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Modelling of Dual-Battery Energy Storage System in a Renewable Energy Power System

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As the global energy transition accelerates, integrating renewable energy into off-grid and hybrid systems poses challenges due to intermittency and storage limitations. Battery energy storage systems (BESS) are essential for ensuring stability and reliability. Conventional single-battery configurations, however, suffer from high costs and reduced lifespan, especially in lead-acid batteries, due to frequent incomplete charge/discharge cycles. To address this, a dual-battery energy storage system (DBESS) is proposed, in which two batteries operate in parallel: the main battery performs complete cycles to maintain health, while the secondary battery buffers partial loads. This approach improves system longevity and energy management. A techno-economic optimization model was developed using hourly load and solar irradiation data to minimize the 20 y system cost. The optimized configuration selected lead-acid batteries for both units, with 611.21 kW solar PV, 171.83 kW biomass generator, and storage capacities of 388.23 kWh and 118.59 kWh for the main and secondary batteries, respectively. The total system cost was minimized to $ 1,468,729. These results highlight the effectiveness of DBESS in enhancing performance and reducing long-term costs in renewable hybrid systems.

1. Introduction

The utilization of battery energy storage systems (BESS) has been deemed of utmost importance as the world transitions towards increased implementation of renewable energy. Although renewable energy is abundantly available in nature, its intermittency necessitates the use of BESS. Excess energy can be stored during the availability of solar power during the day, while the stored energy can be supplied to meet demand at night. Biomass, on the other hand, has emerged as a sustainable fuel for power generation. However, its inconsistent supply and high cost compared to fossil fuels make it difficult to rely solely on biomass for an off-grid power system (Ogunrewo and Nwulu, 2024). Therefore, the operation of an off-grid power system that integrates a biomass generator, solar PV, and battery storage can ensure the delivery of consistent and stable electricity to meet variable demand (Come Zebra et al., 2021).

Over the past decades, the efficiency and cost of solar PV have improved tremendously (IRENA, 2021). However, energy storage remains relatively expensive and constitutes the largest cost component of a power system (Balducci et al., 2021). As a result, many researchers have attempted to optimize both the cost and operation of BESS. For instance, Khlifi et al. (2021) proposed a techno-economic optimization of BESS sizing in microgrids. Sharma et al. (2025) developed an advanced control strategy to enhance BESS lifespan. Köppchen et al. (2025) examined battery scheduling for demand-side management. Chen et al. (2023) integrated time-of-use tariffs with BESS operation. Symeonidou et al. (2021) focused on lifecycle cost analysis for different battery chemistries in renewable energy systems.

Despite these advances, conventional single-battery systems often face limitations in terms of flexibility, cycling efficiency, and system degradation. A promising configuration that has shown improved performance is the dual-battery energy storage system (DBESS) (Neto et al., 2018). In DBESS, two types of batteries—main and secondary—work in a complementary manner, each serving different purposes within the power system. The

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main battery typically handles bulk energy shifting, while the secondary battery manages short duration loads or transient events (Atawi et al., 2022). This arrangement can enhance overall system performance, reduce battery stress, and extend operational life.

Nevertheless, the application of DBESS in hybrid off-grid systems remains underexplored, particularly in configurations involving both renewable and biomass-based generation. Given the complexity of managing energy flows between multiple generation sources and two energy storage systems, modelling serves as a vital tool to understand system interactions and improve operational strategies (Tezer, 2025). While single-battery systems have been widely modelled, research on the dynamic modelling and simulation of DBESS remains scarce, particularly in hybrid configurations combining solar PV and biomass generation. This paper presents a comprehensive model that simulates the energy flow, battery charge-discharge cycles, and generator utilization within such a hybrid system. The objective is to evaluate the performance, energy balance, and cost implications of DBESS integration, offering guidance for designing efficient off-grid renewable power systems.

2. Methodology

This section presents the methodology used in this paper. The first part outlines the General Algebraic Modeling System (GAMS) mathematical model formulation for the renewable energy power system with DBESS, while the second part describes the data inputs for the model.

2.1 Mathematical Formulation

A GAMS-based mathematical model is developed with the objective of minimizing the cost of an off-grid power system comprising a biomass generator, solar PV, and the main battery and secondary battery. The model minimize the total system cost over 20 y, which align with the typical lifespan of solar PV systems (approximately 20–25 y) and to provide a sufficient time horizon for assessing the cost-effectiveness and replacement cycles of the energy storage systems, as defined in Eq(1).

$$Minimize\ Cost = biocost + solarcost + EScost1 + EScost2 \tag{1}$$

Eq(2) calculates the total solar PV cost ($solarcost$) using its installed capacity ($solarcap$), capital cost ($solarcapcost$), and fixed O&M cost ($solarfixcost$) over 20 y. Eq(3) defines the biomass cost ($biocost$), combining generation ($biopowergen(t)$) with its variable cost ($biovarcost$), fuel use ($bioutilization$) with cost ($biofuelcost$), and capacity ($biocap$) with capital ($biocapcost$) and fixed O&M costs ($biofixcost$). Eq(4) and Eq(5) compute costs for the main and secondary batteries, respectively, based on energy ($AcapESE1/2$) and power capacities ($capESP1/2$), their capital ($ESEcost1/2$, $ESPcost1/2$) and fixed O&M ($ESPfixcost1/2$) costs. Battery replacements are included: once for the main (10 y lifespan) and three times for the secondary (5 y), using multipliers of 2 and 4. No replacements are needed for solar or biomass (25 y lifespan).

$$solarcost = solarcap \cdot solarcapcost + (solarcap \cdot solarfixcost) \cdot 20 \tag{2}$$

$$\begin{aligned} biocost = {} & \Sigma_t biopowergen(t) \cdot biovarcost + bioutilization \cdot biofuelcost + biocap \cdot biocapcost \\ & + (biocap \cdot biofixcost) \cdot 20 \end{aligned} \tag{3}$$

$$EScost1 = (AcapESE1 \cdot ESEcost1 + capESP1 \cdot ESPcost1) \cdot 2 + capESP1 \cdot ESPfixcost1 \cdot 20 \tag{4}$$

$$EScost2 = (AcapESE2 \cdot ESEcost2 + capESP2 \cdot ESPcost2) \cdot 4 + capESP2 \cdot ESPfixcost2 \cdot 20 \tag{5}$$

Energy balance is maintained by matching demand with supply from solar, biomass, and storage in Eq(6), where $InvEFF$ and $ESEFF$ represent the inverter efficiency and the round-trip efficiency of the batteries, respectively. The energy balance for biomass and solar is shown in Eq(7) and Eq(8), respectively, where excess energy from both sources is stored in the main and secondary batteries. Biomass generation ($biopowergen(t)$) must be less than or equal to the biomass capacity ($biocap$), as constrained in Eq(9), and is modeled using heat rate ($bioHR$), fuel utilization ($bioutliziation$), and biomass heating value ($bioEP$) in Eq(10). Bioutilization must not exceed the annual biomass availability ($\mathrm{BioAnnualAvailability}$) in Eq(11), while solar generation depends on installed capacity ($solarcap$) and irradiation ($SolarRadiation(t)$) in Eq(12).

$$\begin{aligned} FixDemand(t) = {} & biotodemand(t) + solartodemand(t) \cdot InvEFF + EStodemand1(t) \cdot ESEFF \\ & \cdot InvEFF + EStodemand2(t) \cdot ESEFF \cdot InvEFF \end{aligned} \tag{6}$$

$$biopowergen(t) = biotodemand(t) + biotoES1(t) + biotoES2(t) \tag{7}$$

$$solarpowergen(t) = solartodemand(t) + solartoES1(t) + solartoES2(t) \tag{8}$$

$$biopowergen(t) \leq biocap \tag{9}$$

$$\Sigma_t biopowergen(t) \cdot bioHR = bioutliziation \cdot bioEP \tag{10}$$

$$bioutliziation \cdot 365 < \text{BioAnnualAvailability} \tag{11}$$

$$solarpowergen(t) = solarcap \cdot SolarRadiation(t) \tag{12}$$

Eq(12) to Eq(36) model the operation and sizing of the main and secondary batteries in an off-grid power system. The energy balance in Eq(12) and Eq(13) ensures that the DBESS stored energy updates hourly based on charging from biomass/solar and discharging to meet demand. The cumulative stored energy at the next hour ($CumuES(t+1)$) is equal to the energy stored at current hour t ($CumuES(t)$), plus the net charging input, minus the energy discharged to supply the load during the same hour.

$$\begin{aligned} CumuES(t+1) = {} & CumuES(t) + bioES1(t) \cdot InvEFF \cdot ESEFF + solartoES1(t) \cdot ESEFF \\ & - EStodemand1(t) \end{aligned} \tag{12}$$

$$\begin{aligned} CumuES(t+1) = {} & CumuES(t) + bioES2(t) \cdot InvEFF \cdot ESEFF + solartoES2(t) \cdot ESEFF \\ & - EStodemand2(t) \end{aligned} \tag{13}$$

A single daily $\Sigma_p ChargePattern(p,t)$ and $\Sigma_p DischargePattern(p,t)$ as tabulated in Table 3 and 4 for the main battery is enforced with a binary, $x(p)$ by Eq(14) to Eq(17), where L is a very large number. This ensures the main battery restricted to one cycle per day to preserve its lifespan. The model selects patterns in that result in the lowest overall cost while meeting system constraints.

$$\Sigma_p x(p) = 1 \tag{14}$$

$$biotoES1(t) \leq \Sigma_p ChargePattern(p,t) \cdot x(p) \cdot L \tag{15}$$

$$solartoES1(t) \leq \Sigma_p ChargePattern(p,t) \cdot x(p) \cdot L \tag{16}$$

$$EStodemand1(t) \leq \Sigma_p DischargePattern(p,t) \cdot x(p) \cdot L \tag{17}$$

To avoid simultaneous charging and discharging, binary logic $yl(t)$ for charging and $zl(t)$ for discharging in Eq(26) is applied to the secondary battery in Eq(27) and Eq(28).

$$yl(t) + zl(t) \leq 1 \tag{18}$$

$$biotoES2(t) + solartoES2(t) \leq L \cdot yl(t) \tag{19}$$

$$EStodemand2(t) \leq L \cdot zl(t) \tag{20}$$

Finally, Eq(29) to Eq(32) for the main battery and Eq(33) to Eq(36) for the secondary battery ensure that energy and power flows remain within capacity limits, factoring in depth of discharge ($DODES1/2$) for proper battery sizing.

$$CumuES1(t) \leq capESE1 \tag{29}$$

$$EStodemand1(t) \leq capESP1 \tag{30}$$

$$biotoES1(t) \cdot InvEFF + solartoES1(t) \leq capESP1 \tag{31}$$

$$AcapESE1 \cdot DODES1 = capESE1 \tag{32}$$

$$CumuES2(t) \leq capESE2 \tag{33}$$

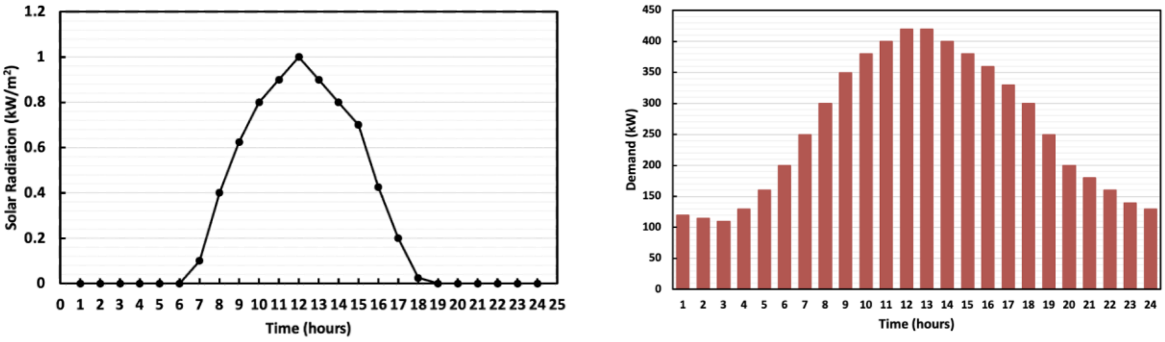
$$EStodemand2(t) \leq capESP2 \tag{34}$$

$$biotoES2(t) \cdot InvEFF + solartoES2(t) \leq capESP2 \tag{35}$$

$$AcapESE2 \cdot DODES2 = capESE2 \tag{36}$$

2.2 Data Inputs

Figure 1a illustrates the hourly solar irradiation profile in kW/m² for a typical day in Malaysia, showing peak irradiance around noon. Figure 1b presents the corresponding hourly electricity demand profile in commercial area, with the highest demand observed between 11:00 and 14:00. Table 1 and Table 2 provides technical and economic parameters for the power generators (solar PV and biomass) and battery storage systems.



a) b)

Figure 1: a) Solar Irradiation b) Hourly Demand Profile

Table 1: Parameters for power generators (IRENA, 2019; Iqbal et al., 2024)

Type of Generator	Capital Cost ($/kW)	O&M Cost ($/kW)	Biomass Cost ($/t)	Heat Rate (GJ/kWh)	Biomass Lower Heating Value (GJ/t)	Annual Availability of Biomass (t/y)	Inverter Efficiency (%)
Solar PV	400	20	-	-	-	-	95
Biomass	2,100	10	16.9	0.01235	4.3	2600	95

Table 2: Parameters for lead-acid battery (Iqbal et al., 2024).

Type of Battery	Energy Capacity Cost ($/kWh)	Power Capacity Cost ($/kW)	O&M Cost ($/kW)	Charging and Discharging Efficiency (%)
Lead Acid	400	125	20	80

To model the behaviour of the main battery in response to the variability of demand profile and power generation, a predefined charging and discharging pattern is introduced, as shown in Table 3 and Table 4. A total of 58 charging and discharging patterns were formulated. Each pattern is defined over 24-time steps, representing hourly intervals in a day. These patterns were developed to represent all feasible combinations that allow the main battery to complete one full charging and discharging cycle per day by using the binary parameters *ChargePattern(p,t)* and *DischargePattern(p,t),* which permit (1) or prohibit (0) the charging/discharging of the battery during specific time windows. During each period, the charging and discharging patterns correspond to each other.

Table 3: Charging pattern for the main battery

p	t1	t2	t3	t4	...	t22	t23	t24
p1	0	1	1	1	...	1	1	1
p2	0	0	1	1	...	1	1	1
...								
p58	0	1	1	1	1	1	1	0

Table 4: Discharging pattern for the main battery

p	t1	t2	t3	t4	...	t22	t23	t24
p1	1	0	0	0	...	0	0	0
p2	1	1	0	0	...	0	0	0
...								
p58	1	0	0	0	0	0	0	1

3. Result and Discussion

The optimization model yields a minimized cost of $ 1,468,729 for 20 y. The capacity and cost for each component are summarized in Table 4. In terms of cost, solar PV represents the largest total cost at $ 488,968, followed by the main battery, biomass generator and secondary battery. This is justified as solar PV contributes the most during peak demand, as shown in Figure 2a.

Table 4: Optimal Modelling Result for Renewable Energy Power System with DBESS

Component	Capacity	Cost ($)
Solar PV	611.21 kW	488,968
Biomass Generator	171.83 kW	395,392
Main Battery	388.23 kWh	412,954
Secondary Battery	118.59 kWh	171,415

During the peak demand period from 11:00 to 14:00, when the demand reaches 420 kW, most of the load is satisfied by solar PV generation, as illustrated in Figure 2a. The solar system with a capacity of 611.21 kW, produces excess energy that charges both batteries, ensuring adequate stored energy for periods with low or no solar input. Additionally, the biomass generator with a capacity of 171.83 kW is used to supplement energy production when solar availability is insufficient, especially during early morning and late evening hours. This complementary operation between solar PV and biomass reduces the dependency on large battery storage and contributes to the overall cost-effectiveness of the system. Overall, the model presents a well-balanced hybrid renewable energy system that maximizes the use of solar energy while relying on biomass and battery storage as flexible support. The results emphasize the importance of optimal sizing and operational coordination of generation and storage to achieve both reliability and cost minimization in renewable-powered microgrids.

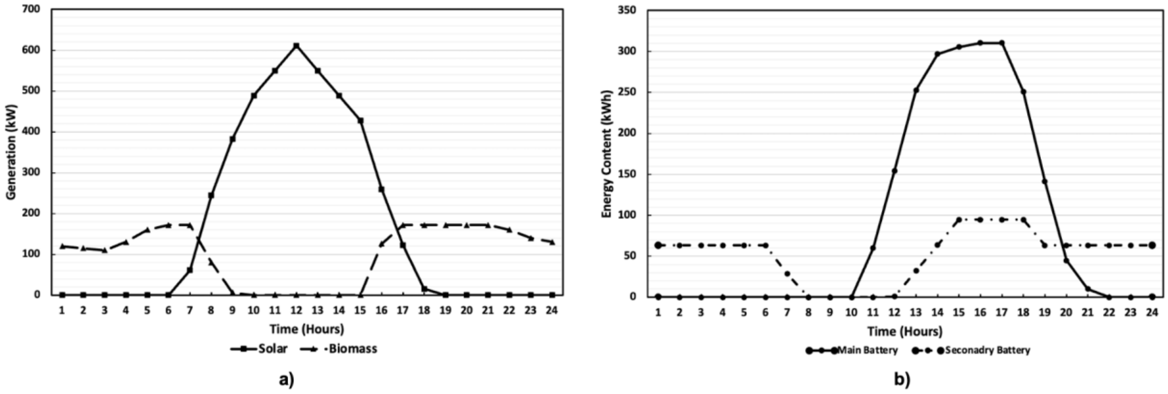


Figure 2: a) Power Generation with Solar PV and Biomass Generator b) Daily Energy Content of DBESS

According to Figure 2b, which illustrates the daily energy content of the DBESS, the main battery has a significantly higher energy capacity of 388.23 kWh compared to the secondary battery's 118.59 kWh. The data shows that the main battery charges from 10:00 to 17:00, when solar energy is abundant, and discharges from 17:00 to 22:00 to meet residual demand, reducing reliance on the biomass generator. The secondary battery acts as a buffer, supplying power when the main battery is unavailable, typically between 05:00 and 08:00. It also operates in coordination with the main battery, charging and discharging between 12:00 and 19:00. The secondary battery handles rapid, minor energy fluctuations and smooths short-term variations in supply, especially during transitional periods such as sunrise and sunset. This behaviour demonstrates that the model effectively optimizes DBESS sizing by leveraging the secondary battery's support function, avoiding the need to oversize the main battery

4. Conclusion

The optimization model successfully identified the most cost-effective configuration for a hybrid renewable energy system incorporating solar PV, biomass generation, and DBESS over 20 y with minimized total system cost of $ 1,468,729. The model effectively balanced generation and storage capacities, ensuring a reliable power supply during peak demand and periods of solar unavailability. The system's design leverages the strengths of each component, where solar PV supplies most of the power during midday peak hours, excess solar energy is stored in both batteries, and the biomass generator supplements the supply during low solar periods. The DBESS configuration enhances system reliability and flexibility. The main battery handles bulk energy storage with a single daily charge-discharge cycle. In contrast, the secondary battery provides critical support during short-term fluctuations and transitional periods, reducing stress on the main battery and improving overall efficiency. The results confirm that coordinated operation between generation sources and dual batteries allows for a balanced, cost-effective, and reliable power supply.

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