Techno-Economic Analysis of PV and BESS for Residential Loads

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Abstract. Energy sustainability is a critical issue, particularly in residential areas where renewable energy sources, such as solar photovoltaic (PV) systems, are becoming increasingly integrated. Battery Energy Storage Systems (BESS) play a pivotal role in optimizing energy utilization, balancing supply and demand, and reducing reliance on the power grid. This research contributes to the field of sustainable energy management by providing a detailed analysis of energy flow, battery performance, and degradation in a residential PV-BESS setup, introducing a comprehensive financial analysis, including Net Present Value (NPV), Internal Rate of Return (IRR), Return on Investment (ROI), and Payback Period, to assess the feasibility of BESS deployment, highlighting the impact of current tariff regulations on the financial outcomes of residential energy storage systems, offering practical recommendations for optimizing battery usage to balance energy demand and supply while preserving battery health, and scalability tha propose a scalable model for integrating PV-BESS systems in residential areas, contributing to broader renewable energy adoption and grid stability. The findings of this research conclude that, based on the load conditions in this study, a BESS with a capacity below 500 kWh can be a viable investment option for utilities, offering both technical and economic benefits. However, when considering unmet demand, the best choice is a BESS with a capacity of 350 kWh.

Keywords: *PV-BESS, Charging-Discharging, Cost Benefit Analysis, Residential BESS, Communal BESS, Energy Export-Import.*

1 Introduction

Energy sustainability is a critical issue, particularly in residential areas where renewable energy sources, such as solar photovoltaic (PV) systems, are becoming increasingly integrated. Battery Energy Storage Systems (BESS) play a pivotal role in optimizing energy utilization, balancing supply and demand, and reducing reliance on the power grid [1]. This study focuses on the design and evaluation of a BESS for residential applications, aiming to manage PV generation, meet demand, and ensure economic feasibility. The research utilizes a simulation-based approach to analyze energy flow dynamics, State of Charge (SoC), State of Health (SoH), and economic outcomes, providing insights into the integration of renewable energy systems in a typical residential setting. Despite the growing

Received ________, Revised _________, Accepted for publication __________

adoption of renewable energy technologies, challenges remain in managing the intermittent nature of solar power generation. The problem are the mismatch between PV generation and residential energy demand leads to excess energy wastage or unmet demand. Second, how to ensuring optimal battery usage, maintaining State of Health (SoH), and minimizing degradation are critical challenges. The high upfront cost of BESS systems raises concerns about the financial viability of these investments especially for utility providers, is the third problem.

Several related studies on residential photovoltaic (PV) systems with battery energy storage systems (BESS) have been conducted. Studies across different countries show that while BESS can increase self-consumption and reduce grid dependency, its economic viability remains challenging [2]-[4]. Current high costs and unfavorable regulatory frameworks often make PV-BESS investments unprofitable [2]-[3]. However, future scenarios with higher electricity tariffs, reduced export tariffs, and falling technology costs could improve economic feasibility [2]. Optimization of system sizing and operation can enhance performance and economic viability [5]. Researchers propose various strategies to improve feasibility, including new business models, subsidies, and policy changes [3]. Despite current challenges, PV-BESS systems show potential for residential applications, with one study achieving a five-year payback period in optimal conditions [5].

Integrating solar photovoltaic (PV) systems with battery energy storage (BESS) is a competitive approach for achieving energy sustainability in residential sectors. Several studies have addressed different aspects of this integration [6]. For instance, an optimization method for determining cost-optimal battery and power electronics sizing in residential PV-BESS systems, considering various battery technologies, is presented in [7]. A review of key parameters and challenges in the optimal planning of solar PV and battery storage systems for grid-connected residential areas is provided in [8]. Additionally, [9] discusses a residential photovoltaic energy storage system that utilizes a DC-DC power converter and BESS to optimize power utilization and grid integration. The current status, challenges, and future directions of hybrid PV-BESS systems are reviewed in [10], emphasizing their role in sustainable energy solutions for residential areas. Finally, [11] analyzes optimization techniques for managing BESS in renewable energy systems, aiming to achieve both financial and technical objectives.

This study addresses these issues by simulating the operation of a PV-BESS system in a residential area, analysing technical performance, and evaluating economic viability. This research contributes to the field of sustainable energy management by:

1. Providing a detailed analysis of energy flow, battery performance, and degradation in a residential PV-BESS setup.
2. Introducing a comprehensive financial analysis, including Net Present Value (NPV), Internal Rate of Return (IRR), Return on Investment (ROI), and Payback Period, to assess the feasibility of BESS deployment.
3. Highlighting the impact of current tariff regulations on the financial outcomes of residential energy storage systems.
4. Offering practical recommendations for optimizing battery usage to balance energy demand and supply while preserving battery health.
5. Scalability: Proposing a scalable model for integrating PV-BESS systems in residential areas, contributing to broader renewable energy adoption and grid stability.

By addressing both technical and economic aspects, this study serves as a guideline for stakeholders, including utility providers, homeowners, and policymakers, in designing and implementing sustainable energy solutions, although the focus of this study is on the utility company side.

2 Proposed Method

A. *Research Flowchart*

The method proposed in this study is illustrated in Figure 1. The flowchart depicts the workflow of the PV and BESS system according to load demand and the initial State of Charge (SoC) of the battery, aiming to provide benefits for utilities in future BESS investments. This system employs key parameters, including the BESS capacity, initialized with a specific initial SoC condition, and inverter capacity limitations to regulate the electrical energy entering the battery/BESS. The primary objective of this PV and BESS system is to ensure that demand is optimally met by combining the contributions of both PV and BESS.

- The system begins with the initialization of the battery's initial SoC, where this study assumes an initial battery SoC of 50%. The battery capacity is varied with values of 200 kWh, 350 kWh, and 500 kWh.
- The export and import process is carried out by observing load demand based on time and BESS capacity. The study assumes a maximum SoC of 90% and a minimum SoC of 30%, with the charge-discharge condition set within the range of 30% ≤ SoC ≤ 90%.

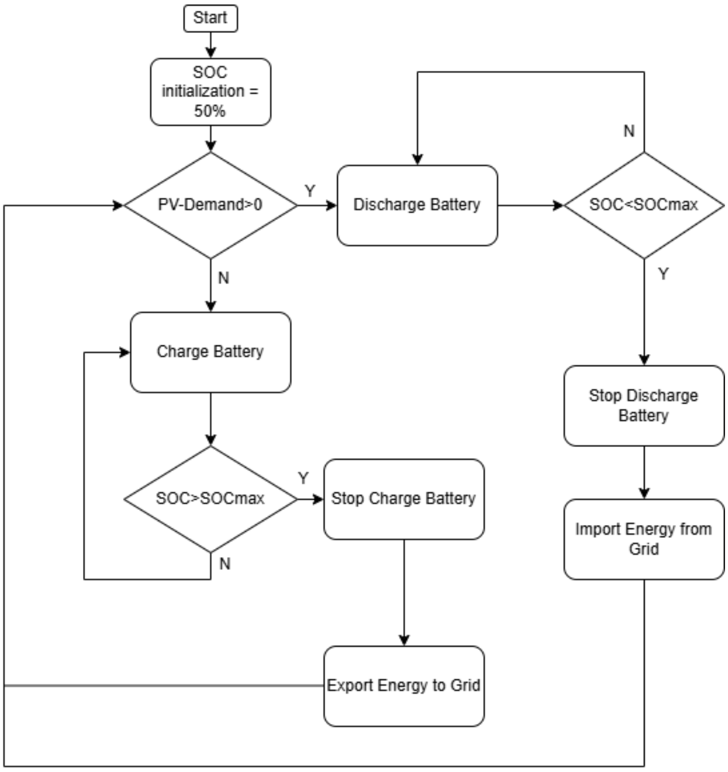

Figure 1 The Flowchart of Proposed Method

- The energy export process for PV customers occurs when the load demand is lower than the PV power at a given time, allowing PV customers to export energy. However, this depends on the battery's condition at that time. If the battery's SoC is below its maximum limit, energy export to the battery is permitted. If this condition is not met, PV customers can directly export energy to the grid. In this process, the study assumes that the inverter limits the energy entering the battery, but there are no restrictions on energy export to the grid.
- The energy import process for PV customers occurs when the load demand exceeds the PV power at a given time, meaning the PV system cannot cover the load. In this case, PV customers can import energy from the utility. The utility can supply electricity either from the battery or directly from the grid. If the battery's SoC is within the acceptable range, energy import from the battery is allowed. However, if this condition is not met, energy import from the grid will be performed.

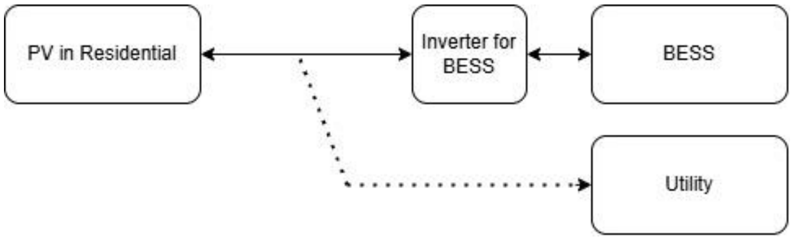

Figure 2 Block Diagram PV-BESS System

Meanwhile, Figure 2 shows the block diagram of the PV-BESS system, providing a clearer representation of the flowchart in Figure 1. Essentially, energy from the residential PV system will be sent to the BESS if there is surplus energy after meeting the demand. However, if the BESS is full, the excess energy will be sent to the utility grid. Conversely, when the residential PV system cannot meet the demand, energy will be drawn from the BESS. If the BESS is depleted, energy will be drawn from the utility grid.

B. Software

In this study, the author utilizes the PV-BESS Analysis and Sizing Tool (PVBT), a self-developed MATLAB-based program designed to assist in the analysis and optimization of Photovoltaic (PV) systems integrated with Battery Energy Storage Systems (BESS) on a small scale. This application aims to provide technical and economic evaluations to determine the optimal size and performance of the PV-BESS configuration.

C. On Grid Communal BESS

On-Grid Communal BESS (Battery Energy Storage System) is a battery-based energy storage system connected to the main power grid (on-grid) and used collectively by a community or group of users. This system is designed to support energy management at a local scale, offering various benefits such as grid stability, reduced electricity costs, and enhanced use of renewable energy.

Main Components of On-Grid Communal BESS: battery, inverter, Energy Management System (EMS), and Grid Connection. With proper management, On-Grid Communal BESS can become a sustainable solution to support the energy transition, improve electricity efficiency, and maximize the benefits of renewable energy at the community level.

3 Testing

A. Algorithm

Algorithm 1: Techno-Economic Analysis of PV and BESS for Residential Load

Initialization:
- Set the simulation parameters such as in Table 1
- Define simulation time: create a time vector t in a year, sampled at the desired simulation interval
- Load the data (demand and PV generation) from inputs.csv
- Set initial BESS capacity to some values, such as: 200, 350, and 500 (in kWh)

Simulation Loop:
- For each time step, calculate excess_pv, which is subtraction of demand from PV generation
- If excess_pv is more than or equal to zero, calculate charge_to_battery, else calculate required_from_battery

Result:
- Plot result: Demand and PV Generation, BESS State of Charge (SOC), and Unmet Demand
- Display result: Technical Result Annual, Economic Result for Provider (Utility), and Conclusion, which states whether the investment case with a specific BESS capacity is feasible or not for the utility to undertake

B. Formulation

In this study, the load demand and PV output are obtained from dummy data, with several assumption parameters listed in Table 1. Below are the parameters used to determine the feasibility of an investment:

1. Technical Part
   - Import Energy
     Energy import occurs when the load demand of PV customers exceeds the installed PV output.

$$d_t = \min\left(-excess\ PV/efisiensi, \frac{1}{data\ resolution} \times battery\ SoC \times initial\ minimum\ discharge\ battery, inverter\ capacity\right)$$

Equation 1 Energy Import

   - Export Energy

Energy import occurs when the load demand of PV customers is less than the installed PV output.

$$c_t = \min(excess\ PV \times efisiensi, \frac{1}{data\ resolution} \times battery\ capacity \times percent\ maximum\ charge - battery\ SoC, inverter\ capacity))$$

where,

$$Excess\ PV = PV\ Utilized_t - Load\ Demand_t$$

Equation 2 Energy Export

- SOH Battery
  State of Health (SoH) is an important parameter used to indicate the overall condition of a battery compared to its initial state (when it was new). SoH reflects the battery's ability to store and deliver energy effectively, and serves as a key indicator in monitoring the performance and lifespan of the battery.

$$SoH\ (\%) = \frac{Initial\ SOH - SOH\ Threshold}{Daily\ Degradation \times 365 \times 100}$$

Equation 3 Battery SOH

- Battery Lifetime (LB)
  Battery Lifetime is the period of time or the number of charge and discharge cycles a battery can undergo before its capacity decreases to a level that is no longer considered optimal or usable effectively. The battery's lifetime is greatly influenced by various factors such as the battery design, the type of chemicals used, and the conditions under which it is used.

$$LB\ (years) = \frac{Initial\ SOH - SOH\ Threshold}{Daily\ Degradation \times 365 \times 100}$$

Equation 4 Battery Lifetime

2. Economical Part
   - Annual Saving (AS)
     The utility's profit is generated from the export and import of electricity between the customers and the BESS.

$$AS = \sum_{t}^{N_t} Charge\ to\ battery_t + Required\ from\ baterry_t$$

Equation 5 Annual Saving

- Payback Period (PP)
  The Payback Period (DPP) measures how long it takes to recover the initial investment using the annual cash flows generated by the project, expressed in terms of Present Value (PV).
$$PP = \frac{Battery\ Investment}{Annual\ Saving - Maintenance\ cost}$$

Equation 6 Payback Period

- Net Present Value (NPV)
  Net Present Value (NPV) is the difference between the present value of incoming cash flows and outgoing cash flows over a specific period. An investment is considered viable or approved if its NPV is positive or higher.
$$NPV = \sum_{t}^{N_t} \frac{Cash\ Flow_t}{(1 + discount\ rate)^t}$$

Equation 7 Net Present Value

- Internal Rate of Return (IRR)
  An investment is considered feasible by the company if the Internal Rate of Return (IRR) generated is higher than its cost of capital. This indicates that the planned investment will provide a return greater than expected, making the investment viable to proceed.
$$IRR = \frac{NPV_1}{NPV_1 - NPV_2}$$

Equation 8 Internal Rate of Return

- Return on Investment (ROI)
  Return on Investment (ROI) is a metric used to evaluate the efficiency or profitability of an investment. ROI is calculated by comparing the net profit from the investment to the cost of the investment.
$$IRR = \frac{Total\ Benefit - Battery\ Investment}{Battery\ Investment}$$
  Where,
  $Total\ Benefit = (AS - Maintenance\ Cost) \times LB$

Equation 9 Return on Investment

C. Proposed PVB

The input data is stored in the file `Inputs.csv`, which consists of two columns. Column 1 contains demand data (in kW) at each time step, while Column 2 contains PV generation data (in kW). The dataset spans 1 year, comprising 17520 data points, meaning there are 48 data points per day, with data recorded at 30-minute intervals (data resolution). The predefined parameters with fixed values can be seen in Table 1 below:

Table 1 The parameters for simulation in MATLAB.

Parameter	Description	Value	Unit
battery_charge_efficiency	The efficiency during BESS charging	0,95	Per hundred
battery_discharge_efficiency	The efficiency during BESS discharging	0,95	Per hundred
data_resolution	Data resolution	0,5	Hour
daily_degradation_rate	The degradation rate of BESS capacity at each time step	(0,0005/48) *3,9	Per hundred
inverter_capacity	Inverter capacity for BESS	3* total_house	kW
maximumfullcharge	The percentage of the maximum possible SoC condition	0,90	Per hundred
minimumdischarge	The percentage of the minimum possible SoC condition	0,30	Per hundred
percent	The percentage of the initial BESS SoC condition	50	%
tariff	The amount in Rupiah (Rp)/kWh that the customer pays for importing electricity from the grid to meet the unmet demand for a 2200 VA capacity	1444,70	Rp/kWh
total_house	The number of houses in the residential area	50	Unit

4 Result and Discussion

The simulation and feasibility analysis are conducted by dividing the BESS capacity into several values. Using MATLAB as the software for simulation and analysis in this study, the simulation produces output in the form of plots, namely:

1. Demand and PV Generation, both in kW, which is a plot of the input data from the file Inputs.csv.

2. BESS State of Charge (SOC), in kWh, showing the battery's charge level over time.
3. Unmet Demand, in kW, which plots the demand that cannot be met by PV or BESS at each time step.

In addition, the main output will be displayed in the MATLAB Command Window, containing values from the following sections: Technical Result Annual, Economic Result for Provider (Utility), and Conclusion, which states whether the investment case with a specific BESS capacity is feasible or not for the utility to undertake.

The testing focuses on examining which values of the initial BESS capacity (initial_battery_capacity) result in conclusions of feasibility or infeasibility for investment by the utility company. Three values of initial_battery_capacity are simulated as follows:

1. Initial BESS capacity 200 kWh
2. Initial BESS capacity 350 kWh
3. Initial BESS capacity 500 kWh

The limitations of the study in this paper are as follows:

1. For this simulation study, battery_cost_per_kWh, which represents the initial investment cost that the utility must incur per kWh for installing BESS in residential areas, is set at 400 USD/kWh or 6.377.420 Rp/kWh.
2. For this simulation study, maintenance_cost_per_year, which represents the annual maintenance cost that the utility must incur for the BESS installed in residential areas, is set to 0 rupiah.
3. The price per kWh is assumed to remain constant, as Indonesia has not yet adopted dynamic pricing.

Here are the results of the simulation in figure 3-9:

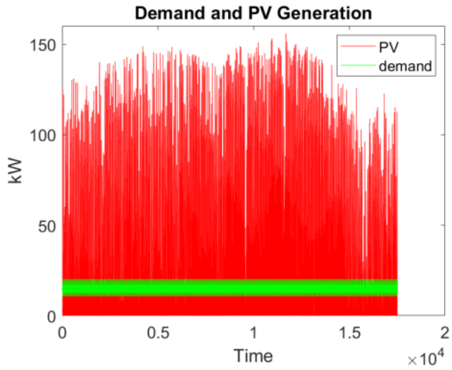

Figure 3 Demand and PV Generation from Inputs.csv.

Figure 3 shows the load demand over time and the condition of the installed PV system of the customer.

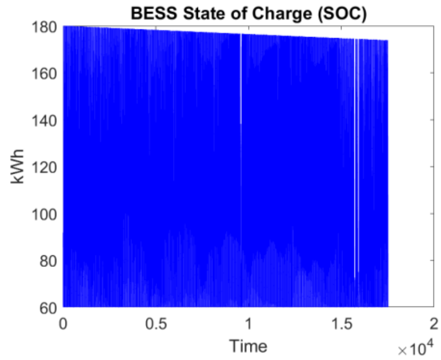

Figure 4 BESS SOC for Initial BESS Capacity 200 kWh.

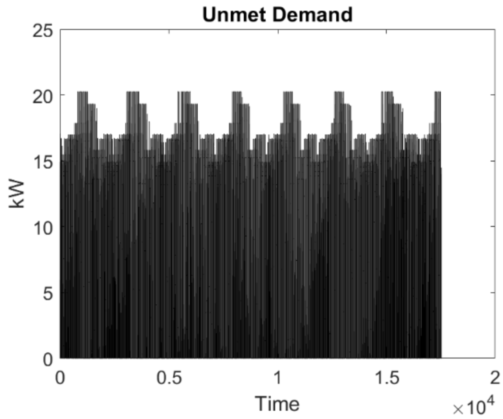

Figure 5 Unmet Demand for Initial BESS Capacity 200 kWh.

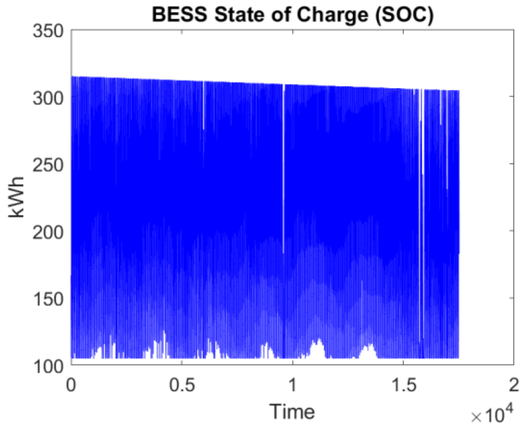

Figure 6 BESS SOC for Initial BESS Capacity 350 kWh

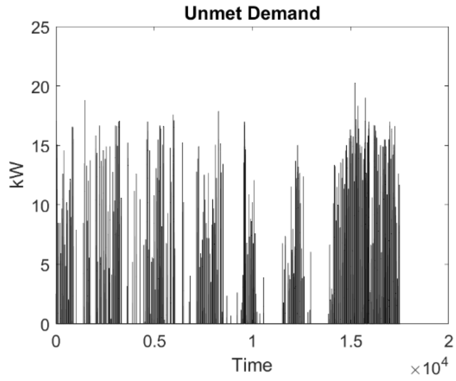

Figure 7 Unmet Demand for Initial BESS Capacity 350 kWh

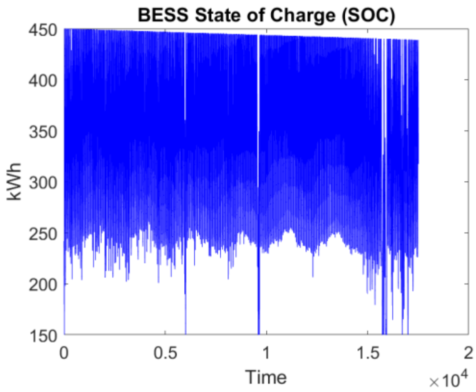

Figure 8 BESS SOC for Initial BESS Capacity 500 kWh

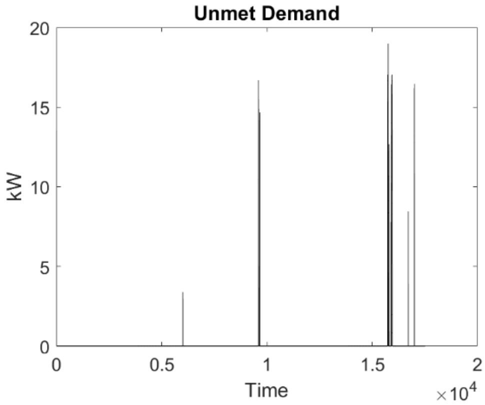

Figure 9 Unmet Demand for Initial BESS Capacity 500 kWh

Table 2. Simulation Result

Battery Capacity	200 kWh	350 kWh	500 kWh
Import Energy	66.044,76 kWh	7.776,78 kWh	1.223,32 kWh
Export Energy to BESS	84.930,17 kWh	146.360,65 kWh	153.378,00 kWh
Export Energy to Grid	374.567,07 kWh	309.903,41 kWh	302.516,73 kWh
Total Export Energy	459.497,25 kWh	456.264,06 kWh	455.894,73 kWh
SoH (1 years)	96,54%	96,59%	97,50%
Lifetime BESS	20,23 years	20,23 years	20,23 years
Annual Saving	Rp. 122.756.411,25	Rp. 211.435.850,34	Rp. 221.487.877,31
Payback Periods	10,29 years	10,56 years	14,39 years
NPV	Rp. 132.522.366,07	Rp. 193.055.546,22	Rp. -648.261.496,38
IRR	7,25%	7,05%	3,36%
ROI	92,49%	89,45%	38,92%
Conclusion	**Feasible**	**Feasible**	**Not Feasible**

In this study, the author assumes different battery capacities with the same initial SoC condition (50%), based on the load demand over time and the output of the installed PV system of the customer, resulting in:

1. Battery capacity determines the amount of electricity that can be exported by PV customers, where a smaller battery capacity leads to a larger amount of electricity being exported by the PV customer to the grid. This can cause the grid voltage to rise significantly, potentially damaging electrical components. Additionally, it could render the voltage sent to the grid as wasteful.

2. For a 200 kWh BESS capacity, situations of unmet demand frequently occur. For a 350 kWh capacity, unmet demand becomes less frequent. Meanwhile, for a 500 kWh capacity, unmet demand rarely occurs.
3. Annual savings will vary based on the proposed Battery Capacity, due to the ability of the system to store energy in excess events and redistribute energy as needed, which in this simulation resulted in higher annual savings in higher battery capacity.
4. The State of Health (SOH) of the battery will vary for every simulated battery capacity, based on differences in battery utilization in each scenario.
5. As we can see in Table 2, in this study, when the battery capacity is 200 kWh and 350 kWh, it still provides a benefit for the utility to invest in BESS. However, with a 500 kWh battery capacity, it is highly disadvantageous for the utility due to the high investment cost. Based on economic analysis considering the values of NPV, IRR, and ROI, it is deemed unfeasible.
6. As a result, out of the three BESS capacity variations analyzed, the best and most feasible option is the 350 kWh BESS capacity.

5 Conclusion And Future Work

This study aims to determine the optimal BESS capacity in meeting load demand while considering battery parameters. The findings of this research conclude that, based on the load conditions in this study, a BESS with a capacity below 500 kWh can be a viable investment option for utilities, offering both technical and economic benefits. However, when considering unmet demand, the best choice is a BESS with a capacity of 350 kWh. Implementing this BESS would benefit utilities by utilizing the energy exported from residential PV systems to the BESS, ensuring that the excess energy generated by PV after meeting the load is not wasted. Therefore, the use of BESS not only supports energy efficiency but also facilitates the integration of renewable energy, grid stability, and cost savings. With proper management, batteries can become a reliable solution for future energy needs.

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