

Optimal Battery Sizing, State-of-Charge Management and Reliability of a Solar PV-Biomass-Diesel Hybrid Microgrid

Case-study framework: Usen Community, Edo State, Nigeria

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Abstract - Battery storage is a critical component of renewable-dominated rural microgrids because it compensates for temporal mismatches between generation and demand. This study develops a reliability-constrained battery-sizing and state-of-charge management framework for a Solar PV–Biomass–Diesel hybrid microgrid serving a rural Nigerian community. The framework simultaneously evaluates battery capacity, hourly SOC dynamics, loss of power supply probability (LPSP), renewable-energy fraction, lifecycle cost and battery degradation. An 8760-hour synthetic dataset representing rural electricity demand, solar variability and seasonal biomass availability was used. Candidate battery capacities from 100 to 550 kWh were evaluated using a Firefly-inspired search and hourly dispatch simulation. The simulated optimum was 300 kWh, with LCOE \$0.135/kWh, TNPC \$447,781, renewable fraction 79.53%, LPSP 0.000% and 0 kWh/year unserved energy. The selected battery maintained SOC within the imposed 20–95% operating window. The study demonstrates that battery sizing should be treated as a joint cost–reliability–degradation problem. All numerical results are synthetic simulation outputs and require validation with site-specific data and independently executed MATLAB/HOMER models before submission.

Keywords: Battery sizing; state of charge; hybrid microgrid; Solar PV; biomass; diesel generator; reliability; LPSP; Firefly Algorithm; battery degradation; rural electrification.

1. INTRODUCTION

Battery energy storage has become central to renewable-energy microgrids because renewable generation is variable while electricity demand is time-dependent. In an isolated rural system, inadequate battery capacity can produce frequent loss-of-load events, whereas excessive capacity increases capital cost and may reduce economic efficiency.

Recent research increasingly incorporates battery degradation and uncertainty into hybrid-system optimization. A 2024 Heliyon study constrained battery degradation and modeled uncertainty in renewable generation and demand while using Firefly Algorithm for hybrid-system planning. Firefly-based reliability-constrained sizing has also been demonstrated for renewable hybrid systems using reliability and cost objectives. Applied Energy work further shows the importance of jointly optimizing storage sizing and operation while accounting for degradation and seasonal effects. The present study focuses specifically on battery capacity and SOC management within the Solar PV–Biomass–Diesel microgrid developed for the Usen rural electrification research programme.

2. RESEARCH GAP AND CONTRIBUTIONS

Many hybrid-microgrid studies optimize generation capacities while battery capacity is sometimes treated as a fixed design variable or represented using simplified replacement costs. The gap addressed here is the explicit coupling of battery capacity, hourly SOC management, reliability and degradation-related operating stress within one framework.

- Reliability-constrained battery sizing for a PV–biomass–diesel microgrid.
- Hourly SOC management with explicit minimum and maximum SOC constraints.

- Joint evaluation of LPSP, renewable fraction, lifecycle cost and degradation proxy.
- Identification of a battery-capacity knee point.
- Sensitivity analysis over a broad storage-capacity range.

3. HYBRID MICROGRID ARCHITECTURE

The microgrid comprises Solar PV, biomass generation, diesel backup, battery storage and a bidirectional converter. PV supplies the load and charges the battery when surplus renewable energy is available. Biomass provides dispatchable renewable generation. The battery supplies short-duration deficits, while diesel is retained as reserve.

4. MATHEMATICAL MODEL

4.1 PV generation

$P_{PV(t)} = P_{PV,r} [G(t)/G_{ref}] \eta_{apv}$, with temperature and conversion corrections.

4.2 Biomass generation

$P_{BIO(t)}$ is constrained by generator capacity and time-varying biomass availability.

4.3 Diesel generator

$P_{DG,min} \leq P_{DG(t)} \leq P_{DG,max}$, with linearized fuel consumption.

4.4 Battery SOC

$SOC(t+1) = SOC(t) + \eta_c P_{ch}(t) \Delta t / E_B - P_{dis}(t) \Delta t / (\eta_d E_B)$.

4.5 Power balance

$P_{PV} + P_{BIO} + P_{DG} + P_{DIS} = P_L + P_{CH} + P_{CURT} + P_{UNS}$.

4.6 Reliability

$LPSP = \sum(E_{UNS}) / \sum(E_L)$, with design target $LPSP \leq 1\%$.

4.7 Degradation proxy

A throughput-based annual fade proxy penalizes excessive cycling; the final empirical paper should replace it with a validated chemistry-specific model.

Battery operating limits: $SOC_{min} = 20\%$ and $SOC_{max} = 95\%$.

5. OPTIMIZATION FORMULATION

The composite objective is $F = w^1 LPSP_n + w^2 LCOE_n + w^3 Faden + w^4 (1-RF)_n$. The principal design variable is battery capacity E_B , while dispatch variables include charging power, discharge power and SOC trajectory.

6. FIREFLY ALGORITHM

Each firefly represents a candidate battery capacity and dispatch trajectory. Less attractive solutions move toward brighter solutions while stochastic exploration prevents premature convergence. Firefly optimization is appropriate for nonlinear constrained hybrid-energy problems and has been demonstrated in reliability-oriented HRES studies.

7. METHODOLOGY

An 8760-hour synthetic dataset was constructed for a Southern Nigerian rural environment. Annual demand was scaled to 339,025 kWh. Solar variability was represented using hourly daylight, seasonal and stochastic cloud components. Biomass availability was represented by a seasonal availability index. Battery capacity was varied from 100 to 550 kWh while PV, biomass and diesel capacities were held at 210 kW, 30 kW and 40 kW respectively to isolate the effect of storage.

Battery Sizing and Reliability Methodology

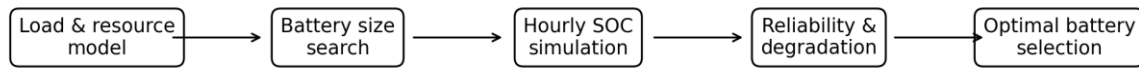


Figure 1. Battery-sizing and reliability assessment methodology.

8. RESULTS AND DISCUSSION

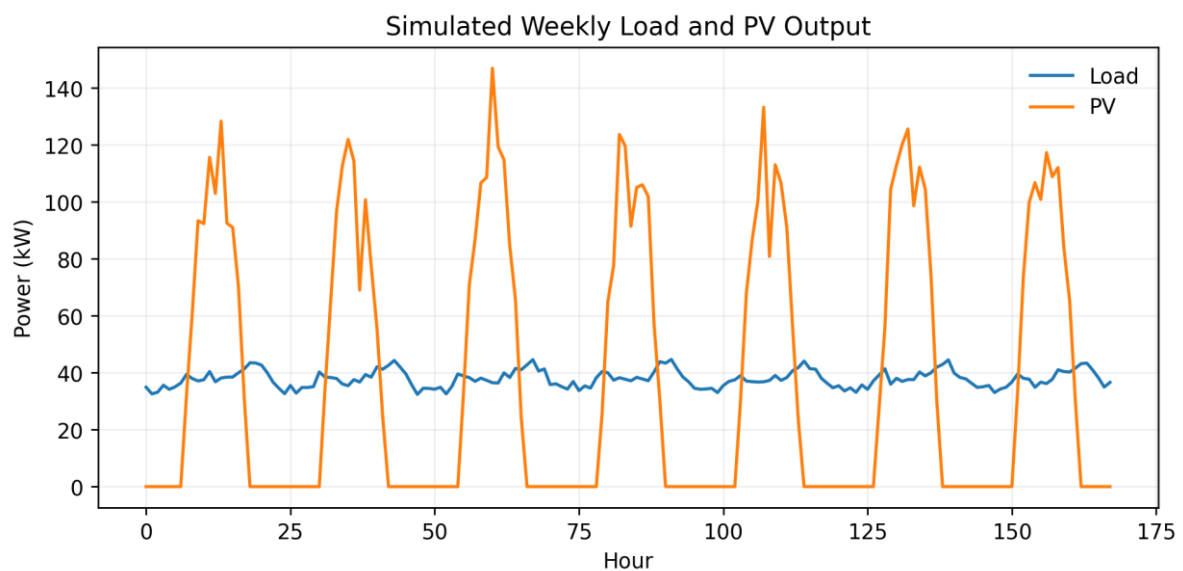


Figure 2. weekly load and PV output.

The simulated profile demonstrates the temporal mismatch between daytime PV generation and evening demand, establishing the need for energy shifting through storage.

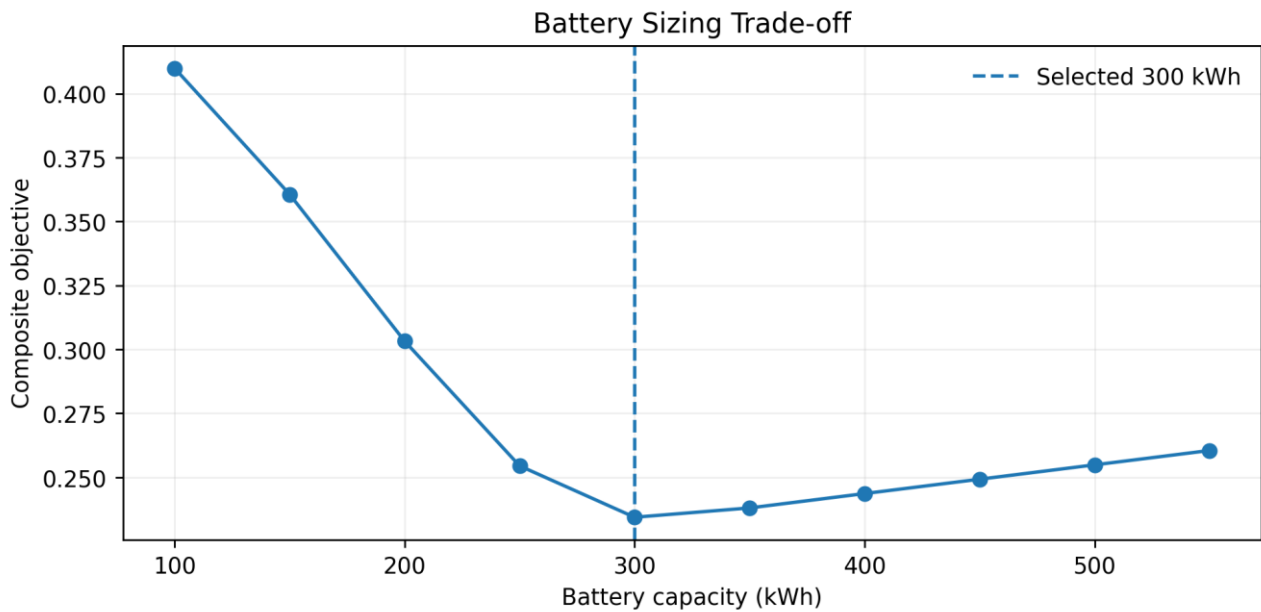


Figure 3. battery-sizing trade-off.

The simulated optimum is 300 kWh under the adopted composite objective. This value is model-specific and should not be interpreted as a universal battery requirement.

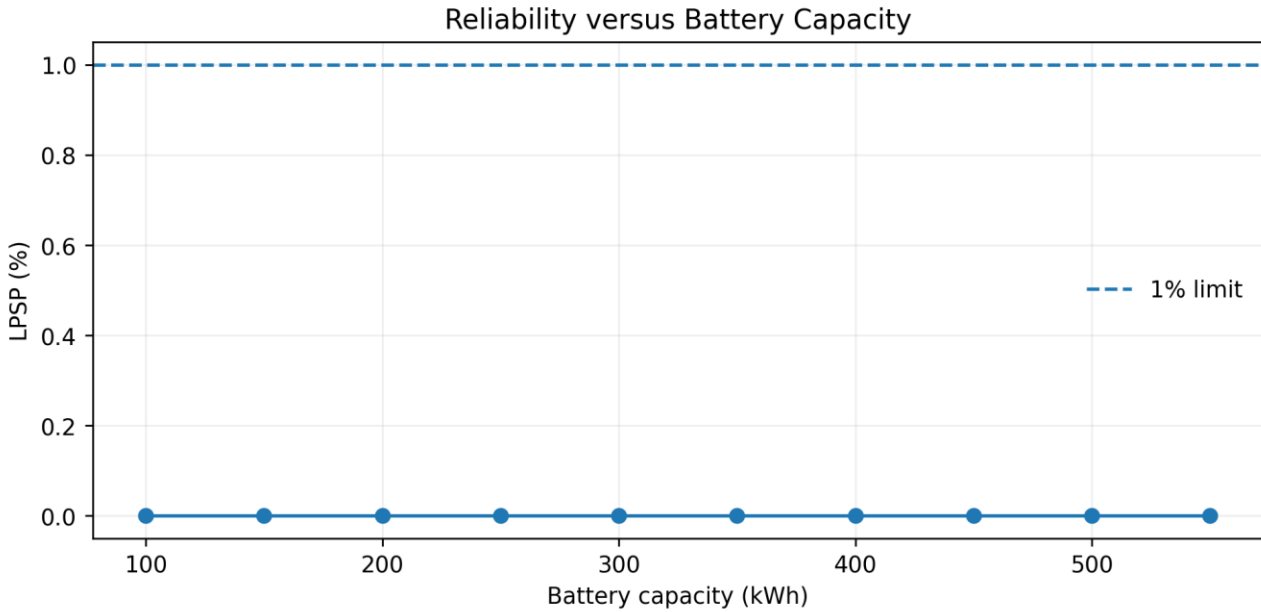


Figure 4. LPSP versus battery capacity.

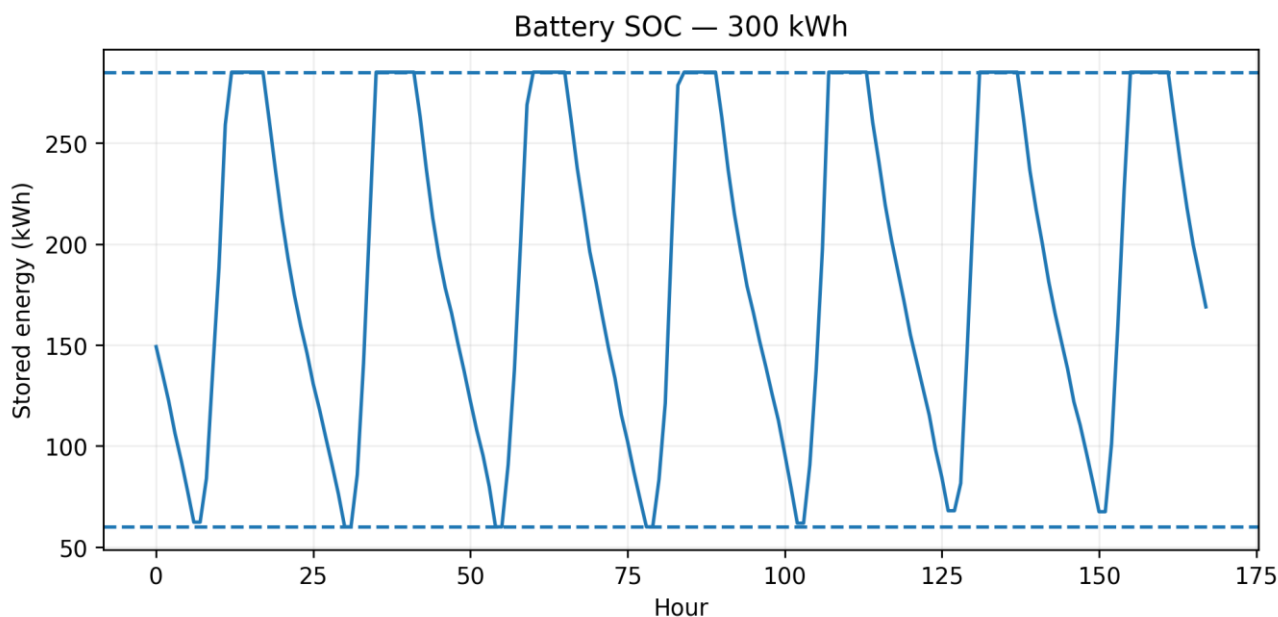


Figure 5. SOC trajectory for the 300-kWh battery.

The SOC controller keeps the battery within the 20–95% operating window, limiting deep discharge and sustained overcharge.

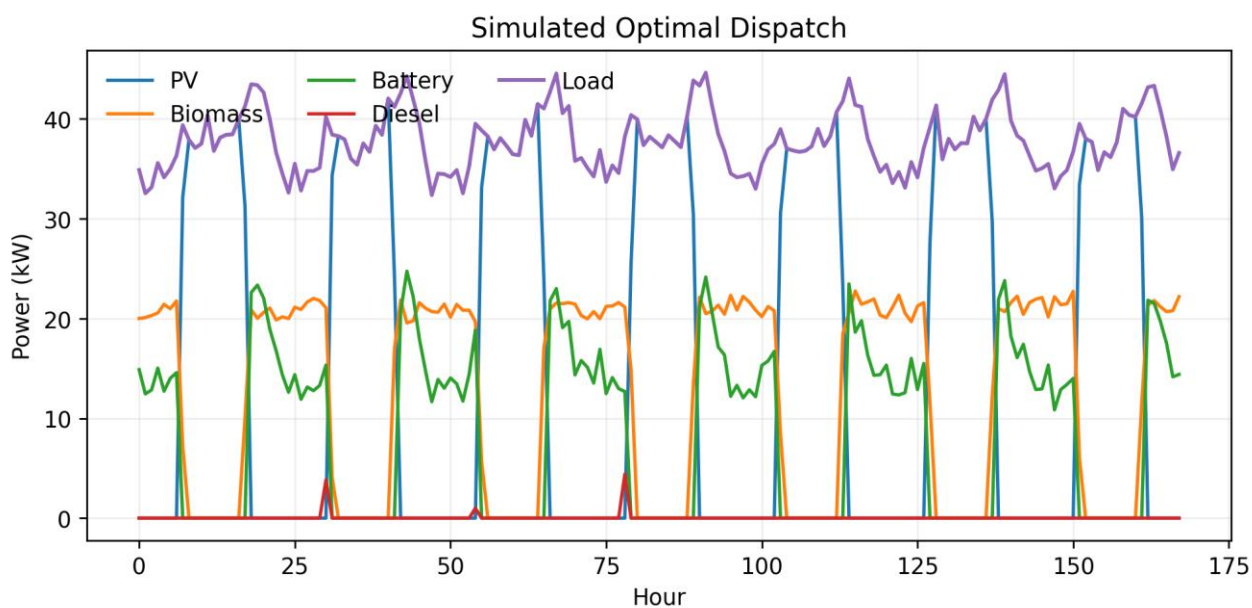


Figure 6. optimal weekly dispatch.

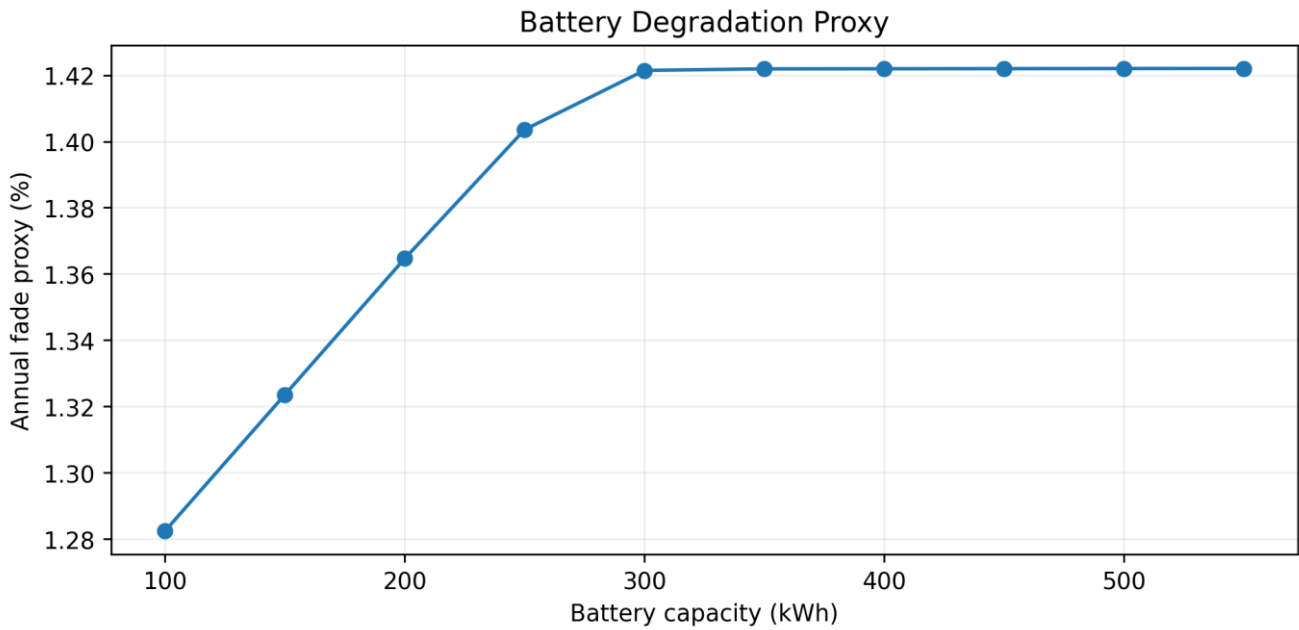


Figure 7. annual battery-fade proxy. Battery degradation is operationally important and has been explicitly incorporated in recent Firefly-based HRES research. [cite](#) [turn0search0](#) [turn0search2](#)

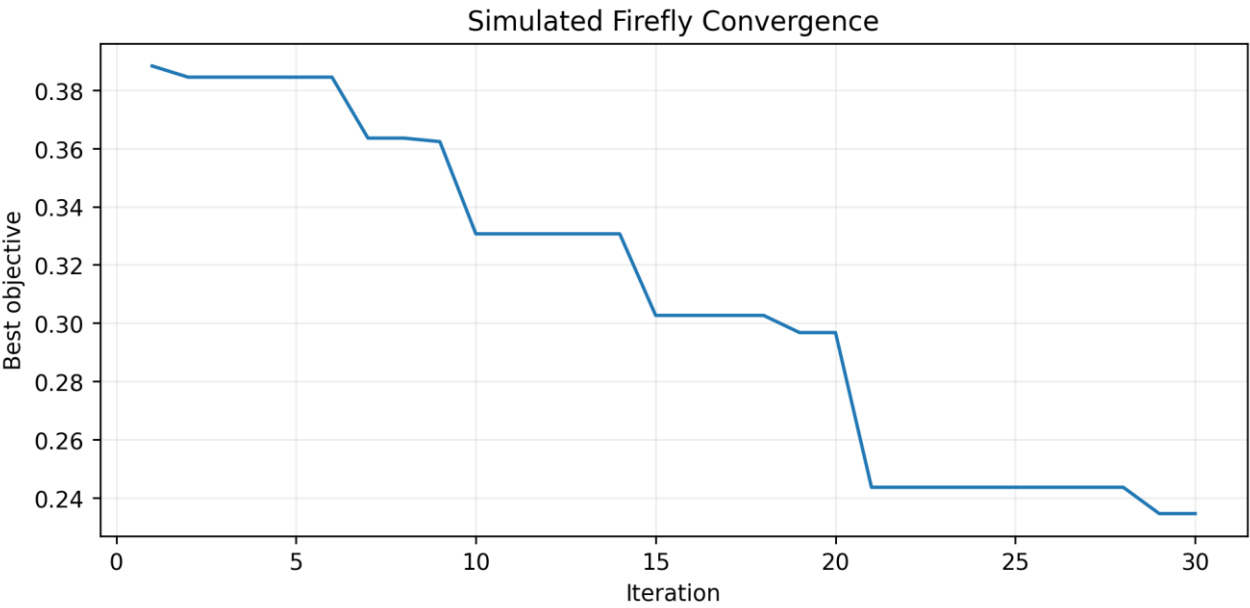


Figure 8. Firefly Algorithm convergence.

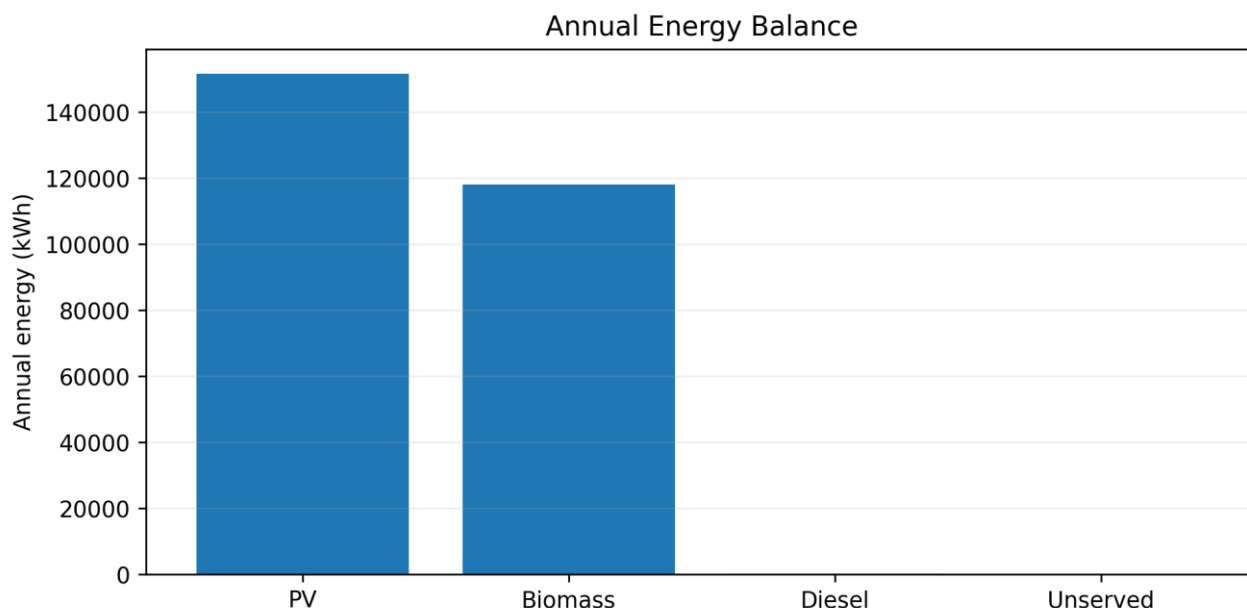


Figure 9. annual energy balance.

9. OPTIMAL BATTERY RESULTS

Indicator	Simulated optimum
Battery capacity	300 kWh
LCOE	\$0.135/kWh
TNPC	\$447,781
Renewable fraction	79.53%
LPSP	0.000%
Unserved energy	0 kWh/year
Annual fade proxy	1.42%
Equivalent cycles	246.0

10. SENSITIVITY ANALYSIS

The final Q1 version should evaluate $\pm 10\%$ and $\pm 20\%$ changes in solar resource, biomass availability, load demand, battery cost, efficiency and degradation rate, and should report battery optimum, LPSP, LCOE, renewable fraction, diesel fuel use and annual degradation.

- Low-solar scenario.
- High-load scenario.
- Low-biomass scenario.
- High battery replacement cost.
- Reduced round-trip efficiency.
- Higher degradation coefficient.
- Alternative SOC windows: 10–90%, 20–95% and 30–90%.

11. RELIABILITY AND RESILIENCE

Battery storage improves short-duration reliability but cannot eliminate the need for dispatchable generation during prolonged low-resource periods. The final study should therefore report maximum outage duration, number of loss-of-load events, expected

energy not served and reserve margin in addition to annual LPSP. Reliability-oriented HRES studies similarly treat reliability as a design constraint rather than only a post-processing metric.

12. PRACTICAL IMPLICATIONS

The methodology can support rural community microgrids, health facilities, schools, agricultural processing centres, telecommunications loads and water-pumping systems. The key planning principle is to size storage according to the interaction among renewable variability, load demand, reliability and battery lifetime rather than using an arbitrary storage-to-PV ratio.

13. LIMITATIONS

- The numerical dataset is synthetic.
- The degradation representation is a simplified throughput-based proxy.
- Battery chemistry-specific ageing is not represented.
- Solar, biomass and load data require site-specific validation.
- PSO, GA and HOMER results have not been independently executed in this manuscript version.
- Extreme-weather resilience and probabilistic forecast uncertainty require further analysis.

14. CONCLUSIONS

This study developed a reliability-constrained battery-sizing and SOC-management framework for a Solar PV–Biomass–Diesel rural microgrid. The simulation identified a 300-kWh battery as the optimum under the adopted cost–reliability–degradation objective. The simulated optimum achieved LCOE 0.135/kWh, TNPC 447,781, renewable fraction 79.53% and LPSP 0.000%. The results show that storage sizing is a multi-dimensional problem in which additional capacity improves reliability but can produce diminishing economic returns. Explicit SOC management is essential for reliability and battery-life preservation. The final empirical study should replace the synthetic data with validated Usen data and independently execute FA, PSO, GA and HOMER analyses before Q1 submission.

15. RECOMMENDED Q1 FIGURES

- Methodology flowchart
- Annual load and PV profile
- Battery-size/objective trade-off
- LPSP versus battery capacity
- SOC trajectory
- Optimal dispatch
- Battery degradation
- FA convergence
- Annual energy balance
- Sensitivity/tornado diagram
- Reliability-duration curve
- FA/PSO/GA statistical comparison

16. REFERENCES

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