Residential battery storage sizing based on daily PV production and consumption load profile characterization

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***Abstract*—The integration of battery energy storage systems (BESS) to existing grid-connected residential PV systems can reduce issues stemming from the increased PV penetration and at the same time improve the performance of the existing system. In this paper, a methodology for determining the optimal sizing of BESS is presented based on a clustering method by considering energy profiles of residential prosumers in Cyprus. As such, the daily energy required for residential premises with existing 3 kWp photovoltaic system in Cyprus is determined in three primary clusters. The clustering procedure is carried out based on the daily import electricity profiles recorded for the prosumers over the period of one year which revealed the daily energy needs of each cluster targeting to maximize self-consumption. Additionally, the battery capacity level of each cluster is compared with the daily export electricity of each prosumer within the same cluster to reveal the amount of users with enough surplus electricity to meet the capacity requirement of each cluster. Finally, a power rate dimensioning of the BESS power converter is performed by analyzing the import power measurements over the one year test period.**

Keywords— Photovoltaics, Battery Energy Storage Systems, Clustering, K-means.

I. INTRODUCTION

Environmental concerns, energy security and the fossil fuel resources have driven towards the integration of renewable energy sources, and more specifically solar photovoltaic technology, into the modern power grid. Despite the intermittent nature of photovoltaics (PV) and the initial high capital cost, in recent years governments around the world have encouraged the integration of PV systems into the electricity network either as residential-scale (rooftop) systems or large-scale (PV parks) systems. The financial incentives and governmental subsidies in conjunction with the recent drop in the cost of PV modules and the increasing electricity prices, have driven to the dramatic uptake of residential PV in some countries [1], [2].

Taking Cyprus as an example, photovoltaic technology has seen a remarkable growth during the last few years, with the installed PV capacity almost doubling in consecutive years, as it can been seen in Fig. 1. Grid parity conditions combined with the implementation of favourable policies such as the net-metering, have contributed to this trend of increasing PV system installations on the island to promote PV penetration towards achieving the 2020 national energy targets.

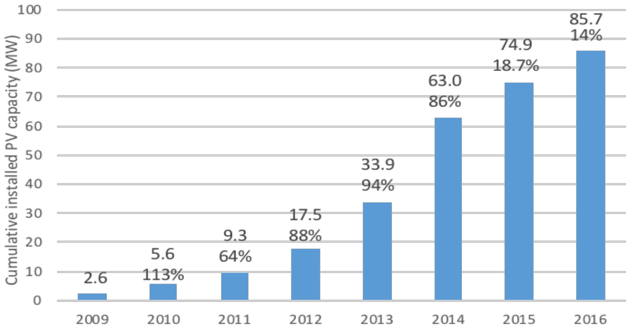

Fig. 1. Cumulative installed PV capacity (power) in Cyprus for the years 2009 till the end of 2016.

Considering the isolated electricity network of Cyprus along with the steadily increasing PV penetration in the energy mix of the island, adverse consequences can impact the performance of the low-voltage (LV) distribution network. For instance, voltage rise can be noticeable in areas with dense rooftop PV systems connected to the grid [3]–[8]. At the same time, voltage deviation occurs mainly from the intermittent generation of PV systems [5], [9], [10] and is primarily affected by the sky clearness conditions, thus compromising the power quality and stability of the grid [3], [11].

Several solutions exist for balancing grid voltage level; one of them is to limit the PV generation that is injected to the grid in order to preserve voltage fluctuations within an acceptable range [12], [13]. However, such an approach is not optimal without incorporating financial incentives since spilling PV generation leads to loss of revenue for the prosumer and also increases the overall integration cost of PV systems. Other solutions include the adoption of energy management strategies to control the flow of PV generation in the LV grid. An example is the use of direct and price-responsive load management by facilitating Advanced Metering Infrastructure (AMI). This approach requires end-to-end communication between the smart utility meter and the utility company [14], [15] and also the utilization of residential Battery Energy Storage Systems (BESS) for storing or delivering electricity to the low voltage (LV) grid. Towards this direction, the utility can respond to a price-responsive load control mechanism in order to push prosumers to schedule battery operation based on time-varying tariffs. For instance, the network peak demand can be reduced by allowing prosumers to interact with the grid based on the electricity cost or by reducing the power flow from the grid when premise demand is higher than the PV production by discharging the local BESS system. Therefore, a battery scheduling mechanism in line with proper battery sizing are important parameters towards achieving a sustainable environment for the residential use of BESS.

Relating the above with the current situation in Cyprus, BESS technology is still at its infancy and technological improvement is needed in order to lift off the barriers before it becomes a reliable and affordable solution. Towards this end, proper battery sizing is required to reduce the aggregated battery cost to the end-user. The objective of this paper is to study the energy profile of residential prosumers with PV systems in Cyprus and reveal the daily energy levels imported from the LV grid. This reflects the additional energy that is required to balance grid demand. Finally, since self-consumed electricity fluctuates between users and week days, the evaluation of surplus PV electricity to achieve the same import energy levels will also be examined.

II. METHODOLOGY

A. *Residential Pilots in Cyprus*

Sixty-five prosumers in Cyprus have been selected, in the prospect of sizing a BESS unit ideally coupled with an existing 3 kWp PV system. All participating prosumers were geographically spread throughout the island to cover different socio-geographical situations. Two smart metering (SM) devices were installed as depicted in Fig. 2 to acquire energy profiles for each prosumer. In particular, one SM device is placed on the AC side of the PV power converter (inverter) in order to measure the PV generation and the second one is placed on the grid side to measure the energy exchange with the grid (i.e. import and export electricity). The SM device used is the Elster A230, a single-phase bidirectional meter which operates as a data logging equipment transmitting 30-minute average power values. The datasets are being post-processed and the premise power and energy exchange is calculated based on the registered power (30-minute interval), before they are stored to a central database platform.

B. *Load Characterization*

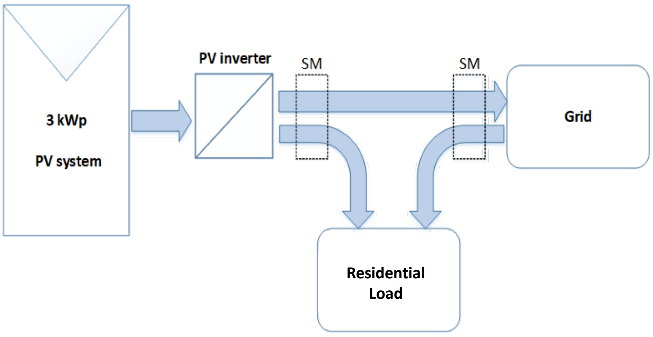

Fig. 2 Schematic diagram of a typical residential PV system in Cyprus.

Towards achieving a 100% renewable energy system, several parameters that affect the current electricity network should be taken into consideration. Particular emphasis is given on the energy demand of households, since by achieving dynamic user response could efficiently alleviate issues concerning the gradual increase of PV deployment to the grid. At the same time, electricity consumption depends on the daily habits and societal level [16] of the individuals, and comprises an important step towards achieving resilience to the existing energy system. Towards this direction, the process of collecting energy datasets from the 65 participating prosumers begun in 2015 for the period of one year (reference year). Grid exchange electricity such as import and export electricity along with PV production data were collected from the installed SMs and were used for the characterization process described next.

To start with, only the imported power samples were taken into consideration as they provide a significant indication of the additional energy that is supplied from the grid. This is the main objective towards achieving 100% self-sufficiency rate. Having this in mind, the cumulative daily import electricity values (in kWh) were extracted for the entire test group throughout the year and used for the grouping process. Then, the *k*-means technique was applied to perform the characterization between different import profiles and obtain an initial knowledge about the interaction of the prosumers with the grid. In particular, the *k*-means method uses fixed input dimensions, in this case the import electricity time series of each user, to separate them based on the input data-series. The algorithm applies an autocorrelation-based procedure to compute a dissimilarity vector between the time series as a function of the weighted Euclidian distance expressed in Eq. 1 below [17], [18].

$$d_{ACF} = \sqrt{\left(\hat{\rho}_{X_T} - \hat{\rho}_{Y_T}\right)^T \Omega \left(\hat{\rho}_{X_T} - \hat{\rho}_{Y_T}\right)} \qquad (1)$$

The parameters $\hat{\rho}_{X_T}$ and $\hat{\rho}_{Y_T}$ are defined as the autocorrelation vectors of X_T and Y_T time-series respectively having length L, whereas Ω denotes the weight coefficient matrix. For this study, the weight matrix is chosen to be identical such that $\Omega = I$, and let Eq. 1 become:

$$d_{ACF} = \sqrt{\sum_{i=1}^{L}\left(\hat{\rho}_{X_T} - \hat{\rho}_{Y_T}\right)^2} \qquad (2)$$

Once the Euclidian distance is calculated, the *k*-means clustering technique is applied. The idea behind clustering is to partition the observations with length L into k sets $S = \{S_1, S_2, \ldots, S_k\}$ such that $L \leq k$. Finally, the k-means clusters are derived as in Eq. 3, where μ_i is the mean of points in S_i.

Recalling the fact that the number of clusters k must be a known priori and is user-defined, the elbow method is used in this study to identify the optimum number of clusters that the data will be partitioned to. This is expressed in Eq. 4, where the variable k is chosen such that the total intra-cluster variation, also known as the within-cluster sum of squares (WSS) is minimized. The parameters $W(C_k)$ denotes the intra-cluster variant of sequence C_k, where k is the number of clusters in each iteration, ranging from 1 to K clusters.

$$argmin \sum_{i=1}^{k} \sum_{x \in S_i} \| x - \mu_i \| \quad (3)$$

$$wss = \min\left(\sum_{k=1}^{K} W(C_k)\right) \quad (4)$$

C. Battery Storage System Sizing

The dimensioning of the BESS system in terms of power and capacity is an important technical aspect towards achieving an efficient battery system coupled with a grid-connected PV system. The BESS should be able to fully utilize the excess PV generation in terms of storing and supplying energy, fully or partially the residential loads. In light of this, the capacity sizing in this study is initiated by taking the cumulative daily import electricity time series and applying the *k*-means clustering method as described above. This results to the classification of the daily import profiles based on the grid-imported electricity behaviour and also it categorizes the prosumers into groups. However, taking into account the environmental variations throughout the year, which affect the PV generation and hence the power demand of end-users, the battery dimensioning with respect to capacity levels, is performed seasonally. In particular, the reference year is divided into three main periods, the summer, winter and intermediate as shown in Table I. Next, the annual import profile of each cluster is divided into the aforementioned periods and the average seasonal battery capacity of each period is determined. With this, the accumulated daily import electricity of each period is determined, as this reflects to the additional electricity that the BESS needs to compensate during each season.

Additionally, a comparison between the desired battery capacity and the cumulative daily export PV electricity of the prosumers within the same cluster is performed. This provides an indication of the number of end-users that have adequate surplus energy to satisfy the average battery size allocated to each cluster. For this study, deep cycle Lithium-based BESS technology is considered for the battery capacity calculation of each cluster. Assuming that the BESS coupling topology is done on the AC side, the approximated system round-trip efficiency is 90%. The rest 10% of the surplus energy is lost on the AC-to-DC and DC-to-AC conversion, in the battery system itself and the cable losses. Finally, a power analysis of the users is examined as well. The 30-minute import power measurements were used to study the average import behaviour of each cluster seasonally and gain insights about the power dimensioning of the proposed BESS.

TABLE I. SEASONAL PARTITIONING OF DATASET

Season	Days of year	Period Length
Winter	Jan – Feb, Nov-Dec	121
Summer	May – August	123
Intermediate	March – April, Sep-Oct	121

III. RESULTS

The clusters determined from the cumulative import energy time series using the within-cluster sum of squares (WSS) plot is shown in Fig. 3. This is a graphical demonstration of the intra-cluster variation for various cluster values. The optimal *k* value is retained from the elbow point, in this case 3 clusters, and the representative patterns were extracted as depicted in Fig. 4. The majority of prosumers fall in Cluster 3 with 34 out of 65 users (52.3%), Cluster 1 follows with 20 users (30.7%) and finally Cluster 2 with 11 users (17.0%). The clusters revealed a similarity on the daily import energy profiles over the benchmark year, however with different energy levels as this mainly depends on the seasonal and environmental conditions. This was also validated by comparing the import energy profiles with the average ambient temperature profile of each season as depicted from the green dashed line in Fig. 4. It can be observed that the grid imported electricity has significantly higher levels during the summer period, where the ambient temperature peaks (average temperature reaches 29.7 ºC) and electricity demand for cooling purposes is increased. Similarly, during the winter period, import electricity remains high but it is lower than the summer period. This stems from the fact that during the winter season, the power demand for heating and domestic hot water is relatively high (average temperature 13.2 ºC). On the other hand, grid import electricity levels remain low during the intermediate period. Taking into account that the PV yield peaks during this season, a significant share of power demand is supplied instantaneously from the PV production.

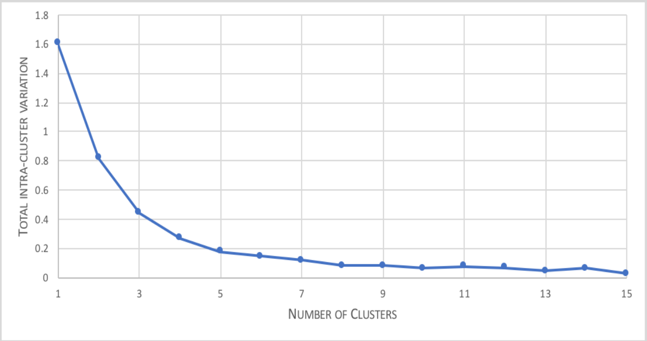

Fig. 3 Scree plot of cumulative daily import energy time series.

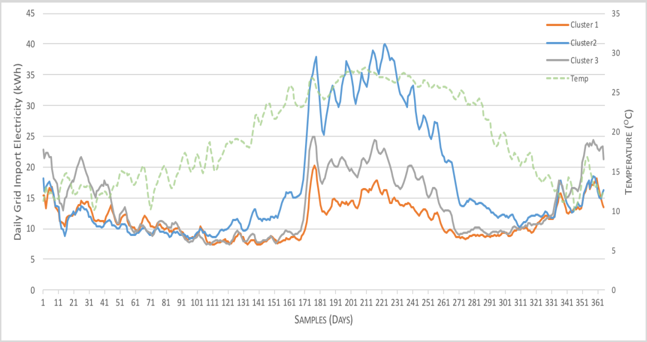

Fig. 4 Clusters of the cumulative daily import energy and average ambient temperature (dashed green line) over the test year.

Following the analysis described, the seasonal import levels of each cluster are shown in Table II. More specifically, it can be noted that Cluster 1 has the lowest import energy needs during the entire test year. On the contrary, prosumers with significantly high import energy levels, especially during the summer period, fall in the second cluster with the average daily grid consumed energy during the summer period to be 24.95 kWh. Also, prosumers that have energy needs in between the other two clusters are categorized in Cluster 3 and represent the majority of prosumers within the test group. Nevertheless, the energy requirements for the entire year reveal the high dependency of residential prosumers in Cyprus to be grid-connected as significantly high energy levels are required to meet the demands. The high energy levels reveal that additional PV capacity is required to cover the on-site demand. Considering that the estimated annual PV yield in Cyprus, is around 1600 kWh/kWp per year (or 4.3 kWh/kWp per day) for a 3 kWp system [19], residential PV system oversize may be required to balance demand and PV production.

TABLE II. DAILY IMPORT ENERGY PER CLUSTER

	Cluster 1	**Cluster 2**	**Cluster 3**
Winter	12.76 kWh	12.85 kWh	15.93 kWh
Summer	12.13 kWh	24.95 kWh	15.55 kWh
Intermediate	10.67 kWh	13.62 kWh	12.09 kWh
Average	**11.85 kWh**	**17.14 kWh**	**14.52 kWh**

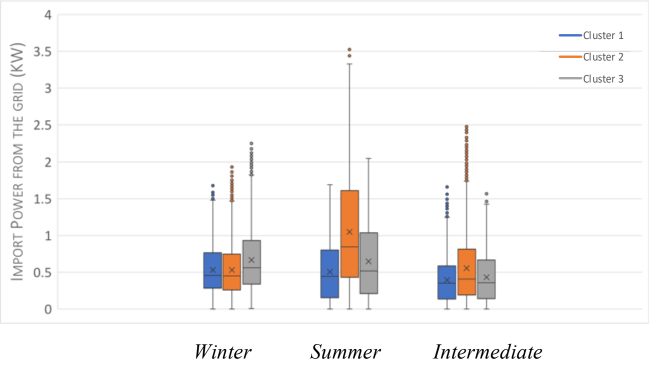

Fig. 5 Box-plot representing the average daily import power of the seasons, divided in Cluster 1 (blue), Cluster 2 (orange) and Cluster 3 (gray).

TABLE III. DAILY IMPORT POWER PER CLUSTER

	Cluster 1	**Cluster 2**	**Cluster 3**
Winter	1.48 kW	1.47 kW	1.82 kW
Summer	1.69 kW	3.32 kW	2.05 kW
Intermediate	1.25 kW	1.75 kW	1.42 kW
Average	**1.47 kW**	**2.18 kW**	**1.76 kW**

Further to the daily grid import energy analysis, the BESS power dimensioning comes next as it comprises another important parameter to consider. Ideally, the battery converter power rate should be sufficient enough to supply the load power demand in a way to minimize the power flow coming from the grid side. In this scope, the power rating is determined by analyzing the actual 30-minute grid import power data of the users within the same cluster for each season as shown in Fig. 5. Starting with Cluster 1 and Cluster 3, both clusters follow a similar power distribution profile. During the winter period, the average power of Cluster 1 is at 0.53 kW with the upper quartile (Q3) reaching up to 0.76 kW, where for Cluster 3, the mean power and upper quartile are 0.66 kW and 0.93 kW respectively. It can also be noted that for both clusters, numerous extreme observations (outliers) occur, revealing the fluctuation of import power demand during these seasons. On the other hand, the clustering algorithm classifies users with relatively higher import levels to Cluster 2. The wide interquartile region (IRQ) especially during the summer period, ranging between 0.43 kW to 1.61 kW, confirms the comparably high import energy demand during this period. At the same time, there are very few outliers but with high power demand reaching up to 3.6 kW. Based on the above observations and also considering the system topology, the battery power rate can be chosen to fulfill the maximum seasonal observation (excluding outliers) as shown in Table III. This is to ensure that the battery converter is properly sized to supply the expected power range and also maintain the battery converter operation close to the peak efficiency point. In other words, oversizing of the BESS power can cause the battery converter to operate at a lower power point and thus at low efficiency conditions. From the analysis above, it is possible to understand the user behaviour and interaction with the grid over the entire test year. However, for the BESS sizing, the surplus electricity needs to be taken into consideration. As already mentioned, the scope of this study to integrate BESS into existing residential PV systems to increase prosumer self-sufficiency rate. Towards this direction, the export power measurements were used to study the seasonal surplus energy delivered to the grid. In Fig. 6, the daily export electricity of each cluster and season is illustrated using a box-and-whisker plot. The schematic representation clearly shows that the export electricity during the intermediate period is higher than in the summer and winter, whilst winter season has the lowest surplus energy. At the same time, the wide interquartile region during winter reveals the fluctuation of export energy observations due to PV intermittency and variation in environmental conditions. To evaluate the adequacy of users to supply the cluster energy requirements shown in Table II, with the daily PV export energy, various import energy levels were compared with the surplus energy levels of users within the same cluster, reduced by 10% to consider also the BESS system losses. The optimum battery capacity is chosen such that the adequacy of users within the clusters to range between 20% and 80%. As shown in Fig. 7, Cluster 1 battery capacity can be selected between 50%-70% of the average cluster import energy (i.e. 5.9 - 8.3 kWh) since this is the transitional region until none of the users within the Cluster meeting the energy requirements. Even though Cluster 2 achieves high export energy levels, the required import profile limits battery sizing to a maximum usable capacity between 27% - 42% of the average import energy (i.e. 4.6 –

7.2 kWh). On the other hand, Cluster 3 achieves the highest export levels and the battery capacity can be sized in the range of 40% - 55% of the average cluster import energy (i.e. 5.8 – 8.0 kWh). From the battery capacity sizing performed above, it can be noted that Cluster 1 reaches the highest surplus electricity levels allowing the battery to be sized up to 8.3 kWh. At the same time, the quite large energy needs of Cluster 2, this does not a great impact on the battery sizing as the capacity is very close to the other clusters.

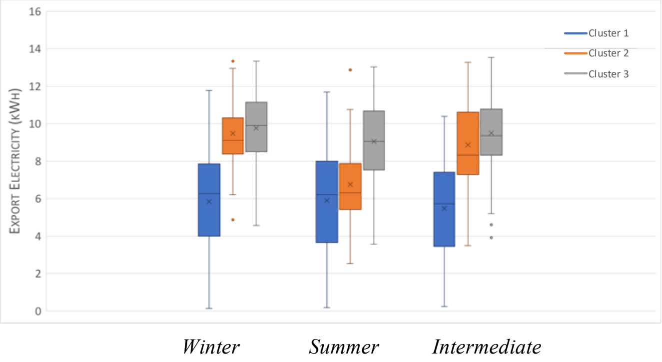

Fig. 6 Box plot representing the average daily export energy of the seasons, divided in Cluster 1 (blue), Cluster 2 (orange) and Cluster 3 (gray).

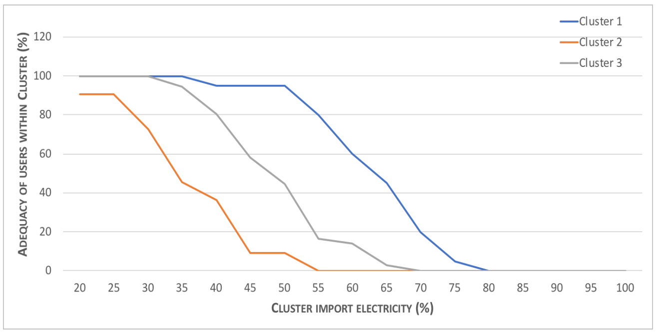

Fig. 7. Adequacy of export PV energy to meet cluster import energy requirements.

IV. CONCLUSIONS

A methodology to characterize the import energy profiles of typical prosumers in Cyprus was presented. The annual energy measurements taken from Smart Meters (SMs) were taken for a group of prosumers, and based on the k-means clustering technique, the import energy clusters were determined.

The extracted clusters presented useful information about the prosumer daily import energy levels over the test year as power and energy fluctuations depend on seasonal variations. The clustering technique revealed that 52.3% of the users are predominantly classified in Cluster 3 which represents a typical import profile over the year. On the contrary, Cluster 1, which holds the other 30.7%, has significantly low import needs over the year in comparison to Cluster 2, which has the rest 17% of the users, and has the highest grid import energy needs over the test year.

Next, the BESS sizing in terms of power rating and energy were extracted from the 30-minute power measurements of the import and export profiles. Starting with the energy sizing first, the analysis demonstrated that the PV export electricity can partially supply the premise demands since the relatively high import energy levels cannot be compensated from the daily surplus PV electricity and hence by the energy stored in the BESS unit. In particular, the surplus PV electricity for Cluster 1 is between 5.9 kWh to 8.3 kWh, whereas for Cluster 2 and Cluster 3 is between 4.6 kWh to 7.2 kWh and 5.8 kWh to 8.0 kWh respectively. As for the power dimensioning of the BESS, a statistical analysis of the power measurements was performed for each cluster. The analysis was performed on a seasonal basis over the year and revealed similar import profile for Clusters 1 and 3 with the average power to be 1.47 kW and 1.76 kW respectively. Finally, the summer period is characterized by significantly high power levels with a suitable power rate dimensioning to be 2.18 kW.

V. FUTURE WORK

In this study, a BESS unit that is AC-coupled with a PV system is considered and the battery energy and power rate dimensioning were chosen based on the daily import behaviour of three (3) dominant clusters of prosumers in Cyprus. As part of StoRES project scope, the optimum battery energy and power converter utilization will be discovered based on the measurements collected from the project pilot systems. In particular, a 2.5 kW / 9.8 kWh BESS system has been embedded to five (5) residential premises with an existing 3 kWp PV system forming an AC-coupling topology. The primary scope of the project is to group pilot users into the three primary clusters, and also verify the sizing methodology proposed in this study. Finally, the option of allocating a share of residential BESS units to a centralized storage is also considered as a future work of this project. To validate such a scenario, a 30 kW / 50 kWh centralized BESS unit has been installed to the LV distribution feeder that supplies the five residential pilots.

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