# Assessing the viability of Battery Energy Storage Systems coupled with Photovoltaics under a pure self-consumption scheme

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**Abstract**

Over the last few decades, there is a constantly increasing deployment of solar photovoltaic (PV) systems both at the commercial and residential building sector. However, the steadily growing PV penetration poses several technical problems to electric power systems, mainly related to power quality issues. To this context, the exploitation of energy storage systems integrated along with PVs could constitute a possible solution. The scope of this paper is to thoroughly evaluate the economic viability of hybrid PV-and-Storage systems at the residential building level under a future pure self-consumption policy that provides no reimbursement for excess PV energy injected to the grid. For this purpose, an indicator referred to as the Levelized Cost of Use is utilized for

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the assessment of the competitiveness of hybrid PV-and-Storage systems in the energy market, considering various sizes of the hybrid system, battery energy storage costs and prosumer types for six Mediterranean countries.

*Keywords:* Battery energy storage systems, grid parity proximity, levelized cost of use, photovoltaics, self-consumption.

## 1. Introduction

Solar photovoltaic (PV) systems have seen a significant growth mainly as a result of the increased electricity costs, the decrease in the prices of the solar PV modules, as well as the reduction of the total installation costs [1]. During the last decades, PV generation was encouraged by governments worldwide via a range of financial incentives and other support policies, such as feed-in tariff (FiT), net-metering and net-billing schemes [2, 3, 4, 5, 6].

Nevertheless, the increasing PV penetration in power systems poses several technical issues, mainly related to power quality [7]. Specifically, the mismatch between generation and consumption may lead to the occurrence of reverse power flow phenomena in low-voltage distribution networks, possibly resulting in voltage rise above the operational limits, or grid congestion issues [8, 9, 10].

The integration of battery energy storage systems (BESS) alongside PV systems at the residential level enables the significant increase of the household's energy self-consumption and energy self-sufficiency [11]. This can assist distribution system operators at the mitigation of the aforementioned technical challenges [12]. Additionally, the gradual reduction of FiTs and the steady increase in the electricity prices have created a strong motivation for residential PV system owners to increase their PV self-consumption [13]. Considering the significant reduction trend in the cost of BESS observed in recent years [14], BESS along with PV systems as a hybrid solution arise as an enticing option also for prosumers.

Given the above and the prospective abolition of FiTs and net-metering in the European Union (EU) by 2023, an on-going transition to more costoriented approaches, such as self-consumption schemes can be observed [15]. Such schemes generally favour the exploitation of energy storage systems and thus, there is an increasing interest in the support of storage integration through policy modifications [16].

The main contribution of this paper is the evaluation of the economic competitiveness of hybrid PV-and-Storage systems under a pure self-consumption scheme, i.e. a scheme that provides no reimbursement for excess PV energy injected to the grid. Pure self-consumption is considered for the evaluation of the economic viability of integrated PV and storage systems, since it can be regarded as the most pessimistic scenario, due to the lack of provision of any additional monetary benefits to the prosumer.

Among the methodologies provided in the literature for the economic viability assessment of distributed generation projects, an indicator namely the Levelized Cost of Electricity (LCOE) is usually exploited to evaluate the cost of a generating asset [17, 18]. The LCOE index can be used for the comparison of various electricity generation technologies with different features such as installation capacity, capital cost, lifetime, payback period and risk. Generally, the LCOE indicator is a way to economically assess the total cost of a power generation system throughout its lifetime, considering the total generated energy over that period. It can also be considered as the minimum cost at which the generated electricity must be sold in order to achieve break-even pricing over the lifetime of a system [19]. The well known grid parity for PV systems occurs when the PV LCOE is less than or becomes equal to the retail electricity price [20]. Similarly, the grid parity of a hybrid PV-and-Storage system is reached when the PV-and-Storage system's LCOE is less than or becomes equal to the retail electricity price. However, in cases where BESS operate along with PVs other parameters must also be considered, such as the self-consumption rate (SCR) of the generated energy and the BESS control strategy.

Therefore, a systematic evaluation on how the BESS control strategy affects the LCOE of a hybrid PV-and-Storage system is essential, taking also into consideration the policy under which the hybrid system is operated [21]. This is important since the different applications offered by the storage asset and thus, the specific BESS control strategy, can influence the lifetime of the battery module [22], and subsequently, BESS total cost [23]. For the case of hybrid PV-and-Storage systems the above is considered crucial for their competitiveness on the energy market.

To achieve this, in this paper, a specific index is employed to accurately identify the LCOE of hybrid PV-and-Storage systems, referred to as the Levelized Cost of Use (LCOU). The LCOU index is employed to assess whether the grid parity of the hybrid system can be reached under the current market prices or when a future decreased BESS cost is considered. This is of great importance, since the LCOU could also act as an indicator that fewer incentives are required for a specific country towards a future pure self-consumption policy. The LCOU is assumed as a more appropriate indicator given the absence of PV sales, since it does not consider the existence of the power network as a balancing factor compared to the classic definition of the LCOE.

In addition, in this work a thorough comparison between the LCOU index of a hybrid PV-and-Storage system and the retail price when purchasing electricity directly from the grid is provided, considering various sizes of the hybrid system, BESS costs and prosumer types. For this purpose, actual historical data of solar irradiation and load demand for six countries of the Mediterranean region, i.e. Cyprus, Greece, Italy, France, Spain and Portugal, are employed.

## 2. Theoretical background

This section reviews the classic definition of the LCOE for a PV system. Moreover, it introduces the PV-and-Storage LCOU indicator and verifies its applicability for the assessment of the competitiveness of hybrid PV-and-Storage systems in the energy market.

### 2.1. Levelized Cost of Electricity calculation for PV systems

Equation (1) describes the classic definition of the LCOE indicator for a PV system, which determines the production cost of electricity from PVs [24].

$$LCOE_{PV} = \frac{CAPEX_{PV} + \sum_{n=1}^{N} \frac{C_n}{(1+r)^n}}{\sum_{n=1}^{N} \frac{E_n^{produced}}{(1+r)^n}} \tag{1}$$

In Eq. (1), $CAPEX_{PV}$ is the capital expenditure of the PV system, while $C_n$ corresponds to the maintenance costs of year $n$ and $E_n^{produced}$ is the PV generation at year $n$. In addition, $N$ and $r$, is the last year of analysis and the discount factor, respectively.

### 2.2. Levelized Cost of Use for hybrid PV-and-Storage systems

In cases of hybrid PV-and-Storage systems, the LCOE of the combined system could also be derived by the standard definition of the PV LCOE, i.e. Eq. (1), including the capital and maintenance expenses of both assets, $CAPEX_{PV\&Battery}$. However, Eq. (1) should be further modified when specific policy schemes are examined to incorporate the costs or revenues foreseen in these schemes. In this work, the modified Eq. (2) is exploited, which is better suited for hybrid PV-and-Storage systems under policy schemes that encourage a higher SCR of PV generation. Specifically, it is assumed that any surplus energy injected to the grid is not reimbursed in the examined scheme. Under such a policy, the most suitable BESS control strategy would be as follows: charge the battery asset by absorbing the excess power as soon as PV production is greater than consumption, and discharge when PV production is not adequate to supply the load demand [25]. In Eq. (2) the use of the self-consumed energy in the denominator can be noticed, resulting to a more representative indicator for the case of PV-and-Storage systems, under the specific BESS operation mode that aims at self-consumption maximization.

$$LCOU = \frac{CAPEX_{PV\&Battery} + \sum_{n=1}^{N} \frac{C_n}{(1+r)^n}}{\sum_{n=1}^{N} \frac{E_n^{produced} \cdot SCR_n}{(1+r)^n}} \tag{2}$$

Note that $SCR_n$ stands for the self-consumption rate of year $n$ as defined in [26]. It should be clarified that the LCOU term is highly dependent on the $SCR_n$ and consequently on the consumption profile of each prosumer.

As already mentioned, the LCOU term is targeted to act as an indicator that fewer incentives are required for a specific country towards a pure self-consumption policy. Specifically, the LCOU indicator does not intend to show the actual economic viability of an investment since other parameters must also be considered, such as the possible provision of any ancillary services.

Summarizing, in this work, Eq. (2) is used to implement the necessary simulations and estimate the corresponding LCOU values for each country, which are then compared with the corresponding retail electricity cost.

## 3. Proposed assessment methodology

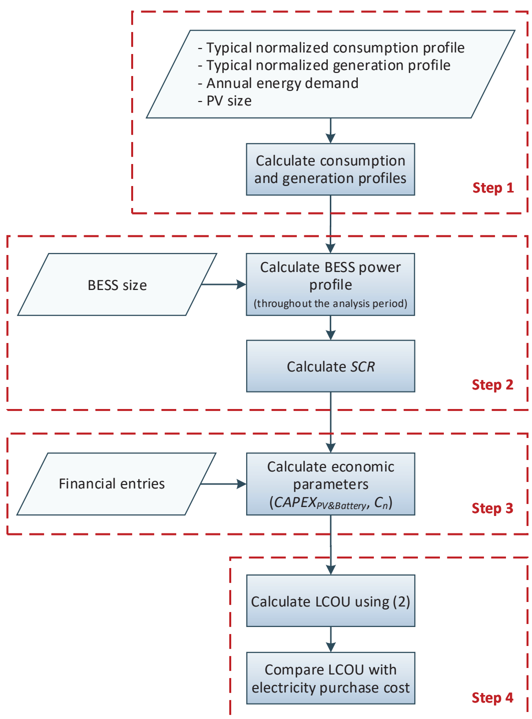


Figure 1: Flow chart of the adopted metholodogy.

The adopted methodology is presented in Fig. 1 by means of a flowchart. A four-step process is followed to determine the LCOU index:

- Step 1: Initially, the PV generation and load demand profile over the analysis period is calculated, based on the typical normalized consumption and generation profiles of the examined country, the annual energy demand and the PV system size.
- Step 2: The BESS size is inserted. The BESS power profile is constructed, by simulating the battery operation over the analysis period, based on the adopted BESS control strategy, and the generation and consumption power profiles of Step 1. Note that the above mentioned power profiles are in the form of time series with a 15-minute time-step. Consequently, $SCR_n$ is estimated.
- Step 3: The financial entries, i.e. PV system and BESS costs, discount factor and electricity purchase cost, are provided as inputs. Afterwards, $CAPEX_{PV\&Battery}$ and $C_n$ are calculated.
- Step 4: Finally, the LCOU index is calculated by Eq. (2) and then it is compared with the corresponding electricity cost to determine whether grid parity is reached.

The proposed methodology allows the evaluation of multiple PV and BESS sizes, as well as of different consumption levels and systems costs, due to the specific design for inputs. Therefore, the adopted methodology can be employed to assess the economic viability of hybrid PV-and-Storage systems for different countries. Nonetheless, the examination of various consumption levels and system costs for different countries yields some methodological dependencies, which are discussed in Subsection 3.2.

### *3.1. Methodological assumptions*

Energy storage systems can have many applications, such as power balancing and frequency regulation of power networks. Thus, the LCOE of a PV-and-

Storage system differs significantly given the operating conditions of the storage asset and especially of any possible monetary reimbursement of this operation.

To this context, the LCOU index is employed, when a self-consumption maximization mode of the BESS operation without financial benefits for providing any services to the power system is considered. As previously stated, regarding Eq. (2), the operation mode of the energy storage asset targets to maximize the self-consumption of the PV generation and does not benefit financially from the interaction with the grid, as there are no PV power sales. Specifically, excess PV generation is stored to the BESS rather than injected to the grid, whereas when PV generation is not adequate to meet the household's demand the energy stored to the BESS is used. It must be noted that due to this operation mode, only the surplus PV energy can be stored in the BESS. Also, due to the asset's round-trip efficiency the energy delivered by the energy storage system is reduced [19]. Given Eq. (2), such losses are taken into consideration through the use of the SCR. This rate is defined as the portion of the PV produced energy, which is finally used for own needs. Finally, note that the LCOU term is applicable only for newly installed hybrid PV-and-Storage systems, as it incorporates all relevant costs of both PV and BESS in the $CAPEX_{PV\&Battery}$ and $C_n$ terms of the hybrid system, as seen in Eq. (2).

### *3.2. Dependencies of the adopted methodology*

The SCR of different systems imposes restrictions in the calculation of Eq. (2) as mentioned above, and may result in more system-specific LCOU values. As presented in subsection 4.1, this issue can be resolved by investigating different levels of consumption, in order to determine a more generic case.

Furthermore, the LCOU values are highly dependent on the system's location, due to the variation of solar irradiance that has a direct effect on the PV energy output. For this purpose, typical monthly production curves are generated for each country. Additionally, to take into account the distinct characteristics in terms of load demand, typical residential consumption profiles are employed for each country.

Moreover, the LCOU values depend on the regional cost differences of the systems [27]. For this reason, a common price for the hybrid system is considered for all countries for ease of comparison.

Finally, it should be clarified that the LCOU values are compared with the current electricity prices of each country and assuming a flat pricing scheme.

## 4. Case studies

This Section analyzes the categorization of the prosumers, as well as the examined PV and BESS capacities considered in this work. Moreover, the typical consumption and generation profiles utilized are discussed. Finally, a brief overview regarding the electricity charges and the assumed individual costs of the hybrid system is given.

### *4.1. Categorization of end-users*

The assessment of the economic viability of hybrid PV-and-Storage systems is performed for six countries of the Mediterranean region. In all cases, three different types of prosumers are studied so as to generalize the results at a country level. This categorization of end-users is conducted by means of the annual energy demand, as follows:

- **Type A**: 4500 kWh consumption per year.
- **Type B**: 7500 kWh consumption per year.
- **Type C**: 10500 kWh consumption per year.

These types are considered to represent low, medium and high end-user consumption, respectively.

Moreover, the examined PV system capacity is varied in a predefined range of values, according to the type of prosumers, as determined below:

- **1-5 kWp** PV installed capacity for type A prosumers.
- **3-8 kWp** PV installed capacity for type B prosumers.
- **5-10 kWp** PV installed capacity for type C prosumers.

Finally, the BESS capacity is determined according to the PV rated power. To examine different BESS capacities the following three ratios are assumed:

Table 1: Calculated annual PV generation in kWh per kWp installed, using the solar radiation database of the PVGIS platform.

| Country | kWh/kWp |
|---|---|
| **Cyprus** | 1463.85 |
| **France** | 981.08 |
| **Greece** | 1367.45 |
| **Italy** | 1277.50 |
| **Portugal** | 1420.28 |
| **Spain** | 1591.61 |

- **0.5 kWh** per kWp.
- **1 kWh** per kWp.
- **2 kWh** per kWp.

### *4.2. Typical consumption/generation profiles*

For each country, typical residential generation and consumption profiles are used. Regarding consumption, data sets of typical load profiles are utilized, whereas differences between working and non-working days are also taken into consideration. As far as PV generation profiles are concerned, typical monthly curves are calculated for the capital city of each country, employing the solar radiation database of the PVGIS platform [28]. In Table 1, the annual PV generation in kWh per kWp installed is summarized for all countries. Note that France and Spain present the minimum and maximum PV generation respectively, due to their distinct irradiation characteristics.

### *4.3. Residential electricity charges and hybrid system cost*

For the calculation of the total electrical energy charges (in €/kWh), three parameters are considered, namely the charges for production and supply of electrical energy, charges for electrical networks use, as well as taxes calculated on electrical energy. The total electricity cost is obtained by adding the corresponding Value Added Tax (VAT) of each country to the charges. The above-mentioned charges correspond to charges that are calculated on the electrical energy absorbed from the utility grid. However, it should be mentioned that standing fees and charges calculated depending on the installed capacity of the installation are neglected, since they are considered as a fixed paid amount. In Table 2 the total residential electricity cost is summarized for each country.

As far as the PV system cost is considered, i.e. PV array and hybrid inverter, a common price of 1300 €/kWp is assumed for all countries [1], for ease of comparison. Additionally, the corresponding VAT of each country is added to the above mentioned price, whereas it should be clarified that no subsidies are provided.

As already mentioned, in terms of the BESS price, two cases are investigated, an assumed current one at 500 €/kWh and an expected future one at 150 €/kWh. Note that the aforementioned values correspond to the assumed prices before applying the corresponding VAT of each country. Within the analysis period, i.e. 20 years, no battery module replacement is required since the service life of solar batteries is considered to be greater than 20 years. Finally, it should be mentioned that for the calculation of the LCOU index, a discount factor equal to 4 % is considered.

Table 2: Total residential electricity cost per country in €/kWh, as of April 2019.

| **Country** | **€/kWh** |
|---|---|
| **Cyprus** | 0.19270 |
| **France** | 0.16814 |
| **Greece** | 0.17405 |
| **Italy** | 0.21957 |
| **Portugal** | 0.20295 |
| **Spain** | 0.21780 |

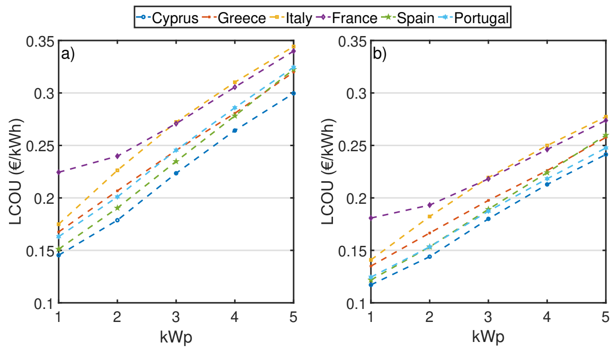


Figure 2: LCOU analysis; 1 kWh/kWp BESS considered. Prosumer type A. Battery module costs: a) 500 €/kWh; b) 150 €/kWh.

## 5. Results

The proposed framework is utilized for the techno-economic evaluation of PV-and-Storage systems, examining various sizes of the hybrid system, BESS costs, and prosumer types, while the corresponding results are presented in this Section. Analysis outputs demonstrate the performance of the introduced LCOU term, while also express the PV-and-Storage grid parity proximity for the countries under study.

Analysis outcomes indicate that the LCOU highly depends on the PV-BESS size. Indeed, considering prosumers of type A, the LCOU follows an ascending trend while the system size increases, as shown in Fig. 2a, assuming BESS of 1 kWh/kWp. Moreover, the comparison between the LCOU values and the costs of Table 2 reveals that the operation of a hybrid PV-and-Storage system leads to a LCOU value below the retail electricity price for lower PV sizes. Specifically, this can be confirmed for PV systems up to 2 kWp for Cyprus, Portugal and Spain, 1 kWp for Greece and Italy, while in France the LCOU is higher than the current electricity price for residential premises for all cases examined. As expected, a reduction of BESS costs diminishes system LCOU values allowing the investment in larger PV and BESS capacities, as illustrated in Fig. 2b.

Analyzing the performance of integrated PV-and-Storage systems owned

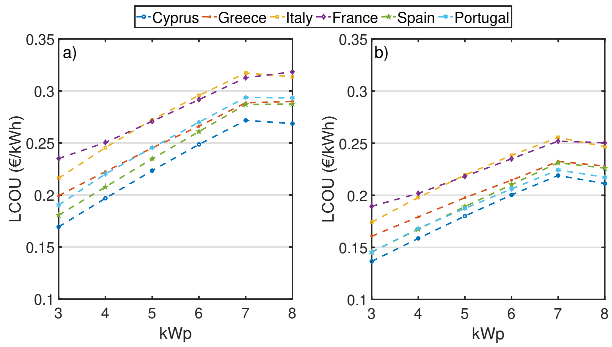


Figure 3: LCOU analysis; 1 kWh/kWp BESS considered. Prosumer type B. Battery module costs: a) 500 €/kWh; b) 150 €/kWh.

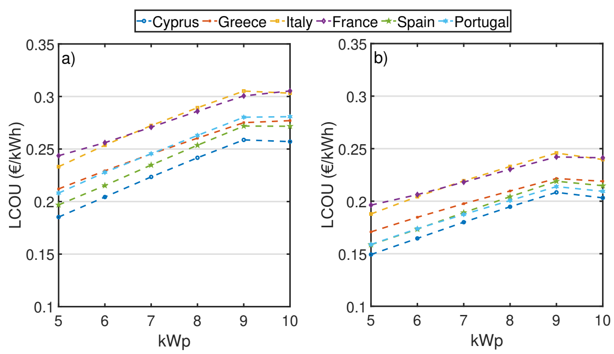


Figure 4: LCOU analysis; 1 kWh/kWp BESS considered. Prosumer type C. Battery module costs: a) 500 €/kWh; b) 150 €/kWh.

by prosumers with higher consumption levels, it was revealed that the LCOU increases proportionally to PV-BESS size, however, this trend reverses for prosumers type B and C, when exceeding 7 kWp and 9 kWp PV capacity, respectively, as shown in Figs. 3a and 4a. Consequently, it has to be noted that in most cases the LCOU exceeds the current retail price of electrical energy. Nevertheless, this condition changes when decreased BESS costs are considered, as presented in Figs. 3b and 4b, making hybrid PV-and-Storage systems profitable for all examined countries excluding France.

Furthermore, to assess the impact of BESS capacity on the techno-economic performance of the hybrid systems, the relation between battery energy capacity and PV system rated power is varied as described in subsection 4.1. Specifically,

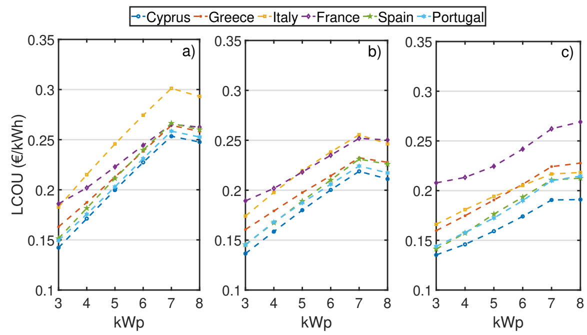


Figure 5: LCOU analysis; prosumer type B. Battery module costs at 150 €/kWh. a) 0.5 kWh/kWp, b) 1 kWh/kWp, c) 2 kWh/kWp.

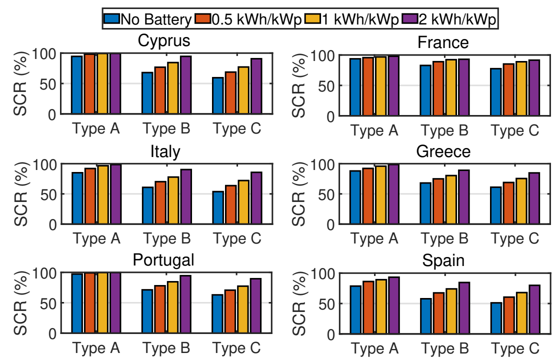


Figure 6: SCR. Type A prosumer: 1 kWp; type B prosumer: 3 kWp; type C prosumer: 5 kWp.

Fig. 5 shows that for the same PV size, lower LCOU values can be achieved with larger BESS capacities, considering a battery cost of 150 €/kWh. In fact, BESS operation improves prosumer's SCR and thus the LCOU is reduced. In Fig. 6 the SCR of different prosumer types and various kWh/kWp ratios is illustrated, considering the PV size that provides the lowest LCOU. It should be noted that in contrast to other countries examined, a slight self-consumption improvement is observed by the use of BESS in the case of France, which results in an increase of the LCOU while BESS capacity rises, as depicted in Fig. 5.

Comparative analysis between BESS sizes in Fig. 7 demonstrates that integrating BESS with a PV system leads to a lower LCOU for prosumers type B and C in Cyprus, assuming a reduced BESS cost. This is expected since

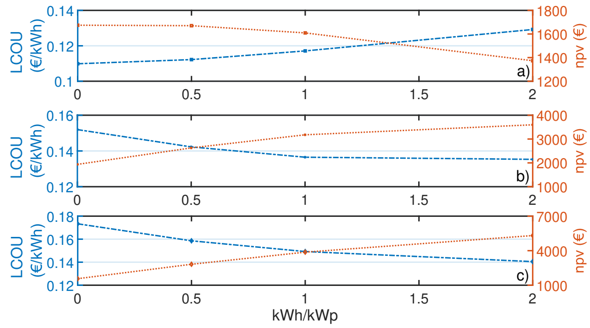


Figure 7: LCOU and NPV analysis for Cyprus per prosumer type, considering the PV size that leads to the lowest LCOU; a) type A: 1 kWp, b) type B: 3 kWp and c) type C: 5 kWp.

the operation of BESS along with PVs increases the self-consumption of such premises, as shown in Fig. 6 for the case of Cyprus. In contrast, the SCR of type A prosumers is barely enhanced by BESS, since PV surplus energy is inadequate for charging the battery; consequently the addition of a BESS is not beneficial and may only result in an increase of the LCOU term. The same conclusions would be derived by evaluating the investment's NPV depicted in Fig. 7, confirming the convenience of the LCOU index.

The previous analyses proved that prosumer's self-consumption plays an important role in the economic evaluation of PV-and-Storage systems, and thus should be taken into account when assessing PV-and-Storage grid parity proximity. The introduced LCOU term incorporates this feature and thus may

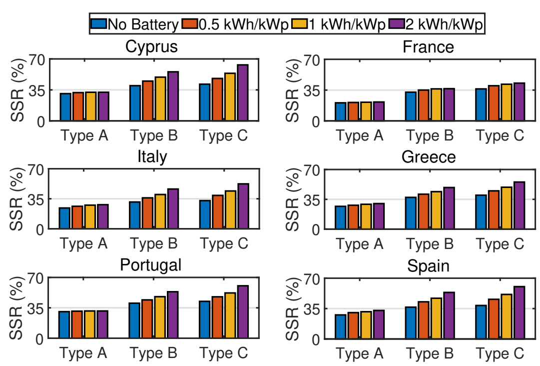


Figure 8: SSR.Type A prosumer: 1 kWp; type B prosumer: 3 kWp; type C prosumer: 5 kWp.

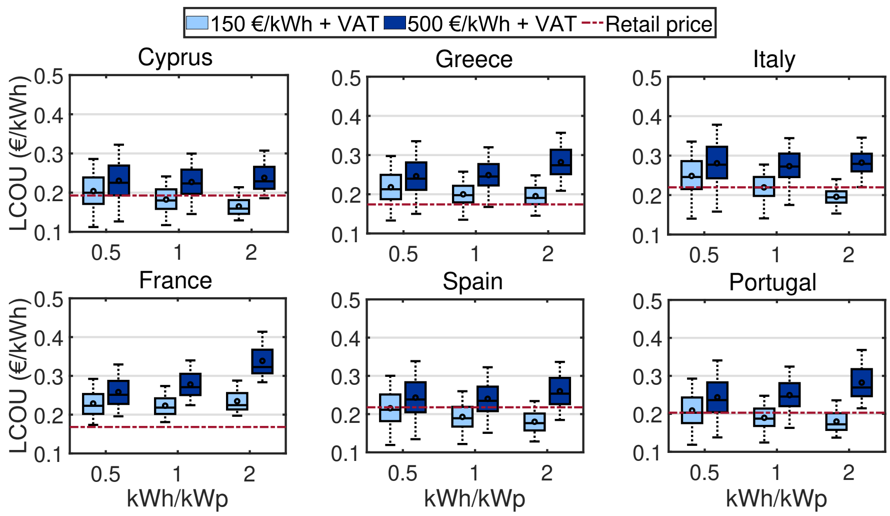


Figure 9: Statistical analysis of LCOU considering all three types of prosumers using box plots.

constitute a useful tool for the feasibility assessment of such hybrid systems, under self-consumption policies with no compensation for surplus energy. Analyses results also prove that when PV-and-Storage grid parity is reached, i.e. the LCOU is lower than the retail electricity cost, the NPV of the investment is always positive, thus indicating a viable investment.

The SCR and the Self-Sufficiency Rate (SSR), as defined in [26], have also been calculated for each case study. The study confirms that in all countries SCR and SSR of prosumers are augmented by the use of BESS as shown in Figs. 6 and 8, especially for premises that present a medium or high consumption level, i.e. prosumers type B and C, respectively. Despite that, the utilization of storage in prosumers of type A slightly improves the performance of the installation when considering a PV capacity of 1 kWp.

Moreover, the assessment of PV-and-Storage grid parity under a pure self-consumption scheme is conducted for all countries under study utilizing the methodology presented in Section 3, and results are concentrated in the box plots of Fig. 9. Specifically, the figure illustrates the allocation of all examined cases per country in terms of LCOU. It can be derived that PV-and-Storage

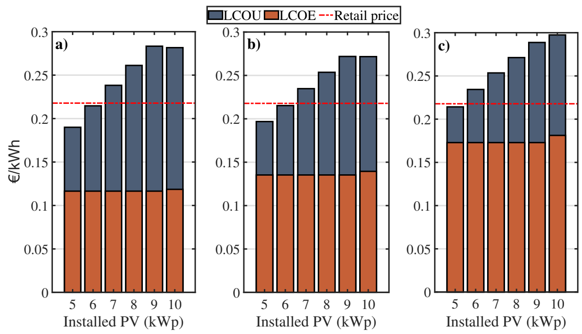


Figure 10: Comparison between the proposed LCOU index and the classical definition of LCOE, considering prosumer type C of Spain. Battery module costs at 500€ /kWh; a) 0.5 kWh/kWp, b) 1 kWh/kWp, c) 2 kWh/kWp.

grid parity is rarely reached under the current market prices for storage systems. However, considering future decreased BESS cost, i.e. 150 € /kWh before VAT, the LCOU of all systems under study is generally reduced, while PV-and-Storage grid parity is reached in most cases for Cyprus, Italy, Spain and Portugal. Indicatively, for all the examined BESS sizes, PV-and-Storage grid parity is reached in 61%, 59%, 73% and 63% of all cases for the above mentioned countries, respectively. In Greece, this only refers to a few individual cases of prosumers, i.e. 22% of all cases, whereas in France PV-and-Storage grid parity is not reached in any case.

Finally, in Fig. 10 the results of the LCOU index for prosumer type C of Spain are compared to the results obtained using the classical definition of LCOE [21, 24], taking into account the total cost of the hybrid system and assuming the current battery module cost. As it can be observed, for the different PV and BESS sizes examined, by employing the LCOE indicator grid parity is reached in all cases. On the other hand, by employing the LCOU indicator grid parity is reached for PV sizes equal to 5 and 6 kWp, when 0.5 and 1 kWh/kWp BESS ratio is considered and only for PV size equal to 5 kWp, when 2 kWh/kWp BESS ratio is assumed. From the results, we can infer that under the specific pure self-consumption policy, the LCOU index is a more appropriate indicator for the competitiveness assessment of hybrid PV-and-Storage systems, compared to the classical definition of LCOE. This is due to the fact that false conclusions may be drawn using the classical definition of LCOE compared to LCOU, since the SCR of the installation is not taken into consideration.

## 6. Conclusions

In this paper, the LCOU indicator is employed for the competitiveness assessment of hybrid PV-and-Storage systems in the energy market under a pure self-consumption scheme. The LCOU term takes into consideration the self-consumed energy and thus results to a more representative indicator for BESS integrated along with PV systems. The performance of the LCOU is evaluated for six countries of the Mediterranean area considering various sizes of the hybrid PV-and-Storage system, BESS costs and prosumer's types.

From the analysis conducted it is shown that the self-consumption rate should be considered when evaluating PV-and-Storage proximity under self-consumption policies with no reimbursement for surplus energy. In addition, it is also derived that in most cases PV-and-Storage grid proximity cannot be reached under the current market prices, unless the cost of BESS is further decreased. Moreover, it has to be recalled that in all cases, similar results were obtained for hybrid system's economic profitability by evaluating the investment's NPV, thus confirming the applicability of the LCOU term on the economic competitiveness assessment of such systems.

To conclude, by comparing the LCOU results with the results obtained using the classical definition of LCOE, it was clear that the LCOU term is a more representative indicator to assess the economic competitiveness of hybrid PV-and-Storage systems under a self-consumption scheme, when no reimbursement is provided for excess PV energy injected to the grid.

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