Abstract—In this paper, a thorough analysis is performed to evaluate the impact of the battery energy storage systems (BESSs) on the electrical behavior of the prosumers. Its distinct feature is the use of real measurements acquired from three pilot case studies located at the region of Northern Greece. Two types of BESS technologies are examined, namely the lead-acid OPzV and the lithium-ion LiFePO4 batteries. The evaluation process is implemented using the most well-known indicators, i.e., the self-consumption and the self-sufficiency rates.

Index Terms—Battery energy storage systems, photovoltaics, self-consumption, self-sufficiency.

I. INTRODUCTION

Climate change is the most important and demanding environmental challenge the global energy society has to face in the 21st century. Towards this direction, several efforts have been made at national and international level to decarbonize the energy sector. These efforts can be classified into two main categories: a) promotion of renewable energy sources that produce clean and carbon-free energy and b) increase of the energy efficiency [1].

Considering electrical networks, the transition to clean and carbon-free energy production is made by giving economic incentives to the stakeholders to install distributed renewable energy sources (DRESs), [2]. Initially, these incentives were consisting of feed-in tariffs or quota obligations to compensate the increased investment cost and reduce the payback period [3]. Nevertheless, the rapid reduction of DRESs cost in the last years – especially in photovoltaic (PV) systems – has led to grid parity, where subsidies are not necessary to ensure the viability of a PV investment [4], [5].

To achieve a constantly increasing deployment of DRESs, other schemes and policies have recently been applied to prosumers. Among them, net-metering is the most profound scheme that has already been implemented in several countries, promoting the long-term self-consumption [6]. By adopting this scheme, prosumers are encouraged to consume the on-site generated energy within a specific time period, e.g., day, month, etc. [7]. However, the impact of the DRESs on the distribution network is not fully compensated, since increased amounts of power may be injected during time instants of high irradiation and low demand. As a result, a series of technical challenges may occur that affect the secure and reliable network operation such as overvoltages, overloading of network equipment, etc. [8].

A promising solution to this problem is the use of electrical storage to increase the flexibility of the prosumer in terms of power management [9]. In this way, the self-consumption and the self-sufficiency of the prosumer can be further increased, while the impact of the DRESs on the distribution network is reduced. Nevertheless, this solution has not been thoroughly evaluated under real-field conditions.

Scope of this paper is to fill this gap by investigating the effect of electrical storage on the prosumer performance using real measurements from three pilot case studies in Greece. Well-established indicators, i.e., the self-consumption and self-sufficiency rates, are employed to quantify the variation of the prosumer’s electrical behavior due to the integration of the electrical storage. Furthermore, two different battery types are considered, namely the lead-acid OPzV and the lithium-ion LiFePO4 batteries, to further investigate whether the adopted battery technology affects the electrical performance of the prosumer.

The remainder of this paper is organized as follows. The metrics used in the evaluation process are analytically described in Section II, while the technical details of the three pilots case studies are presented in Section III. The data acquisition process is analyzed in Section IV, whereas the results of the evaluation process are presented in Section V. Finally, Section VI concludes the paper.

II. EVALUATION METRICS

Energy storage modifies the electrical consumption and generation profile of a prosumer, when incorporated in already existing PV installations. Two well-known indicators for the assessment of prosumer’s electrical behavior when operating a PV system are the self-consumption rate (SCR) and the self-sufficiency rate (SSR), as explained in [10]. These indicators can be easily extended to systems where PV and storage
integrated solutions are installed as analyzed below. SCR is defined as the portion of PV produced energy that is either directly consumed on-site or stored in the battery energy storage system (BESS) for later use. It can be defined by (1) with the aid of Fig. 1, where D area denotes the surplus PV energy stored in the battery, while E area refers to the energy supplied to the load by the BESS.

\[
SCR = \frac{C + E}{B + C + D} 
\]

\[
SSR = \frac{C + E}{A + C + E + F} 
\]

Although \(SCR\) expresses the exploitation level of the renewable energy by the prosumer, no information can be obtained regarding the sufficiency of the PV production in regards with on-site consumption. To evaluate PV self-sufficiency, (2) is used, where \(SSR\) stands for the self-sufficiency rate, defined as the portion of the demand energy that is supplied by the PV installation. Since BESS is able to store the PV excess energy during periods of high irradiation, and provide it to the load when PV power is insufficient, \(SSR\) is expected to rise if a BESS is operated.

### III. PILOT IMPLEMENTATION

Certain PV prosumers within the region of northern Greece were selected for the installation of BESSs, featuring various PV installed capacities and consumption profiles, i.e., two public buildings that host the municipality activities of the region (Pilot 1 and Pilot 2), as well as a domestic building (Pilot 3). In the selected pilot sites, BESSs were incorporated through ac-coupling as illustrated in Fig. 2. Two types of BESS technologies are examined, i.e., lead-acid OPzV (type A) and lithium-ion LiFePO4 (type B) batteries, aiming to compare their performance in energy conversion as well as other technical issues (lifetime, self-discharge rate, state of charge (SoC) limits, etc.). Type A installation uses three single-phase converters, while the battery consists of 24 cells, with a nominal voltage of 2 V per cell, connected in series, thus resulting in a battery array of 48 V, as depicted in Fig. 3.

On the other side, type B installations are more compact, using one three-phase converter, while battery array consists of five battery modules enclosed in a rack. Further technical details about PV and storage systems per pilot site can be found in Table I.

Each BESS is controlled by a battery management system (BMS) that measures the total power injected or absorbed by the prosumer at the point of common coupling (PCC) with the utility grid. Based on these measurements, BMS aims to maximize the prosumer’s self-consumption using the following control strategy:

- **Charging mode:** When BMS measures that there is surplus PV power injected to the grid, it charges the battery aiming to store this surplus.
- **Discharging mode:** When the PV power is not sufficient to supply the demand power, BMS attempts to cover this difference by discharging the battery accordingly.

It should be noted that maximum BESS power and SoC limits are taken into consideration during both modes.

### IV. MONITORING SCHEME

One of the main targets of the project is to investigate the impact of BESS on prosumer’s behavior, i.e., how BESS operation affects prosumer’s interaction with the electrical grid. Towards this aim, a complete monitoring system was
TABLE I  
PILOT SITES TECHNICAL DETAILS

<table>
<thead>
<tr>
<th>Pilot</th>
<th>Mean monthly consumption</th>
<th>PV</th>
<th>BESS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Size</td>
<td>Mean monthly production</td>
</tr>
<tr>
<td>PL1</td>
<td>809 kWh</td>
<td>10 kWp</td>
<td>1056 kWh</td>
</tr>
<tr>
<td>PL2</td>
<td>1363 kWh</td>
<td>10 kWp</td>
<td>1016 kWh</td>
</tr>
<tr>
<td>PL3</td>
<td>1550 kWh</td>
<td>5 kWp</td>
<td>613 kWh</td>
</tr>
</tbody>
</table>

Fig. 4. Schematic diagram of monitoring system

Fig. 5. Energy consumption of pilot installations.

Fig. 6. Energy production of pilot installations. Concerning PL2, from December 2018 to February 2019 there was a malfunction on the PV inverter. Thus, the PV system did not produce any power.

V. EVALUATION OF BESSs VIA PILOT CASE STUDIES

In this Section, the performance of BESSs is evaluated using measurements acquired from the pilot installations of Section III, while lessons learned from the pilot case studies are also discussed. The BESSs were installed at the end of May 2018. Thus, the starting and the end month of the examined period are June 2018 and February 2019, respectively.
A. Performance Evaluation of BESSs Through Field Measurements

The monthly consumed energy for each pilot installation is presented in Fig. 5, while the monthly produced energy from the corresponding PV systems is depicted in Fig. 6. As shown, all pilot installations present a similar behavior. In particular, an increased energy consumption is observed during winter months, while the PV production is maximized during summer months. The energy consumption is maximized during January, while energy production is maximized during July. To provide a further insight on the energy consumption/production of each pilot installation, mean values, obtained during the examined period, are presented in Table I.

The impact of the BESSs on the SCR and on the SSR of all pilot installations is demonstrated in Figs. 7 - 9. It is evident that in all cases, both indexes are considerably increased when BESSs are considered. This is further demonstrated on Table II, where the percentage increase of the SCR, due to the use of BESSs, is presented. The increased SCR and SSR actually imply that the interaction of the pilot installations with the utility grid is reduced, i.e., less power is imported/exported from/to the utility grid.

The energy consumption of all pilot installations is further analyzed in Figs. 10 - 12 to better highlight that the interaction with the utility grid is reduced. As shown, in all cases, the total power, imported from the main utility grid, is considerably reduced.

B. Lessons Learned From the Pilot Case Studies

Through the monitoring of the pilot installations, valuable remarks concerning the operation of BESSs are also derived. The most important of them are related with lead-acid batteries and they are summarized in Fig. 13.

Specifically, in order to increase their service life, lead-acid batteries are charged to 95% of their capacity by the BMS once every 15 days. For this purpose, the batteries may be charged directly from the utility grid. As illustrated in Fig. 13a the aforementioned operation has been activated, while between 11:00 and 13:00 the BESS absorbs additional required power from the utility grid. It should also be mentioned that since the SoC value is not a direct measurement, deviations between

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| TABLE II PERCENTAGE INCREASE OF SCR DUE TO THE USE OF BESSs |
|-------------------|--------|--------|--------|
|                   | PL1    | PL2    | PL3    |
| June              | 53.25  | 55.13  | 37.81  |
| July              | 59.90  | 53.21  | 37.77  |
| August            | 68.32  | 56.29  | 45.40  |
| September         | 65.79  | 61.78  | 45.12  |
| October           | 48.74  | 50.01  | 51.18  |
| November          | 10.2   | 15.78  | 36.23  |
| December          | 28.62  | -*     | 19.18  |
| January           | 7.10   | -*     | 5.08   |
| February          | 17.35  | -*     | 16.75  |

*During these months there was a malfunction on the PV inverter. Thus, the PV system did not produce any power.
estimated and actual values are expected [11]. Therefore, the BMS regularly recalibrates the battery SoC, by setting it to 100%, after a full charge. Indeed, this is depicted in Fig. 13a at 18:00, where the SoC is immediately adjusted to 100%.

Additionally, it was noticed that in many cases the BMS charges the lead-acid batteries by absorbing power from the utility grid, to ensure that the SoC is kept in permissible limits. This operation is presented in Fig. 13b, where it can be observed that SoC has reached the lower seasonal limit of 60%, and thus batteries are not discharged to supply the load. However, when the BMS detects that SoC tends to drop below the lower limit due to batteries self-discharge behavior, it absorbs power from the grid to maintain SoC above the limit. On the contrary, in the case of lithium-ion batteries, power absorption from the grid for the maintenance of SoC above the lower operational limit has not been observed during the monitoring period.

An additional operation mode is included in the BMS of both battery types, which aims to eliminate any mismatches between the SoC of individual battery cells. This is achieved by the full charge of batteries on a regular basis, while it targets to increase the battery service life. It has to be noted that during this operation mode, power may be absorbed from the grid when PV surplus power is not sufficient.

VI. CONCLUSIONS

In this paper the impact of electrical storage on the performance of prosumers is assessed, using field measurements from different pilot case studies in Greece. In order to evaluate the electrical behavior of prosumers two evaluation metrics are examined, i.e., the SCR and the SSR. Moreover, the actual design of the pilot installations, as well as the technical details of each pilot are briefly discussed. The complete monitoring system that is implemented at each pilot site for the acquisition of electrical measurement data is also described.

In the examined pilot installations, two different types of BESS technologies are employed, i.e., lead-acid OPzV and lithium-ion LiFePO4 batteries. One valuable remark concerning the operation of BESSs of the former technology, which emerged from the monitoring of the pilot sites, is that lead-acid batteries are occasionally charged directly from the utility grid due to maintenance issues.
From the analysis conducted, it is evident that in all cases the evaluation metrics are noticeably increased when BESSs are considered. Consequently, the autonomy of each pilot installation is enhanced and thus, the impact of the DRESs on the distribution network is further reduced.

REFERENCES


