [10]. In the last decade, the installed capacity of PV power has significantly increased worldwide due to the widespread acceptance of PV technology among the world's population. This is due to the reduction of system costs, high electricity prices, and the implementation of renewable energy policies by governments, as well as the search for savings on energy bills and decreasing GHG emissions, among others [11,12]. In 2021, 25 of 27 EU member states deployed more solar power than in the previous year. Germany consolidated its position as the leading European solar market with an

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Nomenclature

AC	alternating current
BC	battery charge tests
BD	battery discharge tests
DC	direct current
DPV	direct photovoltaic tests
E_C	energy at battery input (charge) [Wh]
E_D	energy at battery output (discharge) [Wh]
E_G	energy from the grid [Wh]
E_I	energy at inverter input or energy at charge controller input [Wh]
E_O	energy at inverter output [Wh]
HV	high voltage
HVI	high voltage installation
i	test number
j	data collection point
LC_1	load consumption 1 [Wh]
LC_2	load consumption 2 [Wh]
LC_c	power supply to control [Wh]
LV	low voltage
LVI	low voltage installation
SOC_{max}	maximum state of charge
SOC_{min}	minimum state of charge
η_j	energy efficiency at every data point
$\eta_{BC,\,j}$	energy efficiency in battery charge tests
$\eta_{BD,\,j}$	energy efficiency in battery discharge tests
$\eta_{DPV,\,j}$	energy efficiency in direct photovoltaic tests
$\overline{\eta}_i$	average test energy efficiency

additional 5.3 GW installed, followed by Spain (3.8 GW), the Netherlands (3.3 GW), Poland (3.2 GW), and France (2.5 GW) [13].

In this sense, an interesting activity is to engage in self-consumption and distributed generation, consuming the energy generated by one's PV installation while reducing the use of energy from the grid [14]. However, the changing and uncontrollable characteristics of both renewable energy generation and building demand curve patterns lead to a mismatch between generation and consumption [15]. Addressing this mismatch has become a widespread problem [16]. To eliminate this existing mismatch, it is necessary to develop forms of energy storage to improve energy management and optimize the operation of PV systems [17].

In recent years, batteries have become of great interest in the building sector due to their fast response and possibility to achieve energy independence [18]. Thus, the combination of solar PV and battery generation has the potential to significantly improve the degree of decarbonization and consumer benefits [19,20]. The global installed battery storage capacity is expected to increase from 29 GWh in 2020 to 81 GWh in 2024 [21]. In Europe, at the residential building level, solar systems with storage are expected to grow by more than 400 %, with a development ranging from 3 GWh of installed storage capacity in 2020 to 12.8 GWh in 2025. Moreover, during 2020, the installation of these systems in the EU grew by 44 %, reaching for the first time the figure of more than 100,000 storage systems installed in one year [22].

In this regard, Klingler [23] stated that lithium-ion batteries are currently the dominant technology, and Mulleriyawage and Shen [24], delving into battery chemistry, ranked the LiFePO (lithium-iron-phosphate) battery as the best choice for use in buildings due to its fast-charging capability, versatility and a constant discharge voltage that favours its durability.

The technical and economic feasibility of energy storage installations has been the subject of study among the scientific community. Baniasadi et al. [25] stated that the use of battery storage is not an attractive solution from the consumer's point of view due to the low capacity for recover the initial investment, reaching a long payback period. Roberts et al. [26] expressed that the cost-effectiveness of PV installations with battery storage for buildings is highly dependent on the heterogeneity of the consumption profile and, if the installation is not subsidized, it is rarely profitable at current existing costs. Jaszczur and Hassan [27] stated that the use of batteries in conjunction with PV systems involves unbearable costs. Although the price of lithium-ion batteries has started to decrease substantially [28], batteries are the most expensive component of a solar PV system [29].

However, the installation of a PV system with batteries for self-consumption is not equally cost-effective for all consumers [30]. Previous research has shown large variability in the cost-effectiveness of these systems, even among identical components operating under the same local conditions and electricity tariffs, installed in different buildings [31]. About that, Li and Tseng [32] exposed that the characteristics of small-scale battery energy storage systems require a thorough analysis of the basic properties such as voltage, current, or capacity of the battery.

From the point of view of the application of PV self-consumption systems with batteries, the analysis of these parameters is of utmost relevance and can be evaluated through the energy efficiency of either the system or the individual components. Thus, system efficiency is defined as the ratio between the alternating current (AC) energy injected into the grid or load and the direct current (DC) energy available in the solar array due to the incident solar irradiance. In turn, the inverter energy efficiency was specified as the ratio between the AC power at the output terminals and the DC power at the input terminals of the inverter [33]. Finally, battery energy efficiency is the amount of energy delivered by the battery compared to the amount of energy that was previously charged in the battery [34]. Given the current uncertainty linked to electricity prices in the EU, variations in energy efficiency have a major impact on the economic profitability of these systems, as losses must be compensated with additional energy. Thus, due to high electricity prices, the extra energy needed to compensate for the energy inefficiency of the systems has a higher impact on energy costs [35].

In this regard, Dufo-López et al. [36] demonstrated the importance of not considering a constant energy efficiency value, as it can induce substantial errors with generation and consumption profiles with large peaks and valleys. The efficiency of these systems varies according to the performance curves of the individual components, which in turn depend on the solar power generated and the power demanded. Thus, the energy efficiency of the system will vary depending on the climate zone and the consumption profile of the building [37].

Nevertheless, so far, to the best of our knowledge there are very few studies dealing with the evaluation and comparison of the energy yield of PV systems with storage for self-consumption in buildings, which would help the user to maximize the cost-effectiveness of his renewable generation system. In this regard, Munzke et al. [38] analysed the performance of commercially available battery PV systems and Li et al. [39] presented the performance of a PV system with battery storage and grid-interconnected electric vehicles in gymnasium buildings. Scientific works omitted the influence of energy storage at different voltage levels to optimize the integration of PV systems in buildings, which is an important parameter with the development of HV lithium batteries. Sepúlveda et al. [40] evaluated the influence of this parameter and warned that new studies are needed in which the power demanded variable is controlled, since an inverter is required to convert and control the flow of electricity generated in the solar field, the operating efficiency of which depends on the operating voltage levels in the installation. Thus, if the connection is made via an inverter with a voltage transformer, additional energy losses are introduced. In contrast, the transformer can be omitted if the voltage levels of the energy storage in batteries and the voltage required in the switchboard to supply the building loads are similar [41,42]. Therefore, to be able to express real and accurate energy efficiency values for these systems, further research needs to be conducted.

Considering the above, the main objective of this work is to analyze the effect of operating at different voltage levels in PV systems with batteries for self-consumption, thus evaluating how the operating voltage level and the electrical power demanded affect the energy efficiency of the systems. To force the operation of both installations, a load-consumption control system (LC control) was designed using infrared lamps, which allowed setting discrete power values, thus enhancing the effect of this variable in the experimentation. Thus, obtaining different efficiency values in PV systems with batteries for self-consumption would corroborate the hypothesis that efficiency is influenced by the voltage level and the power demanded.

2. Materials and methods

2.1. Prototype description

An experimental system was designed consisting of two PV installations for self-consumption with batteries operating at different voltages. One of them operated at Low Voltage (LV), known as Low Voltage Installation (LVI), and the other at HV, so called High Voltage Installation (HVI). It was located at Badajoz School of Industrial Engineering, whose latitude, longitude, and altitude site are $38^0\ 53'$, $6^0\ 58'$ W, and 186 m, respectively.

The prototype consisted of two PV solar fields. Each had an output of 2.7 kWp and was comprised of 6 panels, model CS3W-450MS from Canadian Solar [43]. They were placed on SOLARBLOC® precast concrete supports with 30^0 inclination and south orientation. For LVI, 2 parallel rows of 3 modules were connected in series (2 × 3), while for HVI all modules were connected in series (1 × 6).

In addition, LVI incorporated a MPPT (Maximum Power Point Tracking) charge controller, SmartSolar 250/70, and an inverter, MULTIPLUS-II 48/3000/35-32, manufactured by Victron Energy [44]. For the storage of the energy generated, a LV lithium battery was installed, whose manufacturer and model are BYD [45] and B-BOX PREMIUM LVS 8, respectively. In HVI, a hybrid inverter, model Primo GEN24 3 Plus with 2 MPPT inputs from Fronius [46] was used and a HV lithium battery was chosen, whose manufacturer and model were BYD and B-BOX PREMIUM HVS 7.7, respectively.

However, as a complement to the prototype, a system to control the consumption load was developed and integrated, called LC control system. Its design and installation were based on the need to control the mode of operation of the two PV systems, giving the researcher the ability to emulate and modify consumption patterns according to his interests. Therefore, the outputs of the two PV systems were connected to the LC control, eliminating the uncertainty of operating with uncontrolled and unpredictable power demands.

The new system incorporated two independent load circuits, LC_1 and LC_2, with consumptions between 0 and 3 kW and with the possibility of 250 W increments. The maximum load demanded by the power circuits was sized based on the nominal power of the inverters, as this parameter establishes the limit of energy that can be converted from DC to AC.

Both the loads and the system in charge of their control were integrated into a metallic wall structure with wheels for transport, whose dimensions were 1.909 × 1.190 × 0.550 m (HxWxD). There were 24 infrared lamps with power of 250 W (12 lamps for each circuit). A board with relays, contactors, and the data acquisition card in charge of controlling the switching on/off of these loads was included. For the instrumentation of the variable load controller, Laboratory Virtual Instrument Engineering Workbench (LabVIEW) software was used, being a platform for system design and a development environment with visual programming language from National Instruments. In addition, an external PC was used to set the load pattern (LC pattern), either variable or constant, to be satisfied by the two PV systems during the tests. LC control updated the on-off order of the loads every 15 min so that the power demanded by the loads could be modified in that time. For the power consumption to be identical in the two load circuits LC_1 and LC_2, external power input from the Grid to the load control circuit (LC_c) was required. Fig. 1 shows the integration of the LC control in the two PV systems.

2.2. Test description

Three categories of tests were conducted to determine which of the two systems is more energy-efficient and to analyze how operating conditions influence their performance. They were called "Battery Discharge" (*BD*), "Direct PV" (*DPV*), and "Battery charge" (*BC*) tests.

In *BD tests*, the injection of energy generated by the solar array was disconnected. Therefore, the battery was used to meet the programmed load. These tests lasted 4–5 h, or until one of the batteries reached its minimum State of Charge (SOC) —SOC_{min} set at 10 %—.

In *DPV tests*, the systems were operated as self-consumption PV systems without energy storage, i.e., the energy generated by the solar array was used directly to meet the programmed load. For this purpose, the HVI battery was disconnected. In LVI, however, the control system of the components did not allow the operation of the system with the battery disconnected or switched off. Therefore, by requiring the battery to be on, we tried to eliminate the influence of the battery by running the tests when the battery was fully charged—SOC_{max} set at 100 %—and the solar irradiance was sufficient for the generated power to exceed the charging power. In this way, solar generation was adjusted to consumption, and the influence of the battery charging and discharging processes was reduced as much as possible. The duration of these tests was 4–5 h, or if the global solar irradiance (G) allowed the energy output of the inverter (E_O) to be higher than the consumption load (LC). To this effect, the duration of the tests with higher power consumption decreased but was in any case longer than 1.5 h.

Finally, in *BC Tests*, the energy generated by the solar PV field was used to charge the batteries and not to satisfy any load. The starting point of these tests was fully discharged batteries—SOC_{min} equal to 10 %— and lasted until one of the batteries reached its $SOCmax$, set at 100 %.

Within *DPV* and *BD categories*, different types of tests were carried out by modifying the load demand (LC_1 and LC_2). Thus, constant loads of 0.5, 1.0, 1.5, 2.0, and 2.5 kW were set, and two tests were carried out for each type as shown in Table 1. On the other hand, since these were new systems, degradation was not considered as an intervening variable in the analysis.

The control of the test variables was carried out with the measurement and monitoring equipment of the installed devices. The data were recorded, in parallel, at 5-minute intervals and subsequently stored in the online platforms associated with the inverters. Thus, by accessing Fronius Solar.web [47] —the platform associated with HVI— and VRM Portal Victron Energy [48] —the platform associated with LVI—, energy flow data were acquired. In parallel, climatological data were extracted from a weather station located on the roof of the building (PCE Ibérica, WATCHDOG 2000) to verify the results provided by the equipment. Also, an AC/DC Digital Clamp Multimeter (Pro'sKit MT-3109) was used to validate the operating voltage at different points of the system.

Fig. 2 shows the operating voltage ranges during the tests and the measurement points of the different variables used to calculate the energy yields, such as DC energy before the inverter or regulator (E_I), AC energy after the inverter (E_O), energy charged in the battery (E_C) and energy discharged from the battery (E_D).

With the data obtained from the variables, the energy yields for each data record (η_j) were calculated and compared based on the losses produced in the inverter-battery set during the battery charging and

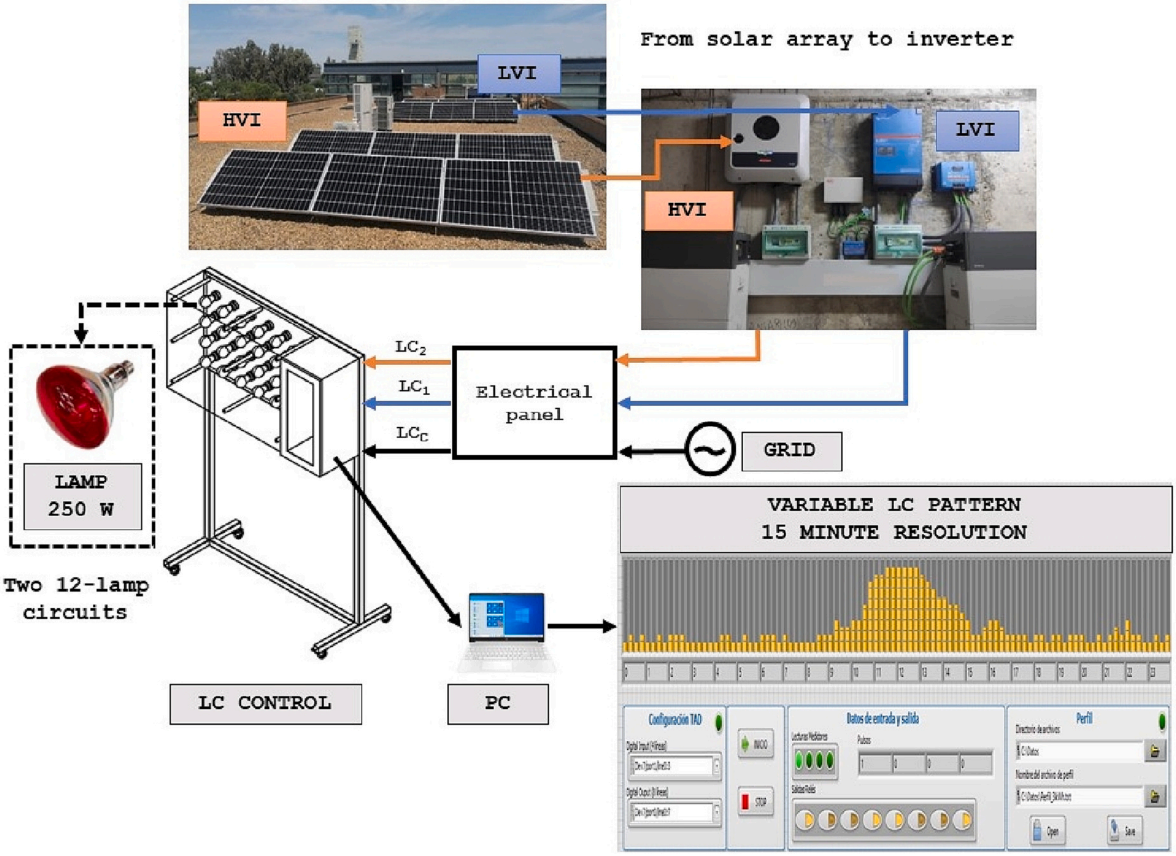

Fig. 1. LC control system.

Table 1
Categories and types of tests.

Test categories	Duration	LC Pattern	LC (kW)									
			1					2				
BD	4–5 h or SOC$_{min}$	Constant	0.5	1.0	1.5	2.0	2.5	0.5	1.0	1.5	2.0	2.5
DPV	4–5 h or $E_I \geq$ LC	Constant	0.5	1.0	1.5	2.0	–	0.5	1.0	1.5	2.0	–
BC	SOC$_{max}$	–	–					–				

discharging processes—BD and BC Tests—and in the inverter during the direct consumption of the energy produced without prior passage through the battery—Direct PV Tests—, influenced by the different operating voltage of each installation. For LVI, the charge regulator was included in the inverter-battery assembly.

Depending on the test category, the performance of the PV systems changed. Thus, Eqs. (1), (2) and (3) were used to calculate the efficiency based on the test category, where *j* is each recorded data acquisition. In BD Tests, the battery operated in Discharging Mode, so Eq. (1) was used. In DPV Tests, the influence of the batteries was eliminated and Eq. (2) was used to calculate the energy efficiency. Finally, in BC Tests, the battery operated in Charging Mode, using Eq. (3). All these energy efficiency calculations were performed under controlled load operation via the LC control system.

$$\eta_{BD\,j} = \frac{E_{O\,j}}{E_{D\,j}} \tag{1}$$

$$\eta_{DPV\,j} = \frac{E_{O\,j}}{E_{I\,j}} \tag{2}$$

$$\eta_{BC\,j} = \frac{E_{C\,j}}{E_{I\,j}} \tag{3}$$

Subsequently, the average efficiency of each test ($\overline{\eta}$) was determined using Eq. (4), where *j* is each recorded data acquisition, *i* is 1 or 2 depending on the test considered and *n* is the sum of the measurements over a test.

$$\overline{\eta}_i = \frac{\sum_{j=1}^{j=n} \eta_j}{n} \tag{4}$$

3. Results and discussion

First, the performance of HVI and LVI during one of the types of tests performed in each category is presented—BD (Fig. 3), DPV (Fig. 4) and BC (Fig. 5)—.

During one of the BD tests at 1.0 kW, it was observed that the amount of electrical energy discharged from the LV battery (4739.33 Wh) was higher than the HV battery (4514.12 Wh) at equal charging conditions. Therefore, to meet the same energy demand, the LVI system used more energy due to lower system energy efficiency. The average efficiencies of this test were 0.957 and 0.903 for HVI and LVI, respectively.

During the DPV tests, it was observed that the influence of the battery charging and discharging processes could not be completely cancelled out in LVI because it could not operate with the battery

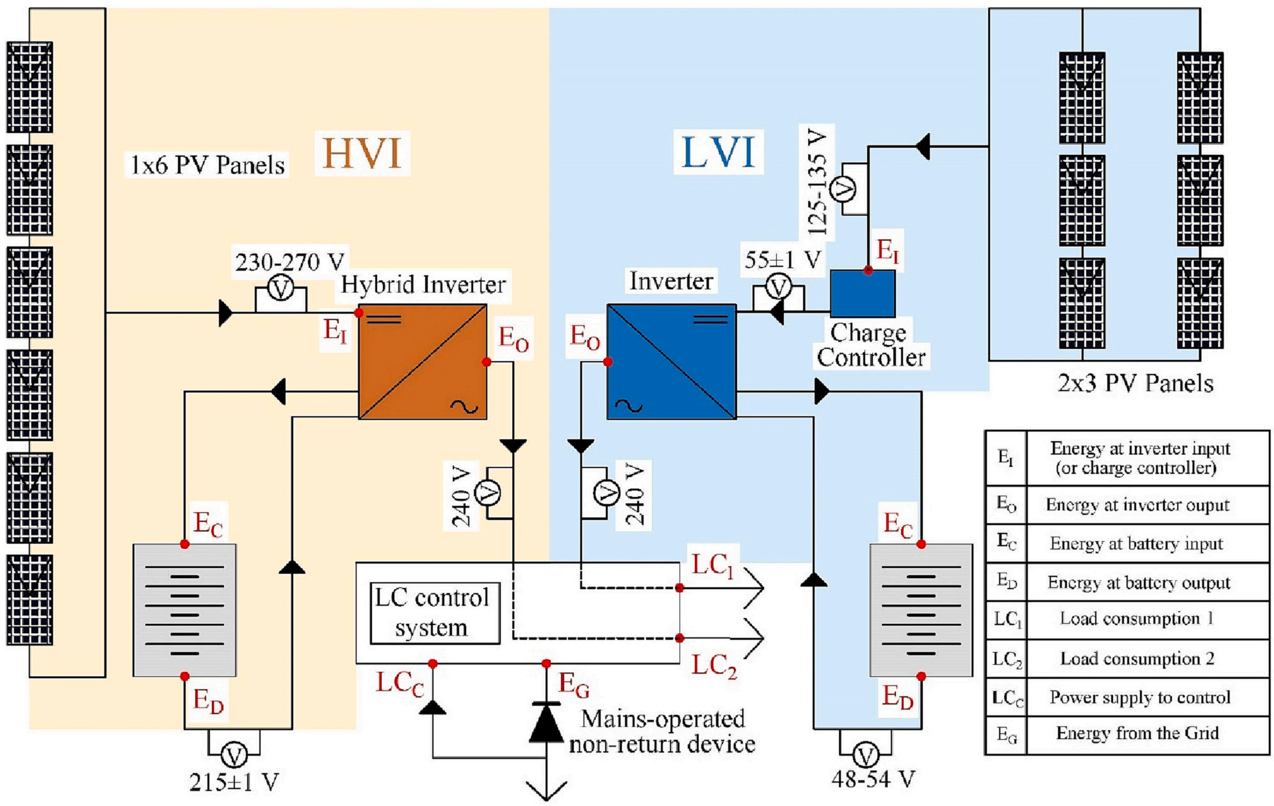

Fig. 2. Characterisation of test variables.

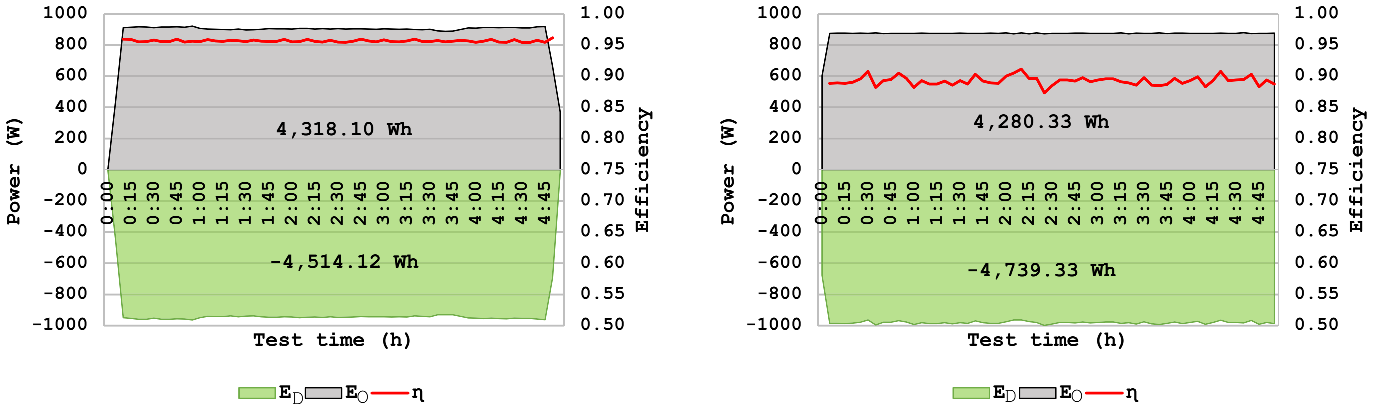

Fig. 3. Energy and efficiency in BD 1.0 kW test. Left: HVI. Right: LVI.

switched off. Also, in contrast to the HVI operation, large variability in the input power of the analysed system was observed in LVI. In HVI, the difference between the measured power at the input and output of the inverter was small and only influenced by the losses of the inverter component. In contrast, in LVI, the difference in energy measured between the input to the charge controller and the output of the inverter was a consequence of the losses caused by the two devices and the minimal amount of energy that was charged and discharged from the battery, due to the impossibility to cancel it. Therefore, the high deviation between the energy efficiency values of the systems, 0.970 in HVI and 0.876 in LVI, could be largely influenced by this fact.

Finally, in the BC tests, a stable operation of both systems was evidenced, causing very efficient charging processes. The average energy efficiency results during the test were 0.954 and 0.977 for LVI and HVI, respectively. Therefore, to store the same amount of energy, the LVI system needed to produce more energy due to its lower system energy efficiency during the charging process. In addition, it should be noted that no inverter power conversion process occurred in these tests.

Fig. 6 below shows the average energy efficiency ($\overline{\eta_i}$) for all tests performed.

In BD test category, the average energy efficiency of the HVI system increased with increasing power demand, reaching energy efficiency values around 97 % for loads between 1.5 and 2.5 kW and slightly below 94 % for 0.5 kW loads. On the other hand, in LVI, the highest average energy efficiency value, around 92 %, was obtained for a power demand of 1.5 kW and decreased more for 2 kW and 2.5 kW loads, around 88 %, than for 0.5 kW and 1 kW loads, above 90 %.

On the other hand, in DPV test category, the average energy efficiency values of the HVI system were like those obtained in BD category,

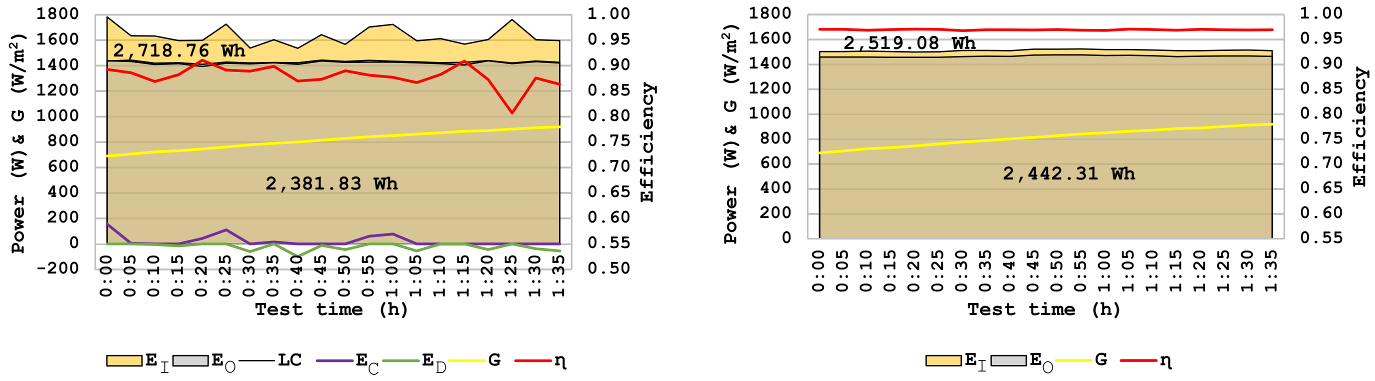

Fig. 4. Energy and efficiency in DPV 1.5 kW test. Left: HVI. Right: LVI.

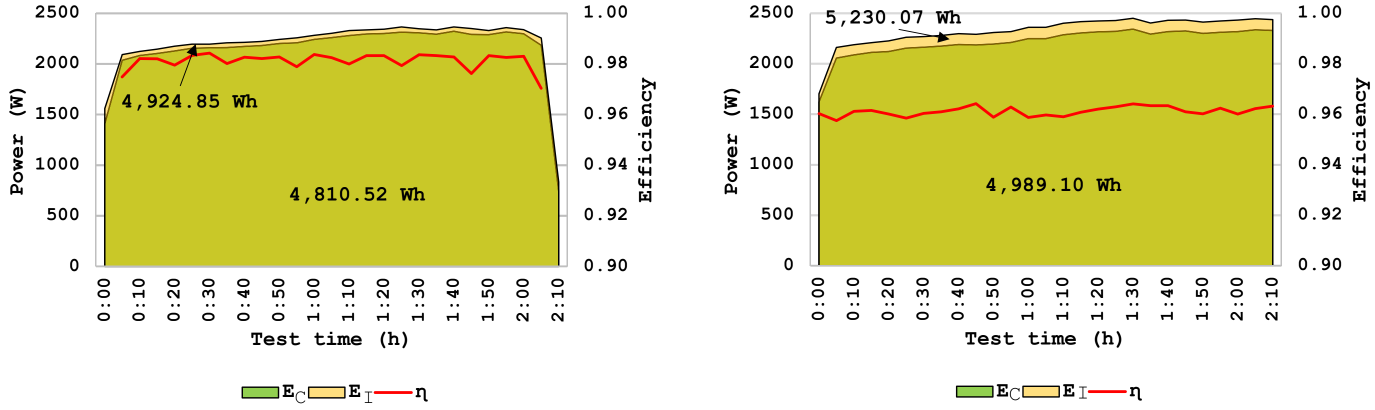

Fig. 5. Energy and efficiency in BC test. Left: HVI. Right: LVI.

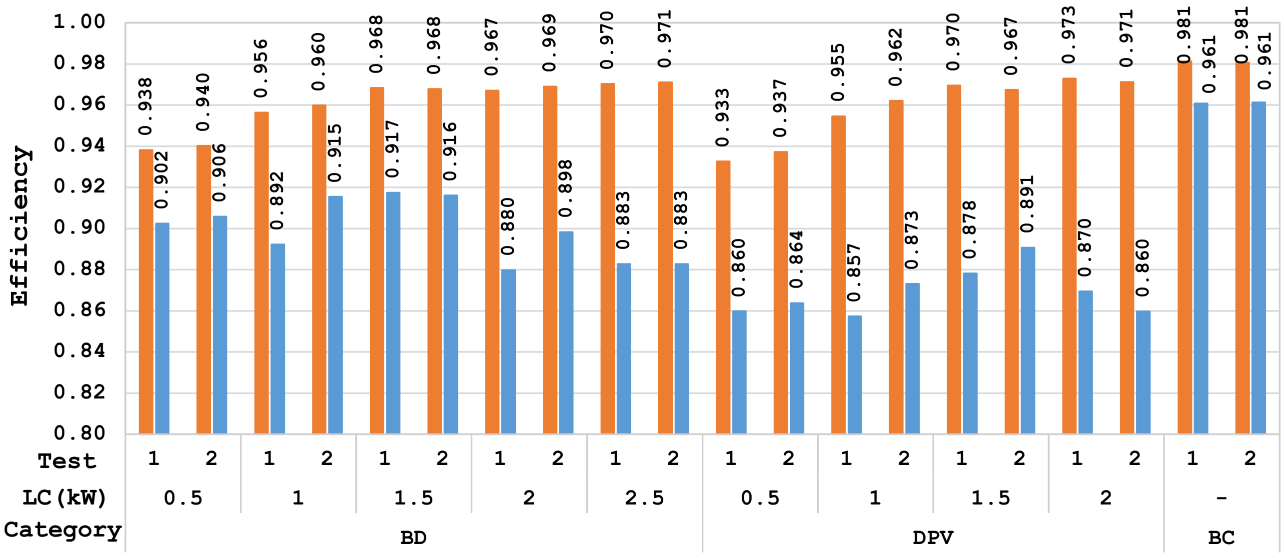

Fig. 6. Average test energy efficiency in BD, DPV, and BC categories.

meaning that the inverter operation included mostly energy efficiency loss. In LVI, comparing the test results of DPV category with BD category, $\bar{\eta}$ decreased by approximately 3 percentage points for a power demand less than or equal to 1.5 kW and, to a lesser extent, for a 2-kW load. As discussed above, this decrease in energy efficiency may have been influenced by the impossibility of operating the system with the battery off, which may have affected the accuracy of the measurements recorded by the monitoring equipment. In addition, LVI did not work at maximum power point as its production was limited according to the load demanded, influencing the decrease in inverter efficiency.

Finally, in BC category, the energy efficiency was 98 % and 96 % for HVI and LVI, respectively. The highest average energy efficiency values were obtained for this type of test, where no DC to AC conversion was required by the inverter. Consequently, as Munzke et al. [38] stated, the most significant energy losses of battery PV systems were influenced by the energy conversion process of the inverter.

According to the results obtained, $\overline{\eta_i}$ in HVI was higher than LVI in all tests. In BD category tests, the difference in efficiencies between systems operating at different voltage levels in energy storage ranged from 3 to 5 % for loads less than or equal to 1.5 kW to 9 % for 2 kW and 2.5 kW loads. In DPV category, due to the drop in energy efficiency at LVI, the difference concerning the HVI values increased, being close to 10 % for the whole range of loads. Finally, during battery charging processes, the average energy yield of HVI was higher than that of LVI by two percentage points. In this line, Munzke et al. [38] analysed the energy efficiency of 12 different lithium-ion PV batteries in terms of their storage capacity and nominal charge and discharge power, their results also expressing a large variability with values between 81.9 % and 94.1 %.

Therefore, the importance of considering the voltage level parameter in a renewable energy production system for self-consumption was evidenced, since the average energy yield of HVI was higher than that of LVI in all tests under the same energy demand conditions and with identical solar irradiance levels. Furthermore, the importance of not considering a constant energy efficiency value in these systems was demonstrated, as it can lead to substantial errors with consumption profiles with peaks and valleys. The systems presented very different energy efficiency values, especially under partial load, with a significant impact on domestic applications where most of the power demand is below 1 kW. Therefore, for a good performance of the complete system, high efficiency is essential for the entire power range of the inverter, as the average energy yields in the same system varied by up to 5 % depending on the power demanded. In this regard, Baumgartner [37] indicated that energy efficiency is not stable in inverters with wide MPPT voltage ranges.

Next, the statistical distribution of the data sets concerning energy efficiency (η_j) in each type of test is shown, representing the extreme values — maximum and minimum—, upper (Q_3) and lower (Q_1) quartile, median, average, and outliers — data that are at a distance greater than 1.5 times the interquartile range (*IQR*) and, therefore, represent observations with very different values from others in the same group—. Figs. 7, 8, and 9 represent the variability of energy yield for the type trials conducted within BD, DPV, and BC categories, respectively. In BD and DPV categories, the statistical distribution results represent Test 1 performed according to Table 1. In contrast, in BC category, the variation of the energy efficiency during the two load tests performed, Test 1 and 2, is shown.

The energy efficiency of HVI was superior to that of LVI regardless of the consumption load tested in BD and DPV categories. In addition, the energy efficiency values of HVI hardly varied during the trials, presenting average and extreme values, both maximum and minimum, very close to each other with a difference of less than half a percentage point for all cases. On the other hand, the energy efficiency in LVI showed results with greater variability, reaching differences in the energy efficiency of more than 5 % between values between Q_1 and Q_3 and close to 10 % between extreme values for power demanded of 0.5 and 1 kW of DPV category. Also, in the tests with 0.5 kW of BD category, an inequality between extreme values of more than 5 % was obtained. Generally, for all tests of BD and DPV categories in LVI, the difference between average and extreme values did not decrease by more than two percentage points. Also, it was observed that most of the outliers for both systems coincided with the lowest load tests (0.5 and 1 kW), which could be due to the longer duration of the tests that generates a larger amount of data in the sample.

In BC category trials, in both HVI and LVI, the sets of energy efficiency values were close. In LVI, the variability of energy efficiency values was significantly reduced compared to the other categories. However, in HVI, high similarity in values was maintained during each test.

4. Conclusions

The development and incorporation of the load control system allowed a comparison of both PV systems for self-consumption with energy storage that operated reliably at different voltage levels. In this way, energy efficiency was compared under the same energy demand conditions and with identical solar irradiance levels.

The results showed the importance of considering the voltage level parameter in a renewable energy production system for self-consumption, as the average energy yield of HVI was higher than that of LVI in all tests, regardless of the power demanded. The average energy yield of HVI increased as the power demanded increased. However, in LVI, the highest average energy efficiency value was not achieved at the maximum power demanded. Thus, in the power range analysed, there were large differences in the average energy efficiencies obtained, with HVI being higher than LVI by between 3 % and 10 %. Therefore, the importance of considering a variable value of energy efficiency in these systems was demonstrated, as it can avoid important errors depending on the consumption profile.

As for the variability of the energy efficiency values, they hardly varied during the HVI trials. On the contrary, the energy efficiency in LVI showed results with higher variability reaching, sometimes, important differences. It can be concluded, therefore, that the system operating at HV showed greater stability in response to the tests and variations in power demand.

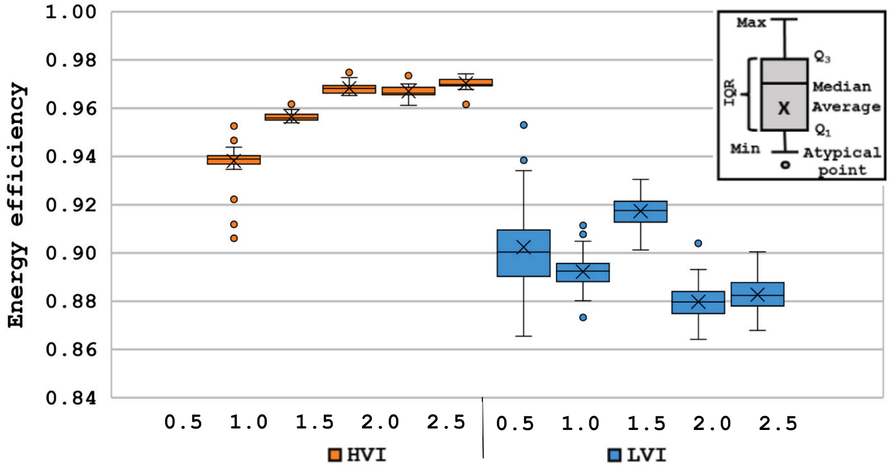

Fig. 7. η in BD category test 1.

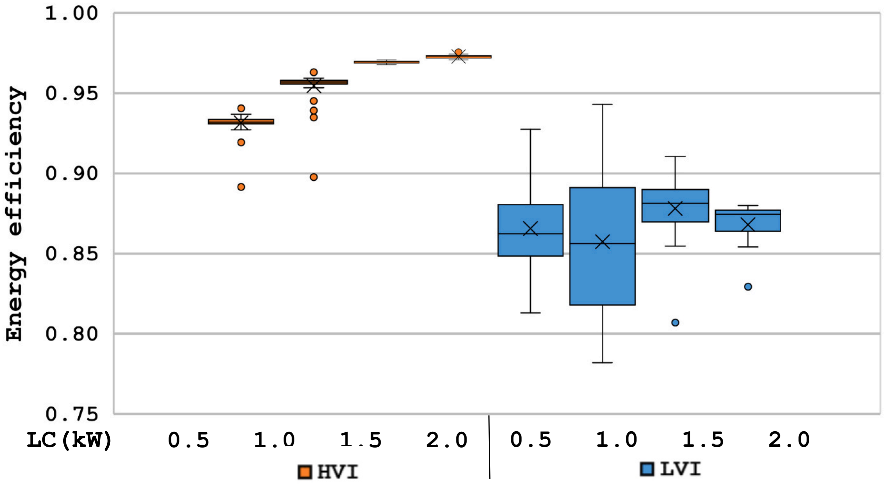

Fig. 8. η in DPV category test 1.

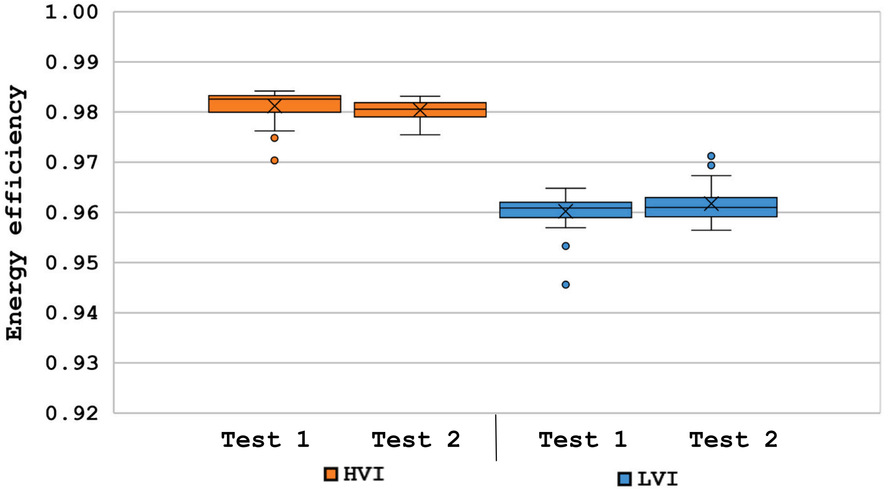

Fig. 9. η in BC category tests.

Also, it was proven that the energy conversion process of the inverter mostly included the loss of energy efficiency of the systems. Therefore, to achieve good system performance and optimization for a given building, manufacturers must ensure high energy efficiency in the operating voltage and power ranges and decrease inverter losses.

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CRediT authorship contribution statement

F.J. Sepúlveda: Methodology, Investigation, Supervision. **I. Montero:** Conceptualization, Supervision, Funding acquisition, Writing – review & editing. **F. Barrena:** Methodology, Investigation, Writing – original draft. **M.A. Domínguez:** Investigation. **M.T. Miranda:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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