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Proceeding Paper

A Load Based Centralized Battery Energy Storage System Allocation for Residential Community with Rooftop Solar PV system †

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Abstract: This paper provides a practical process for evaluating the proper allocation of a centralized BESS in three types of communities with rooftop Solar PV, namely low-cost, medium-cost, and high-end community, by considering the mean and maximum energy consumption and peak demand profiles of each residential unit. Such values are used to allocate for the Solar PV system per residential unit and the centralized BESS at mean, 75% of maximum, maximum, and 125% of maximum energy consumption, to be used for the community and for any excess energy to support the electrical networks reliability improvement. The result shows that allocating the centralized BESS using the maximum and 125% of maximum energy consumption can provide more than enough energy capacity for electrical networks reliability improvement by supplying for the Energy not Supplied (EnS), E_N. The result provides that for a High-end community, the stored energy in the BESS can reach up to 24.578 MW h using 125% of maximum sizing at either mean or maximum energy consumption. While for Medium-cost and Low-cost communities, the stored energy can reach up to 17.549 MW h and 14.527 MW h using 125% of maximum sizing at either mean or maximum energy consumption, respectively.

Keywords: Residential Community; Rooftop Solar PV; Centralized Battery Energy Storage Systems

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1. Introduction

Solar PV technologies even with its popularity and development is identified as a Variable Renewable Energy (VRE) source, providing technical and operational issues in in terms of the networks voltage stability, flexibility, overall power system security [1] and curtailment in its power generation [2]. Centralized Battery energy storage systems (BESS) may provide solutions to the technical and operational issues of Solar PV technology in the electrical network. BESS may address the curtailment of solar PV generation by satisfying gaps between supply and demand and being seasonal storage for the technology [3]. BESS is introduced in various works of literature, such as technical and economic performance [4], sizing and operation [5], community sharing framework [6], and network reliability improvement [7]. In all of this studies allocating shared BESS is essential.

While methods introduced in these literatures provide excellent results, they may give a very complex methodology in sizing BESS in a residential community context. A residential community may vary in energy consumption and peak demand based on specific housing community categories. In the context of the Philippines, housing communities are categorized as socialized housing communities, low-cost housing communities, medium-cost housing communities, and high-end housing communities. Such communities are categorized based on price, lot area, floor area, type of house and amenities [8].

This paper contributes by providing a practical process for evaluating proper allocation of a centralized BESS size in three (3) types of communities categorized as low-cost, medium-cost, and high-end housing with rooftop Solar PV by considering the energy consumption and peak demand profiles of each residential unit. Then with the calculated BESS sizes and stored energy, the excess energy are then further evaluated to support the electrical network's reliability, particularly for energy not supplied (EnS) of the electrical substation.

2. Methodology

2.1. Energy Consumption and Peak Demand Profiling

The study starts by profiling residential communities' energy consumption and peak demand. In this study, a five-year actual metered monthly energy consumption and peak demand data, from 2018 to 2022, for three (3) residential communities classified as low-cost, Medium-cost, and high-end in Cagayan de Oro City, Philippines, is analyzed and assessed. Thus, for five years, the actual metered monthly energy consumption and peak demand data studied for each community are 33 240 from 554 residential units under the low-cost community and 19 877 from 357 residential units under the Medium-cost and 10 385 from 210 residential units under the high-end community. These data were evaluated for each monthly mean and maximum value using excel to characterize the monthly profile for a typical residential unit in a particular community.

However, before these values are generated, the gathered load data needs to be cleaned for some outliers. The lower quartile, Q_1, middle quartile, Q_2, and upper quartile, Q_3 terms in each of the monthly data need to be identified, such that the interquartile range, *IQR* and the Upper and Lower limits, U_{lim} and L_{lim} values can calculate and be used to determine the outliers. Any value greater than U_{lim} and lower than L_{lim} is considered an outlier and removed from the list. The mean, median, and maximum monthly data are then calculated from the remaining list.

2.2. Solar Photo Voltaic (PV) Sizing

To size the rooftop Solar PV systems to be installed in each residential unit per community, the calculated mean and maximum energy consumption per community and the average monthly solar irradiance in Cagayan de Oro City are utilized. This study's average monthly solar irradiance, G_a, data is 5.29 kW h/m^2/day from [9].

Solar PV sizing is then carried out by evaluating the Total peak power rating, P_{pv}, number of Solar PV Modules, n_s, and Solar PV Array area, *S*, for each typical residential unit per community at mean, 75% of maximum, maximum, and 125% of maximum energy consumption. Thus, P_{pv} is calculated using the data and equation:

$$P_{pv} = \frac{E}{\alpha} \tag{1}$$

Where, *E* is the energy consumption in kW h and α is the Panel Generation Factor (PGF) which can be calculated using the equation.

$$\alpha = \frac{G_a \times t_s}{G_s} \tag{2}$$

Where, G_a is the average solar irradiance in kW h/m^2/d, ts is the sunshine hours (set at 4 hours for Philippines), and G_s is the standard test condition irradiance (1000 W/m^2).

Then using the calculated P_{pv} the number of Solar PV modules, n_s, can be calculated using the equation:

$$n_s = \frac{P_{pv}}{P_r} \tag{3}$$

Where, P_r is the Solar PV module peak rated power output (chosen to be 345 W for this study from reference [10]).

Then with the calculated ns the solar PV array area, *S*, in m^2 can be calculated using equation:

$$S = S_p \times n_s \tag{4}$$

Where, Sp is the area of Solar PV module (set at 1.98 m2 in this study based on the chosen Solar PV module from reference [10]).

Lastly, the Monthly Solar PV System generated energy,E_g, in MW h, is then calculated using the equation:

$$E_g = G \times S \times \eta_{pv} \times \eta_B \times K_C \times \eta_I \times K_T \times K_L \times 30 \times n_R \quad (5)$$

Where, G is the Solar Irradiance in kW h/m^2/d, η_{pv} is the Solar PV conversion efficiency (set at 0.14), η_B is the battery efficiency (set at 0.9), K_C is the circuit loss factor to account for the DC Circuit loss (set at 0.95), η_I is the inverter efficiency (set at 0.95) from reference [11], K_T is the transformer loss factor (set at 0.975), K_L is the line loss factor (set at 0.99) from reference [12], and n_R is the number of residential units in a community (set at 100 in the study).

2.3. Battery Energy Storage System (BESS) Size Allocation

Sizing of the centralized BESS is based on the calculated mean and maximum energy consumption per community. The BESS energy capacity, E_C, in kW h is calculated using the equation:

$$E_C = \frac{n_R \times E \times A}{\eta_B \times K_D} \quad (6)$$

Where, η_B is the battery efficiency (set at 0.9 in this study) from reference [11], A is the number of Days of Autonomy (set at 3 days in this study), and K_D is the depth of discharge (set at 0.5 in this study) from reference [13].

Centralized BESS capacity sizing is then done by sizing its capacity based on the mean, 75% of the maximum, maximum, and 125% of the maximum energy consumption per community. The appropriate size is then evaluated by calculating the excess energy stored in the battery per month at different energy consumption conditions, such as the mean and maximum consumption.

The excess energy stored in the battery (E_B) that is available for alleviating E_N is calculated using:

$$E_B = E_g - (E_x \times n_R) \quad (7)$$

Where, E_g is the Monthly Solar PV System generated energy in kW h at a particular rooftop Solar PV size, E_x is the energy consumption in kW h per typical residential unit in each type of community at either mean or maximum energy consumption.

Moreover, the resulting E_B per month is then evaluated to support for Reliability improvement of the Distribution System thru alleviating the Energy not Supplied, E_N due to Power Interruption per month of the electrical substation where the said communities are connected. The most appropriate centralized BESS size(s) that can supply energy for E_N at the mean and maximum load condition is identified to be the suitable size(s) per community. The E_N is calculated using the equation:

$$E_N = \frac{t_I}{60} \times P_D \quad (8)$$

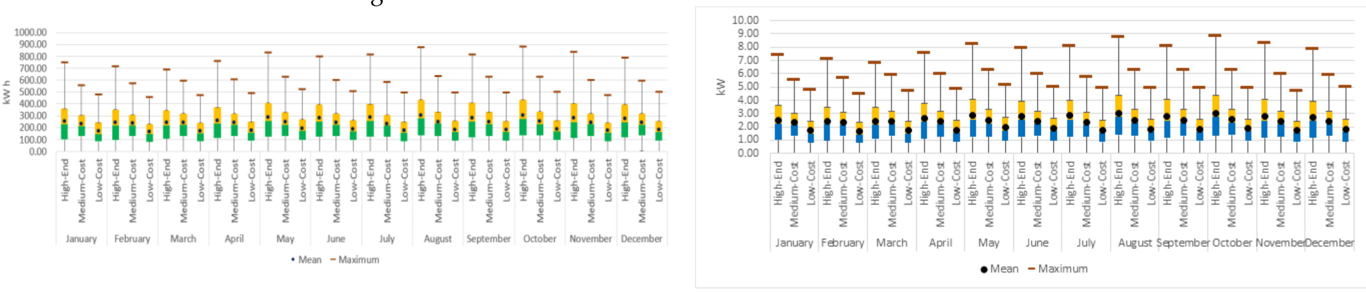
Where, t_I is the Total Customer Interruption Duration in minutes and P_D is the overall peak power demand in kW of the studied community.

3. Result and Discussion

3.1. Residential Community Energy Consumption and Peak Demand Profile

A 5 year actual metered monthly energy consumption and peak demand data, from 2018 to 2022, for three (3) residential communities classified as low-cost, Medium-cost, and high-end in Cagayan de Oro City, Philippines, is analyzed and assessed. This data is provided by the electric distribution utility supplying power for Cagayan de Oro City. The analysis shows that the High-end residential units typically consume 97 - 435 kW h with monthly mean energy consumption of 273.90 kW h and maximum energy consumption of 884.2 kW h. On the other hand, the Medium-cost residential units usually consume 125 - 334 kW h with monthly mean energy consumption of 242.46 kW h and maximum energy consumption of 631.79 kW h.While, the Low-cost residential units typically consume 81 – 270 kW h with mean energy consumption of 178.52 kW h and maximum energy consumption of 523 kW h.

For the Peak Demand data, the analysis shows that the High-end residential units typically load 0.97 - 4.34 kW with a mean peak demand of 2.74 kW and a maximum peak demand of 8.85 kW. On the other hand, Medium-cost residential unit's result shows that it usually loads 1.25 - 3.34 kW with a mean peak demand of 2.42 kW and maximum peak demand of 6.32 kW. While, Low-cost residential units typically load 0.81 - 2.70 kW with a mean peak demand of 1.79 kW and maximum peak demand of 5.23 kW. For these units, the maximum peak demand usually occurs in May, and the lowest peak demand is in February. See figure 1(b) for the illustration of the peak demand profiling result.



(**a**) (**b**)

Figure 1. (**a**) Five Years Energy Consumption, E, Profile Comparison; (**b**) Five Years Peak Demand Profile Comparison.

3.2. Monthly Energy Unserved due to Power Interruption

Using 2018 to 2022 monthly Total Customer Interruption Duration, t_I, data, provided by the electric distribution utility supplying power for Cagayan de Oro City, of the electrical substation where the residential communities are connected, the overall maximum peak demand result and equation 8, the five-year monthly energy not supplied (EnS), E_N, is generated. See figure 2 to illustrate the five-year monthly E_N generated.

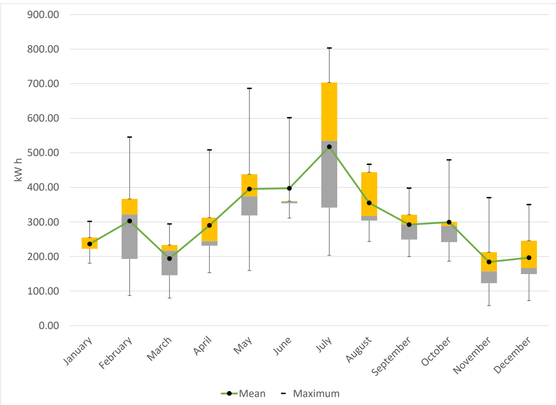


Figure 2. Five Years Monthly Energy not Supplied (EnS), E_N, Profile.

3.3. Residential Community Rooftop Solar Photovoltaic Size

Utilizing the energy consumption profile of a typical residential unit in each community, the sizes of rooftop Solar PV per residential unit are calculated at mean, 75% of maximum, maximum, and 125% of maximum energy consumption. P_{pv} is then calculated using equation 1, and using equation 3, n_s is determined. Then, with the n_s values, the S is determined using equation 4.

Result shows that High-end residential unit rooftop Solar PV is sized between 3 – 12 kW depending on the energy consumption; thus, n_s and S vary between 9 – 36 panels and 17.82 – 71.28 m^2, respectively. For the Medium-cost residential units, rooftop Solar PV is sized 3 – 9 kW, with n_s and S varying between 8 – 26 panels and 15.84 - 51.48 m^2 depending on the energy consumption considered. Then for Low-cost residential units, rooftop Solar PV size is between 2 – 7 kW, with n_s and S between 6 – 21 panels and 11.88 – 41.58 m^2 depending on the energy consumption. Moreover, to normalize the number of residential units in each community, it is assumed that 100 residential units per community will participate. Thus, the aggregated Solar PV size for the High-end community is between 311 – 1 242 kW, while the Medium-cost community is between 276 – 897 kW, and the Low-cost community is between 207 – 725 kW.

Using the resulting sizes per residential unit per community and the solar irradiance, the Solar PV System generated energy in kW h, E_g is calculated using equation 5. See figure 3a for the result per community. The figure shows that due to varying solar irradiance, E_g varies per month. The resulting E_g also varies per community due to the size of Solar PV installed per residential unit. The high-end community provides the largest E_g at 27 – 148 MW h, while Medium-cost and Low-cost communities can only provide 24 – 107 MW h and 18 – 86 MW h, respectively. Lastly, comparing E_g per community with the mean and maximum energy consumption per community, it can be observed that at mean energy consumption, E_g using mean sizing is just enough with little excess energy. In contrast, 75% of maximum, maximum, and 125% of maximum sizing shows more excess energy. However, if the communities consume maximum energy, it can be observed that only the maximum and 125% of maximum sizing can provide enough energy per month with excess energy.

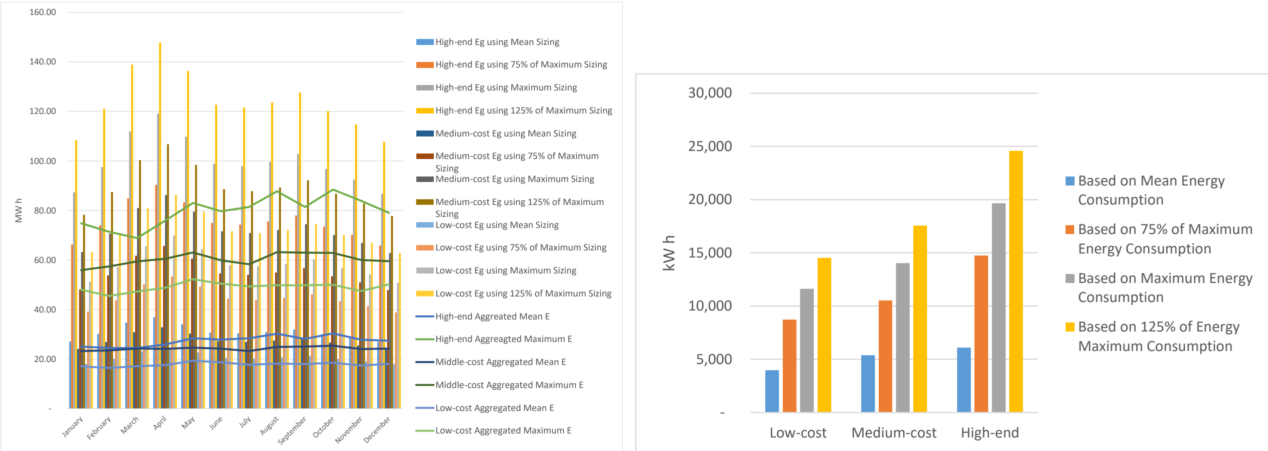
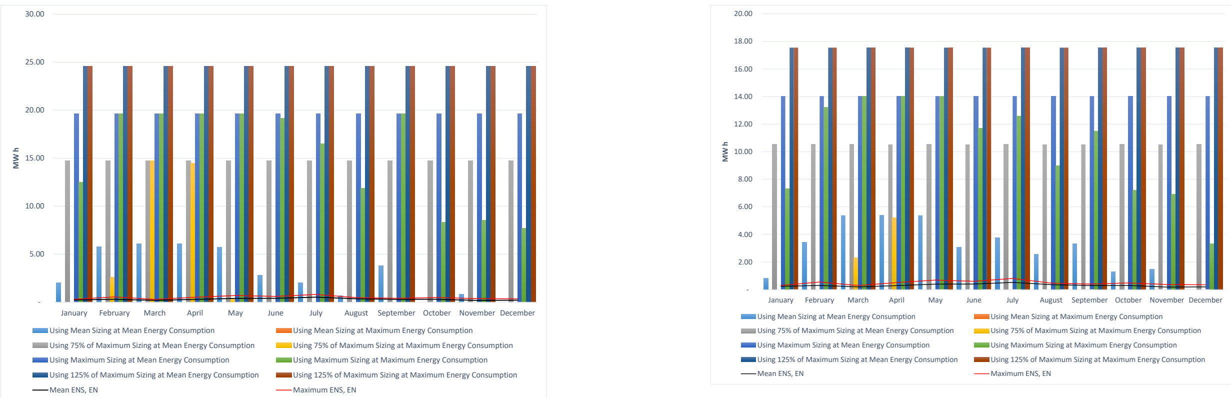


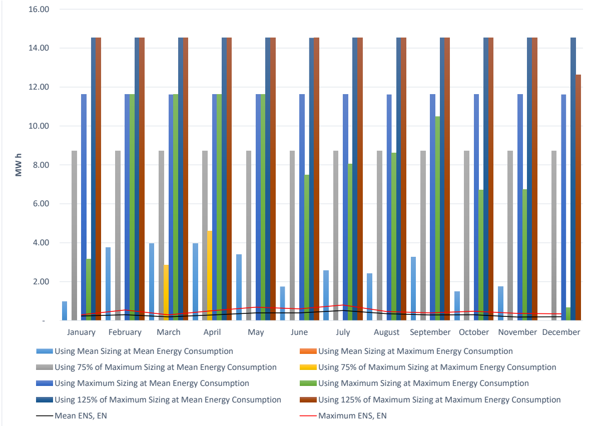
Figure 3. (a) Housing Community E_g vs E, (b) Centralized BESS Size, E_C.

3.4. Battery Energy Storage System (BESS) Size Allocation per Community

Using the energy consumption profile per residential unit per community, the BESS capacity, E_C in kW h at mean, 75% of maximum, maximum, and 125% of maximum energy consumption is calculated using equation 12. See figure 3b for the illustration of the result. The figure shows that E_C for a High-end community is 3 967 – 14 528 kW h, while for Medium-cost and Low-cost communities, its E_C is 5 388 – 17 550 kW h and 6 087 – 24 578 kW h, respectively. This computed BESS capacities per community, together with the Aggregated Solar PV sizes per community, is used to calculate the excess energy stored in the battery, E_B, using equation 7. Figure 5 shows the monthly E_B per community. The figures show that for a High-end community, the stored energy in the BESS can reach up to 24.578 MW h (full) using 125% of maximum sizing at either mean or maximum energy consumption. While for Medium-cost and Low-cost communities, the stored energy can reach up to 17.49 MW h (full) and 14.527 MW h (full) using 125% of maximum sizing at either mean or maximum energy consumption, respectively. In all the communities sizing, the BESS capacity at the mean and 75% of maximum energy consumption do not provide consistent E_B per month if the communities consume maximum energy. The figure further shows that only the BESS sized at maximum and 125% of maximum can clear both the mean and maximum E_N.



(**a**) (**b**)



(**c**)

Figure 5. Excess energy stored in the battery, E_B, per Month (**a**) High-end Housing Community; (**b**) Medium-cost Housing Community; (**c**) Low-cost Housing Community.

4. Conclusion

It is therefore concluded that allocation of the centralized BESS at maximum and 125% of maximum energy consumption may provide more than enough energy capacity to support each community's energy demand and supply for other application, like reliability improvement thru EnS. Rooftop solar PV sizes may also be sized at the same sizing scheme so that the excess energy stored is more than enough to sustain the overall operation. Moreover, with all the results presented, the proposed process of evaluating the proper size of a centralized BESS in a community with rooftop Solar PV could provide a much more practical and less complex sizing methodology for community-based BESS and Solar PV.

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