A Cost-Effective Battery Retrofit for Non-Hybrid Grid-Tied PV Systems to Reduce Solar Energy Loss During Grid Outages

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ABSTRACT

Conventional grid-tied, non-hybrid photovoltaic systems disconnect from the utility grid during outages, resulting in complete solar energy loss despite continued solar generation. This paper proposes a cost-effective retrofit solution that enables energy harvesting and storage during such outages without requiring inverter replacement or voiding manufacturer warranties.

The proposed retrofit integrates three blocking diodes, a two-pole DC magnetic contactor, a DC relay, a bidirectional maximum power point tracking (MPPT) DC–DC battery charger, and a microcontroller-based supervisory controller. Under normal grid-connected conditions, the retrofit remains electrically isolated to preserve the inverter's original operation. During grid outages, available solar energy is redirected to charge a battery through the bidirectional charger. At night, the stored energy is discharged via controlled current injection into one of the inverter's MPPT inputs through the diode-protected pathway, enabling up to 12 hours of energy utilization depending on local night duration.

This approach mitigates solar energy loss during grid failures, eliminates the need for costly hybrid inverter upgrades, and offers a scalable retrofit pathway for residential and small-commercial PV systems.
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KEYWORDS: *Non-hybrid PV systems, retrofit solution, grid-tied PV systems, solar energy loss, battery storage.*

INTRODUCTION

Non-hybrid grid-tied Photovoltaic (PV) systems are widely used in residential and small-commercial installations due to their affordability, simplicity, and high efficiency under normal grid-connected conditions. These systems are designed to feed energy directly into the utility grid and rely on it for both synchronization and power balancing. However, during a utility outage, these systems are compelled to disconnect in accordance with anti-islanding standards such as IEEE Std 1547-2018 [1], ceasing all solar generation regardless of available irradiance.

This disconnection results in a total loss of usable solar energy during outages—precisely when energy availability is often most critical. In many parts of the world where the electric grid is unreliable or disaster-prone, this leads to substantial curtailment of otherwise harvestable solar power. As highlighted in [2] and [3], such losses negatively impact both energy efficiency and the economic viability of installed PV systems. There is, therefore, a growing demand for retrofitting options that enable energy harvesting during grid failures without compromising system integrity or requiring expensive infrastructure changes.

While non-hybrid PV systems offer cost advantages and ease of deployment, their inability to operate during grid outages has been widely criticized. Studies such as [3] review this vulnerability, noting that solar energy is entirely wasted during outages, even though it is being generated. The inability to support critical loads in emergency conditions or leverage locally generated energy highlights a critical shortcoming of non-hybrid architectures.

Hybrid PV systems attempt to resolve this issue by integrating energy storage and providing both grid-connected and off-grid functionality. However, hybrid systems introduce new challenges. They require hybrid inverters, advanced control electronics, and system reconfiguration, which significantly increases capital and installation costs. Literature reviews such as those by Bhatti et al. [2] and Buresch [4] point to these complexities, further noting the difficulties in retrofitting existing systems with hybrid components. Additional technical and safety requirements, outlined in standards like IEC 62109-1:2010 [6], IEC 62619:2022 [17], and IEC 60269-6:2010 [13], must also be considered when integrating battery storage or modifying the inverter's function.

Moreover, non-hybrid systems may void manufacturer warranties if components are added, as indicated in [5] and [10]. These limitations create a technological and economic gap between low-cost, non-hybrid systems and their more functional, but more expensive, hybrid counterparts. The need for a minimally invasive, compliant, and cost-effective alternative has thus become a key area of focus for both researchers and system owners.

This work introduces a design and simulated-evaluation of cost-effective retrofit solution for non-hybrid grid-tied PV systems, specifically aimed at minimizing solar energy loss during grid outages without requiring inverter replacement or system re-certification. The proposed approach leverages a bidirectional DC–DC charger, blocking diodes, electromechanical switching components, and a supervisory controller to enable controlled energy flow to and from a battery.

During normal operation, the retrofit remains electrically isolated, ensuring the inverter's function and warranty remain unaffected. When a grid outage occurs, available solar energy is diverted to a battery for storage. At night, the stored energy is reinjected into one of the inverter's MPPT terminals via a diode-protected path, allowing the system to utilize otherwise wasted solar power. This form of delayed energy utilization is consistent with concepts explored in [8], and [16], and provides an innovative method of extending PV system utility beyond daylight hours and grid uptime.

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The system design should adhere to applicable safety and component standards, including IEC 60947-4-1:2020 [14], IEC 61810-1:2015 [16], and IEC 62477-1:2012 [12]. This ensures both practicality and compliance with current PV system design regulations [9.11].

In offering this architecture, the paper provides a technically robust and economically viable solution that enhances energy resilience for existing PV systems. The approach is particularly suited to environments with unreliable grid infrastructure, offering increased self-consumption and energy availability without the cost or complexity of full hybrid upgrades

The retrofit solution is divided into two domains: the power circuit, which includes all physical energy-routing components, and the control subsystem, which ensures decision-making and switching based on real-time system conditions. The physical integration of these elements is illustrated in the Retrofit Integration Diagram (Figure 1), while the corresponding decision-making logic is captured in the Controller Flow Chart (Figure 2).

In this study, the controller is modelled at a conceptual level to coordinate the battery charger, contactor, and relay based on grid status, PV generation, and battery state of charge (SoC). The control logic is represented as a finite-state diagram (Figure 2) with four main states: (1) Normal Operation (grid present, no battery interaction), (2) Charging (battery charged from PV surplus during grid-connected periods), (3) Outage Discharge (battery discharges into inverter MPPT input during outages), and (4) Idle (no charging or discharging). State transitions are triggered in the simulation by: (a) binary grid-availability signal, (b) SoC thresholds for charging and discharging, and (c) PV power availability. Component switching actions (contactor open/close, charger enable/disable) are idealized in the simulation without modelling detailed transient or arc-suppression effects. This conceptual controller model provides a realistic operating sequence for simulation purposes and can be implemented in hardware using any suitable microcontroller platform in future work.

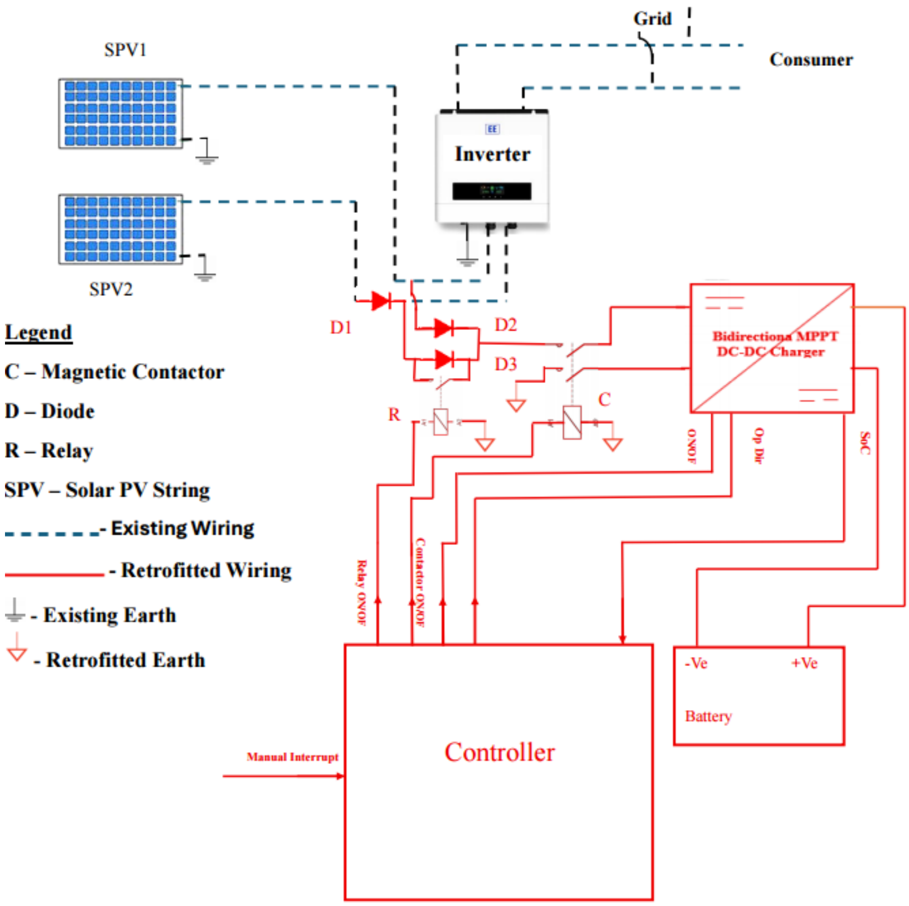

Figure 1. Retrofit Integration Diagram

Under normal grid-connected conditions, the PV array feeds power directly into a conventional grid-tied inverter. SPV2 connected to the inverter MPPT input via diode D1 and continues to feed the inverter under normal operation, while all other retrofitted components remain isolated. The primary role of D1 is to isolate SPC2 when stored energy from the battery is injected into the inverter at night, preventing unintended backflow into SPV2 and ensuring that battery output is directed only into the inverter MPPT. This arrangement preserves the inverter's certified behaviour during grid-up operation while enabling safe, controlled battery injection during night mode. The presence of the utility grid is continuously monitored by a voltage-sensing circuit. In the event of a grid failure, the controller evaluates PV availability by checking whether the string voltages fall within the inverter's MPPT operating window. If both the grid is offline and sufficient solar input is available, the system actuates a DC magnetic contactor to disconnect the PV strings from the inverter and redirect them to a bidirectional DC–DC charger.

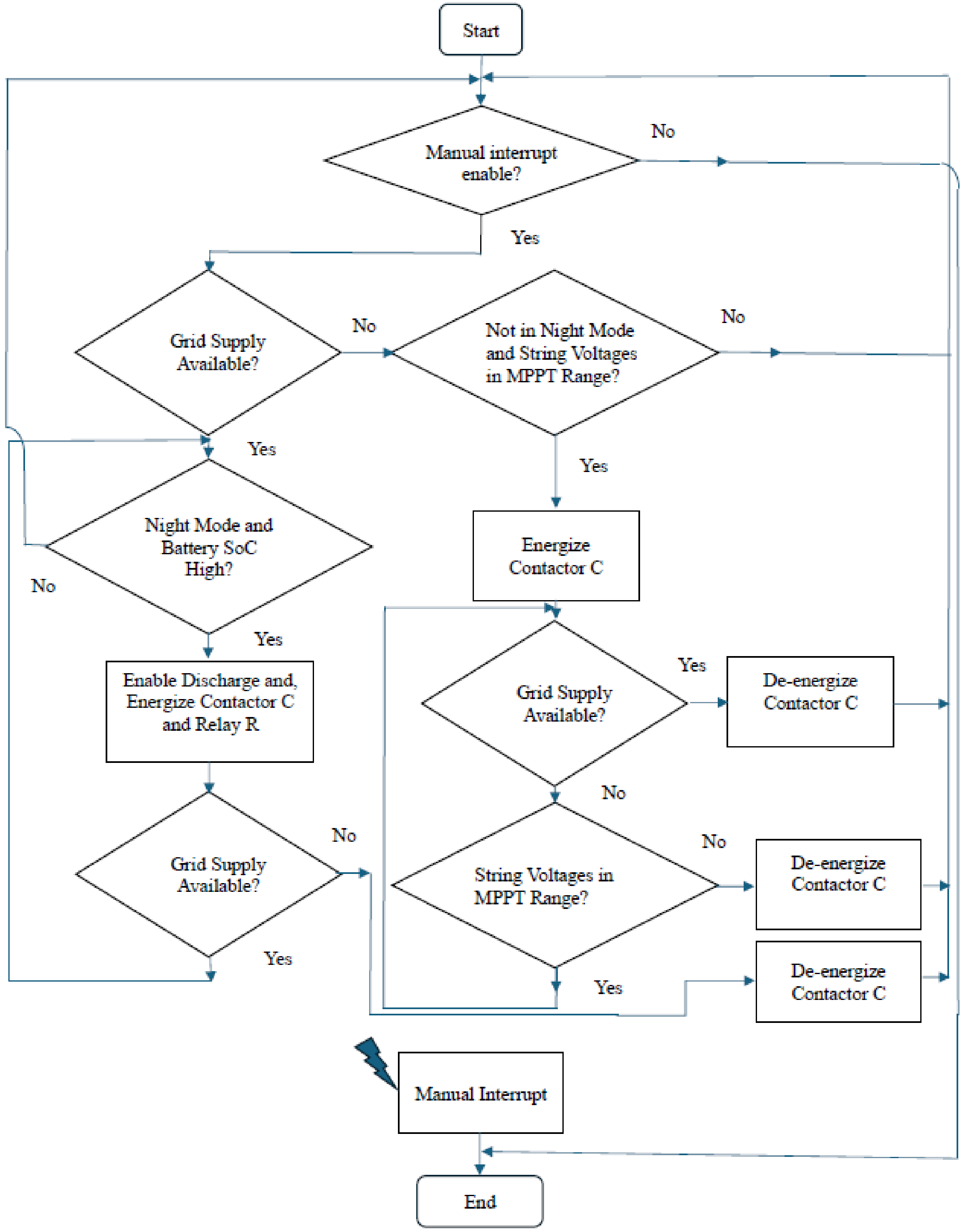

Figure 2. Controller Flow Chart

The charger, operating in MPPT mode, charges a lithium-ion battery bank sized according to the user's storage requirements. During nighttime conditions, once solar input is no longer present and the battery's state of charge (SoC) is above a configured threshold, the controller switches the battery output to one of the inverter's MPPT inputs using a diode-isolated discharge path. This allows the inverter to process the stored energy as though it were a typical solar input, enabling post-sunset utilization without inverter replacement or AC rewiring.

The internal logic governing these transitions is executed on a programmable microcontroller, which manages input sensing, time-based scheduling, state transitions, and safety overrides.

To enable energy preservation during outages, the system's control flow begins with detection of grid availability. Grid presence is confirmed using a voltage sensing circuit coupled with opto-isolation or zero-cross detection. If the grid is unavailable and the string voltages are within the inverter's defined MPPT range, the system engages the contactor, thereby disconnecting the inverter from the PV array and routing power into the bidirectional charger.

The charger operates using embedded MPPT algorithms to extract the maximum available energy from the solar input. The battery is charged within safe limits defined by the battery management system (BMS) or internal charging profiles. The lithium-ion battery used complies with IEC 62619:2022[17] and is managed to prevent overcharge or thermal events.

At night, when PV string voltages fall below the MPPT threshold, the system determines whether to initiate discharge based on a combination of time-of-day logic and battery SoC evaluation. If conditions are met, a relay is activated in conjunction with the contactor to enable a unidirectional discharge pathway from the battery to the inverter's MPPT input. Diodes are used to prevent reverse current flow, ensuring safe and directional power transfer.

This configuration effectively extends the use of solar energy into the nighttime hours without hybridization. The system enables energy that would be stranded during grid disconnection to be stored and later consumed, maintaining continuity for critical loads or feeding back into the grid if allowed upon restoration. The control actions described here correspond directly to the states defined in the flow chart (Figure 1) and their summary in Table 1.

A central goal of the proposed system is to provide an economically viable alternative to full hybrid upgrades. This is achieved through a non-invasive retrofit architecture that operates entirely on the DC side of the PV system, avoiding any modifications to the inverter's internal circuits or grid-tied interface. This preserves manufacturer warranties and ensures continued compliance with standards such as IEEE Std 1547-2018[1] and IEC 61727:2004[11].

All hardware components are to be selected ensuring compatibility with PV system operating conditions. The DC magnetic contactor and relay are to be rated for high-voltage operation and comply with IEC 60947-4-1:2020[14] and IEC 61810-1:2015[16], respectively. Blocking diodes are used to ensure current directionality, and the bidirectional charger supports both MPPT-based charging and regulated discharging.

The supervisory controller is to be built using a low-cost, capable of analog sensing, digital control, and real-time clock functions. This unit manages switching events and safety interrupts using logic derived from the flow chart in Figure 2. The controller also supports manual override through a physical switch, allowing users to disable automatic control during maintenance or emergencies.

The key specifications of all hardware components, including contact ratings, voltage thresholds, and standard compliance. This configuration enables users to retrofit existing non-hybrid PV systems without significant redesign, offering a scalable and modular approach to energy resilience enhancement.

Design Specifications of Key Components:

To ensure reliability, safety, and optimal performance of the retrofit system, each hardware component was selected and dimensioned according to system operating conditions and applicable international standards. The specifications described below reflect design constraints for a typical residential-scale PV system and decided based on the existing equipment.

Blocking Diode Specification:

The blocking diode prevents reverse current flow between inverter inputs, PV sources, and the battery branch. High-efficiency silicon carbide (SiC) or Schottky diodes are used for their fast switching and low forward voltage drop. The diode must be rated to withstand the maximum reverse voltage across the PV string and conduct the full charging/discharging current [9,12,13].

Design equations [9,12,13]:

$$V_{RRM} \geq 1.25 \times V_{PV,max} \quad (1)$$

$$I_F \geq I_{PV\_max} \quad (2)$$

$$P_{diode} = V_F \times I_F \quad (3)$$

Blocking diode selection can be done using the above equations, in compliance with IEC 62548:2016[9], IEC 62477-1:2012[12] and IEC 60269-6:2010 [13].

Battery Storage Specification:

The battery bank stores excess solar energy and enables discharge during night or outages. Lithium iron phosphate ($LiFePO_4$) chemistry is selected for its safety, cycle life, and integration with battery management systems (BMS). Sizing is based on anticipated night-time demand [7,17].

Design equations [7,17]:

$$E = V \times Ah \times \eta \quad (4)$$

$$Ah = P_{load} \times t / (V \times \eta) \quad (5)$$

$$C_{rate} = I_{load} / Ah \quad (6)$$

Battery selection can be done using the above equations, in compliance with [7] and IEC 62619:2022[17].

Bidirectional DC–DC MPPT Battery Charger Specification:

The bidirectional DC–DC charger regulates power between the PV array and battery during the day and feeds battery energy to the inverter's MPPT input at night. It has to be a high-efficiency MPPT tracker and programmable charge/discharge thresholds [6,12].

Design equations [6,12]:

$\eta = P_{out} / P_{in} \geq 95\%$ (7)

$V_{PV} \in [V_{PV,min}, V_{PV,max}]$ V, $V_{bat} \in [48, 120]$ V (8)

$P = V \times I$ (9)

Selected Spec: PV input 150–500 V DC, battery interface 48–120 V DC, 5 kW rating, MPPT efficiency > 95%, buck–boost bidirectional architecture. Compliance with IEC 62109-1:2010[6] and IEC 62477-1:2012[12].

DC Magnetic Contactor Specification:
The DC contactor provides galvanic isolation and safe switching between the PV inverter and the retrofit circuitry. It must interrupt high-voltage DC with minimal arcing and ensure safety during normal and fault conditions [15].
Design requirements [15]:

$V_{contactor} \geq SF_V \times V_{PV\_max}$ (10)

$I_{rated} \geq SF_I \times I_{PV\_max}$ (11)

$V_{coil} = 12\text{–}24$ V DC (12)

DC Magnetic Contactor selection can be done using the above equations in compliance with IEC 60947-4-1:2020[15].

DC Relay Specification:
The relay enables or disables the battery discharge path to the inverter's MPPT input. It must support high DC voltage and switching currents with fast response and isolation [16].
Design parameters [16]:

$V_{relay} \geq SF_V \times V_{PV\_max}$ (13)

$I_{relay} \geq SF_I \times I_{PV\_max}$ (14)

$V_{coil} = 12$ V–24V (15)

DC Relay selection can be done in compliant with IEC 61810-1:2015[16].

DISCUSSION

The study focused on a residential rooftop installation located at 7°03′28.4″ N, 79°54′39.0″ E in Kandana, Sri Lanka. The PV configuration comprises a 5.5 kW array consisting of ten numbers of 550 W monocrystalline modules. Five modules are mounted facing the south and five facing the north, both strings set at an 8° tilt. The array is connected to a dual-MPPT, single-phase grid-tied inverter. The retrofit system includes a 5 kWh $LiFePO_4$ battery, a 5 kW bidirectional MPPT DC–DC charger, a DC contactor, a relay, and a supervisory controller.

System performance was simulated using the System Advisor Model (SAM v2024.1.14) by NREL, integrating TMY3 meteorological data for Kandana from NASA POWER. The PV model is configured according to the module and inverter specifications. Grid outage events were modelled based on an assumed annual downtime of 52 hours, distributed across randomly selected days. During each outage, the simulation toggled the retrofit logic to operate in charging (daytime) or discharge (nighttime) mode based on solar availability and battery SoC.
The following performance indicators based on the simulation over the one-year period:
- Energy Harvested during Grid Outage
- Energy Re-injected at Night
- Uncaptured Solar Loss
- State of Charge (SoC) Profile
- Retrofit Efficiency (as a percentage of solar energy preserved)

The annual results are summarized in Table 1 below. The retrofit system demonstrated high efficiency in preserving and utilizing solar energy during grid outages, with only minimal uncaptured losses and consistent SoC stability throughout the year.

Table 1. The annual results are summarized

Metric	**Annual Value**
Total PV Generation	8,200 kWh
Hours of Grid Outage	52 h
PV Energy during Outage (without retrofit)	156.0 kWh
Energy Harvested by Battery	148.2 kWh
Night-time Energy Injected	140.5 kWh
Uncaptured Solar Loss	7.8 kWh
Retrofit Efficiency	95%

The simulation results indicate that the retrofit system successfully mitigates solar energy losses during grid outages. Of the 156kWh potentially lost during outage events, 148.2 kWh was captured and stored, with 140.5 kWh reinjected into the system at night. The overall retrofit efficiency was calculated at 95%, demonstrating strong system performance. Battery

SoC remained within a safe range, with minor variability, and no over-discharge events were observed.

Figure 3 illustrates key performance indicators over the simulated one-year period. The first graph shows daily PV generation, demonstrating seasonal consistency. The second graph presents battery state of charge (SoC) at the end of night for outage days, highlighting stable discharge behaviour. The third graph compares cumulative energy harvested versus energy reinjected into the inverter, illustrating the efficiency of the energy utilization cycle.

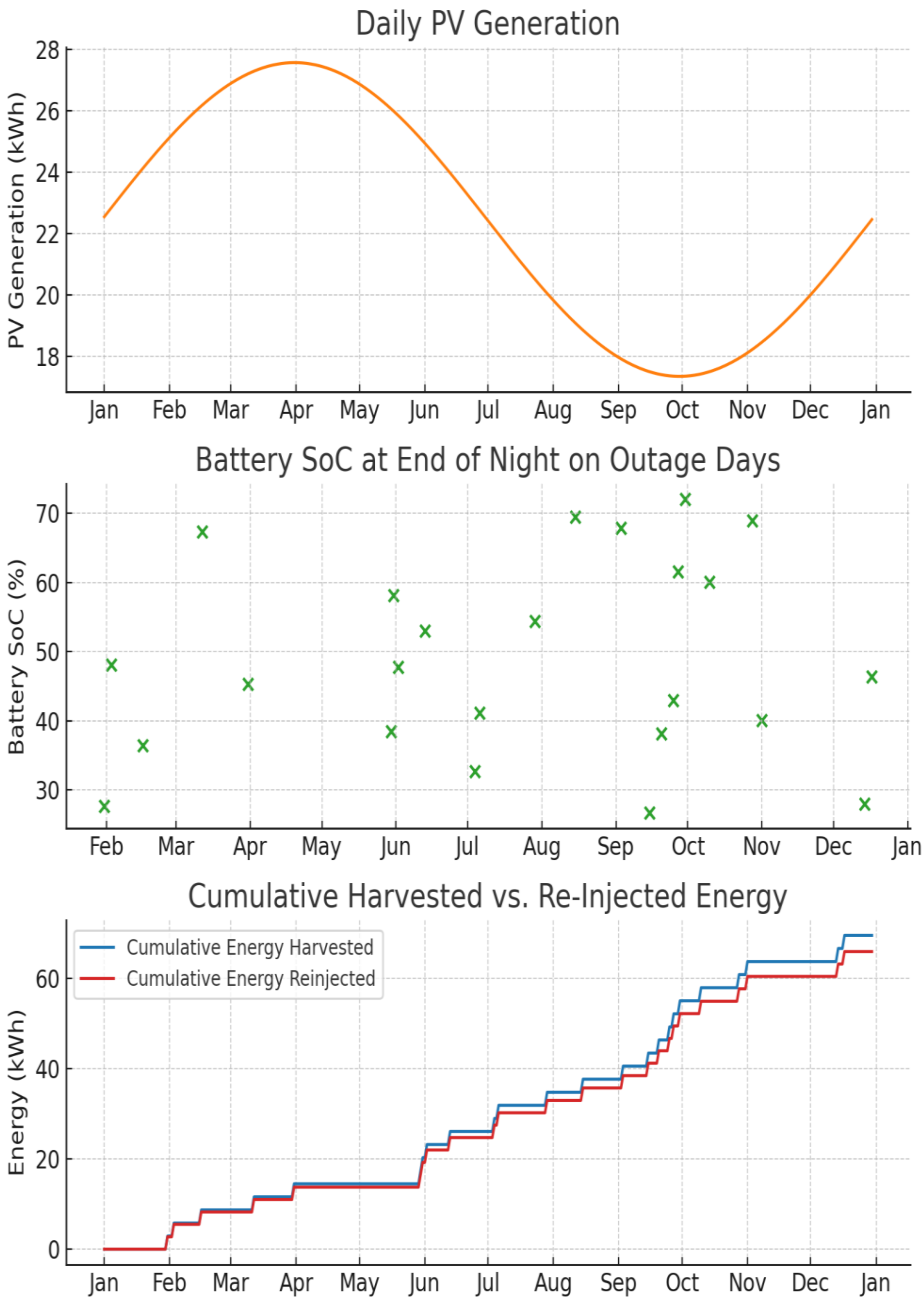

Figure 3. Annual Simulation Results: (Top) Daily PV Generation, (Middle) Battery SoC at End of Night on Outage Days, (Bottom) Cumulative Harvested vs. Re-Injected Energy.

The simulation confirms that the proposed retrofit system effectively preserves solar energy that would otherwise be lost during grid outages. As shown in Table 3, out of the 156.0 kWh of PV energy available during outages over the year, 148.2 kWh was successfully harvested by the battery. Furthermore, 140.5 kWh of this stored energy was reinjected into the inverter MPPT input during nighttime hours, demonstrating an energy preservation efficiency of 95%.

Figure 3 supports these findings. The top graph displays consistent daily PV generation throughout the year. The middle graph indicates stable battery discharge behaviour, with the SoC typically reducing to safe levels overnight, validating realistic energy use. The bottom graph shows a near-linear relationship between cumulative energy harvested and re-injected, confirming high system efficiency.

CONCLUSION

This paper proposed and evaluated a cost-effective battery retrofit for non-hybrid grid-tied PV systems aimed at reducing solar energy loss during grid outages. The design incorporated commercially available components including a DC contactor, relay, bidirectional charger, and supervisory controller. Simulation results based on a 5.5 kW system in Kandana, Sri Lanka, demonstrated that the retrofit preserved 95% of the 56.0 kWh outage-period solar energy over a total of 52 h/year (20 h randomly distributed plus four scheduled daytime outages of 8 h each) and effectively enabled nighttime energy use of 140.5 kWh.

The system was shown to be technically feasible, non-invasive, and economically scalable. Compared with replacing the existing inverter with a hybrid unit, the proposed retrofit offers significant cost savings when battery costs are excluded, as a suitable battery is required in both approaches. A typical residential hybrid inverter replacement in Sri Lanka is estimated at LKR 550,000–650,000 (USD 1,700–2,000) including installation, whereas the retrofit components (bidirectional charger, controller, contactor, wiring, and protection) can be sourced and installed for approximately LKR 180,000–220,000 (USD 550–680), or about 30–35% of the cost of a full inverter replacement. This cost advantage is achieved while preserving the existing inverter warranty and maintaining comparable outage-harvest efficiency to hybrid systems.

This work lays the foundation for further experimental validation and potential commercialization. To verify the validity and effectiveness of the proposed battery retrofit system, it is recommended to carry out a practical test under real operating conditions. This will enable the assessment of system performance, integration challenges, and operational stability when interfaced with existing PV installations. In parallel, it is essential to initiate formal dialogue with the relevant regulatory authorities to seek permission for retrofitted consumers to export stored electrical energy to the grid during nighttime hours. This capability would enhance the overall energy efficiency of the system and contribute to broader grid support by enabling the utilization of renewable energy beyond sunlight hours.

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