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Battery Reserve Assessment for a 1 kW Solar and Pedal Hybrid Power System

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***Abstract*—**This study sizes a lead-acid battery for a proposed 1 kWp solar and pedal hybrid system with grid backup. The system serves four IP cameras and their recording and network equipment, with scheduled lighting and USB charging. Equipment demand is estimated at 2.444 kWh per day. The 15-hour overnight outage case requires 1.460 kWh, including an assumed 10 W auxiliary allowance. An analytical sizing calculation and a one-minute Python simulation use a 50% state-of-charge floor and 90% delivery efficiency. Under the design stress case of 80% retained capacity and 90% starting charge, the calculated minimum nominal capacity is 422.5 Ah at 12 V. A proposed 450 Ah bank meets the simulated load with zero unmet energy and finishes at 52.4% state of charge. A 400 Ah bank under the same conditions leaves 77.6 Wh unmet. At four equivalent sun-hours, the array could yield 3.000 kWh per day before charge limits and dispatch losses. A separate dispatch simulation evaluates how solar timing and charging limits affect grid dependence. The outage results were independently checked against the analytical energy balance at one-minute and five-minute time steps.

***Keywords*—**Battery backup, energy budgeting, exercise-cycle generator, Internet of Things, photovoltaic systems, uninterruptible power supply.

I. Introduction

Continuous CCTV recording requires backup when the grid fails. Photovoltaic (PV) generation offsets part of the energy demand, while a pedal generator demonstrates human-powered conversion. Each source charges the common battery through a regulated path.

Using the load schedule in [1], this study compares daily generation and overnight backup separately and sizes storage for a defined degraded-battery case.

A. Design Questions and Scope

The design must serve two different purposes. During normal operation, the PV array and pedal generator can offset part of the energy bought from the grid. During an outage, the battery must carry CCTV, monitoring and any scheduled lighting until the grid or solar supply returns. A daily surplus can coincide with a storage shortfall because generation and demand occur at different times. This study therefore examines both the overnight outage and the effect of dispatch on a representative repeating day.

The project report [1] supplies the equipment schedule and baseline hardware. Three design comparisons are made: nominal battery capacity under an overnight interruption, renewable-first operation under different equivalent sun-hours, and sensitivity to the charge power limit. The study evaluates energy adequacy and grid dependence under stated assumptions.

II. System Architecture

A. Sources and Load Paths

Fig. 1 shows the power paths. The 1 kWp PV array feeds an MPPT charge controller and the pedal-driven permanent-magnet DC generator feeds a buck–boost charger with constant-current and constant-voltage control. Both feed the protected battery bus. The UPS receives MSEDCL AC and supplies the camera, recording, and network equipment through the AC load path. Scheduled lighting and USB charging use their own protected DC branches. A regulated DC supply keeps the ESP32 and measurement circuits on the storage bus.

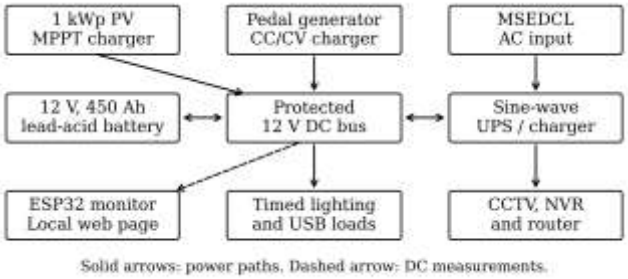


Fig. 1. Proposed hybrid power and monitoring paths.

B. Charge Coordination and Protection

At 14.4 V, 1 kW corresponds to 69.4 A of ideal output. The original 50 A controller [1] can deliver at most 720 W at that voltage. Reuse requires checking array power, cold open-circuit voltage and input current. The combined PV, pedal and UPS charging current must follow the battery manufacturer's limits. The DC branches require rated protection, and the pedal drive needs guarding and reverse-current blocking.

The UPS handles AC transfer independently of the ESP32. Grid-priority operation can limit solar use and should be verified with the selected equipment.

The charge controller output limit and the battery charge acceptance limit act at different points. The first can clip available solar power even when the battery has room. The second can restrict storage of energy that exceeds the immediate load. Their effects depend on the actual settings and the routing of solar energy to the loads. The calculations below keep these two limits separate so that a lower charge setting can be assessed without assuming that all solar production is lost.

C. Monitoring and Load Scheduling

The ESP32 [2] reports PV and pedal charger output, signed battery power, and UPS grid input. INA226 monitors [3] and external shunts measure DC power. The UPS input meter includes any bypass and charger power. The ESP32 operates only the scheduled low-voltage branches.

A battery-backed clock maintains the schedule. Lighting and USB outputs default off if timing or battery data are invalid. CCTV remains on the UPS path.

III. Energy Model

A. Load Schedule

The model treats each load as constant during its assigned interval. Equipment energy is the sum of rated or assumed power multiplied by run time. Table I separates the always-on equipment from the two scheduled loads.

$$E = \Sigma P_i t_i \quad (1)$$

TABLE I
Assumed Daily Load Schedule

Load	W	h/day	Wh/day
Four IP cameras	32	24	768
NVR and HDD	15	24	360
Router	10	24	240
PoE switch overhead	5	24	120
ESP32 and sensors	4	24	96
Two LED tubes	40	8	320
Three USB ports	60	9	540
Total	166[1]	—	2,444

[1] Installed sum. The two scheduled branches operate in separate windows.

The continuous base load is 66 W, of which 62 W serves the CCTV and network equipment and 4 W serves monitoring. The estimated simultaneous load is 126 W during USB charging (09:00–18:00) and 106 W during lighting (22:00–06:00). These are equipment-side figures. Conversion losses and inverter standby consumption are treated separately.

B. Generation and Storage Assumptions

Potential PV energy uses nameplate power, equivalent sun-hours and a 0.75 derating factor before charger clipping. The pedal scenario assumes 60 W at the charger output for one hour, below its 72 W electrical ceiling at 14.4 V and 5 A.

$$E_{pv} = P_{pv} H f \quad (2)$$

The outage model includes 66 W continuous equipment, 40 W lighting from 22:00 to 06:00 and a 10 W effective auxiliary allowance throughout the 18:00–09:00 outage. The total is 1,460 Wh. Grid, PV and pedal input are zero. With 80% retained battery capacity, 90% starting charge, a 50% charge floor and 90% delivery efficiency, the nominal capacity requirement is

$$C = 1{,}460 \div (12 \times 0.80 \times 0.40 \times 0.90) \quad (3)$$

This gives 422.5 Ah. We select a nominal 450 Ah bank. A Python simulation applies the load in one-minute steps. In each step it serves demand up to the energy available above the charge floor, then deducts served energy divided by 0.90 from storage. Any remainder counts as unmet demand. State of charge is relative to retained capacity. We cross-checked all five cases against the closed-form energy balance.

C. Time Resolved Dispatch Model

A separate one-minute dispatch model uses a repeating hypothetical day. The 1 kWp array has a half-sine production profile from 09:00 to 18:00. The profile is scaled to the daily potential PV yield in Table II. It is a timing assumption, and the equivalent sun-hours are sensitivity inputs rather than a weather record for Karad. The pedal source contributes 60 W from 12:00 to 13:00. The equipment schedule in Table I is retained. An effective 10 W auxiliary allowance is included for all 24 hours in this model, increasing the modeled demand to 2.684 kWh per day.

The battery retains 80% of 5.4 kWh nominal energy, giving 4.32 kWh, and operates between 50% and 100% state of charge. The model caps solar output at 720 W, the equivalent of 50 A at 14.4 V. Renewable energy first supplies the load at a common equivalent energy boundary. Excess energy charges the battery with 90% charging efficiency, subject to a 504 W input limit and available storage. The 504 W scenario corresponds to 35 A at 14.4 V and is a sensitivity input. The model does not specify a safe charging current for a particular battery.

When renewable output falls below demand, the battery supplies the deficit at 90% delivery efficiency until it reaches the 50% floor. The grid supplies any remaining load, with no grid charging in this scenario. Unused renewable energy after the array output cap is counted as spill. This simplified renewable-first policy assumes the selected equipment can implement that power flow. It does not separately model direct-path conversion losses or voltage-dependent charging.

Each scenario starts at the charge floor and repeats for 365 model days. The last day is reported after checking that its starting and ending stored energy agree. Minute-level energy balances are summed and checked against the daily demand, source energy and change in battery energy. This eliminates a one-off credit from a full initial battery.

IV. Calculated and Simulated Results

A. Daily Generation and Grid Dependence

Table II compares potential PV and pedal energy with 2,444 Wh of daily equipment demand. Net energy excludes charger limits and downstream losses.

TABLE II
Daily Energy Sensitivity

Sun-hours	PV (Wh)	Pedal (Wh)	Net (Wh)
2	1,500	60	−884
4	3,000	60	+616
6	4,500	60	+2,116

At four sun-hours, doubling PV capacity shifts the ideal balance from a 0.884 kWh deficit to a 0.616 kWh surplus. Battery acceptance and UPS dispatch determine how much of that energy can be used.

B. Overnight Storage Adequacy

TABLE III
SIMULATED OVERNIGHT OUTAGE

Bank Ah	Capacity	Start SOC	Unmet Wh	End SOC
150	100%	100%	650.0	50.0%
350	80%	90%	250.4	50.0%
400	80%	90%	77.6	50.0%
450	80%	90%	0.0	52.4%
450	100%	100%	0.0	70.0%

The 150 Ah baseline leaves 650 Wh unmet with the auxiliary allowance. Excluding that allowance recovers the earlier 500 Wh estimate. The 450 Ah bank at 80% retained capacity and 90% starting charge can deliver 1,555.2 Wh above the floor, a 95.2 Wh margin. At full starting charge and rated capacity it finishes at 70.0% SOC. The model assumes constant efficiency and does not represent voltage sag or transfer transients.

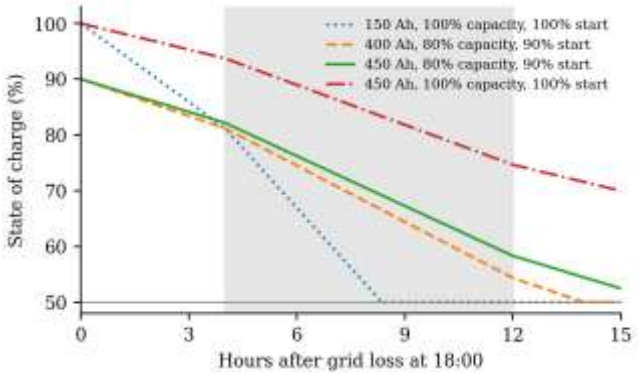


Fig. 2. Simulated charge during outage. Shading marks lighting hours.

Fig. 2 shows the faster decline after 22:00 when the lighting switches on. A horizontal trace at 50% indicates that the battery has reached the modeled cutoff. Table III identifies the unmet energy in those cases. The proposed bank reaches 52.4% in the stressed run, leaving little room for a higher measured night load or a lower starting charge.

C. Dispatch and Grid Energy

TABLE IV
LAST DAY OF SIMULATED RENEWABLE FIRST DISPATCH

Sun-hours	PV clip[1]	Spill[1]	Grid[1]	18:00 SOC
2	0.000	0.000	1.227	58.7%
4	0.000	0.010	0.000	98.7%
6	0.102	1.415	0.000	99.2%

[1] Energy in kWh/day. Results are from the modeled 1 kWp array.

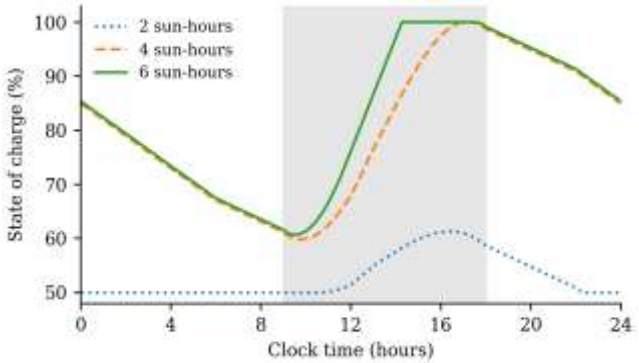


Fig. 3. Simulated daily charge profiles. Shading marks the PV window.

Table IV and Fig. 3 show the distinction between solar potential and useful energy. The two-sun-hour case draws 1.227 kWh from the grid, while the four- and six-sun-hour cases serve the modeled load without grid imports at the 504 W charge limit. At six sun-hours, solar clipping is 0.102 kWh and renewable spill after clipping is 1.415 kWh. More potential generation therefore does not translate directly into more useful energy.

At four equivalent sun-hours, the 500 W array case requires 1.227 kWh of grid energy per day under the same dispatch and storage assumptions. The 1 kWp case requires 0.000 kWh. With pedal input removed, the 1 kWp case requires 0.041 kWh. Reducing the battery charge input limit from 504 W to 288 W raises grid demand to 0.233 kWh per day. Each comparison changes one model input at a time. These results quantify sensitivity within the proposed dispatch model.

V. DISCUSSION

A. Design Implications

For the outage design, a 450 Ah bank at 80% retained capacity must start at approximately 87.6% state of charge to meet the modeled 1.460 kWh load while respecting the 50% floor. This follows from adding the required withdrawal, 1,460 Wh divided by 0.90, to the floor energy and dividing by 4,320 Wh. A charging strategy should therefore be evaluated on whether it can restore the required reserve before the expected outage, especially on a low-solar day. For example, the two-sun-hour case ends the PV window at 58.7% charge. If an outage starts then, only about 0.338 kWh is available above the floor, leaving about 1.122 kWh unmet. The 450 Ah capacity alone cannot guarantee backup if the bank starts below its required reserve.

The time-resolved grid results are sensitive to PV profile and charger behavior. A different distribution of sunshine could change the fraction of energy delivered directly to loads, the period available for charging and the amount of clipping. The model also approximates battery capacity with a fixed retained fraction. Actual lead-acid behavior under load depends on terminal voltage, temperature, discharge rate and age. These effects can change the point at which the UPS cuts out.

For a 450 Ah bank, the minimum starting charge increases from 80.0% at full rated capacity to 83.4% at 90% retained capacity and 87.6% at 80% retained capacity. At 80% retained capacity, starting at 85% leaves 99.2 Wh unmet, while starting at 90% leaves 95.2 Wh above the cutoff after the modeled outage.

B. Implementation and Cost

The original estimate [1] covers the 500 W array and 150 Ah battery. The larger array and battery bank require revised quotations and charger compatibility checks.

VI. COMPLETED SIMULATION VERIFICATION

We checked all five outage cases against a separate closed-form calculation. Delivered energy above the charge floor equals 12 V multiplied by rated ampere-hours, retained capacity, the difference between starting charge and the 50% floor, and delivery efficiency. The analytical

shortfall is the overnight demand minus that available energy, with negative values set to zero.

We also reran the outage model with five-minute steps. Both resolutions place the lighting transitions at exact step boundaries. The two numerical runs and the analytical calculation agreed to within 0.000001 Wh in all cases. Table V reports the shortfall at both resolutions and the analytical result.

A. Energy Balance and Charge Limits

The daily dispatch runs also passed three energy balance checks. Direct renewable supply, battery discharge delivered to the load and grid supply sum to 2.684 kWh of demand. Solar output after clipping and pedal input equal direct supply plus battery charge input and spill. Stored energy changes by 90% of charge input minus delivered battery output divided by 0.90. Each balance closed within 0.000001 Wh in the reported daily scenarios.

TABLE V
VERIFIED SIMULATED OUTAGE SHORTFALL IN WH

Case	1 min	5 min	Analytical
150 Ah at 100% capacity, 100% start	650.0	650.0	650.0
350 Ah at 80% capacity, 90% start	250.4	250.4	250.4
400 Ah at 80% capacity, 90% start	77.6	77.6	77.6
450 Ah at 80% capacity, 90% start	0.0	0.0	0.0
450 Ah at 100% capacity, 100% start	0.0	0.0	0.0

Agreement confirms that the software applies the specified load schedule and battery energy limits consistently. For the 450 Ah case at 80% retained capacity and 90% starting charge, 1,555.2 Wh was available above the floor. After supplying 1,460 Wh, 95.2 Wh remained available. These checks establish numerical consistency under the modeled assumptions. Actual transfer behavior and continuous recording are outside the model.

VII. CONCLUSION

The 450 Ah bank serves the full 15-hour simulated load at 80% retained capacity and 90% starting charge. The verified 95.2 Wh margin depends on starting charge, auxiliary demand and usable battery capacity. The dispatch study shows that a low-solar day can leave insufficient evening charge even with the selected bank.

ACKNOWLEDGMENT

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