Real-Case Analysis of Small-Scale PV-BESS Applications Using Second-Life Batteries

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Abstract

This study presents real-world analyses of three small-scale photovoltaic–battery energy storage systems (PV–BESS) integrating second-life batteries (SLBs) from Nissan Leaf electric vehicles: a solar streetlight, a DC refrigerator, and an EV charger. The streetlight and refrigerator were tested in off-grid operation, whereas the EV charger was evaluated in a grid-connected configuration. Comprehensive monitoring (temperature, state of charge, and electrical variables) demonstrates robust technical performance of SLBs. Economically, viability depends strongly on the load profile and the acquisition cost of storage: stable, cyclic loads (refrigeration) outperform intermittent loads (lighting). Moreover, oversizing the battery—thereby lowering depth of discharge—mitigates accelerated degradation and extends service life. Conversely, even under highly unfavorable conditions—combining elevated purchase prices and premature degradation—SLBs remained more economical than diesel-based systems. For the EV charger, under specific tariff and cost assumptions, we estimate a payback time of approximately 13 years relative to a fully on-grid configuration.

Keywords: Second life batteries, PV-BESS, real-case, economic viability, sustainability

1. Introduction

The rapid increase in electric vehicle (EV) adoption worldwide has led to a growing number of batteries reaching the end of their automotive life but still retaining sufficient capacity for stationary energy storage applications. These batteries, known as second-life batteries (SLBs), represent an important opportunity for enhancing sustainability in the energy sector. Although numerous studies have examined the feasibility and potential applicability of SLBs (Rufino Júnior et al., 2023; Shahjalal et al., 2022), the literature still lacks comprehensive experimental analyses focused on real-world implementations of these batteries.

In the study conducted by Rufino Júnior et al. (2024), it was found that SLBs can serve as an alternative solution for meeting peak demand, accommodating fluctuations in energy demand and supply, regulating frequency, and integrating renewable energy sources. These batteries can be categorized into three distinct applications: off-grid stationary, grid-connected stationary, and mobile applications. Similarly, Moreira et al. (2021) investigated the use of SLBs in the Brazilian context, emphasizing the feasibility of their deployment in stationary energy storage systems and underscoring the importance of economic assessments to evaluate their competitiveness compared to new batteries.

Beyond the Brazilian context, international field evidence further underscores both the promise and the constraints of SLB deployments in real-world settings. International literature highlights that the economic feasibility of SLBs is strongly conditioned by both technical and market-related factors. Nedjalkov et al. (2019) demonstrated the applicability of SLBs in an island microgrid in Tanzania, emphasizing the importance of advanced management systems to ensure safety and reliability. In the same context, Falk et al. (2020) showed that combining PV generation with SLBs can reduce costs compared to diesel-based solutions, while also providing significant social benefits. These two case studies provide concrete evidence of the potential of SLBs in isolated communities and serve as references for the present work.

Despite these advances, the practical deployment of second-life batteries still depends on several technical and economic factors (Roslan et al., 2025). Previous studies have highlighted challenges related to battery heterogeneity, state-of-health estimation, safety, degradation behavior, and the need for appropriate battery management systems to ensure reliable stationary operation (Vignesh S. et al., 2025). In addition, although the literature reports promising

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results for SLB integration into renewable energy systems, many studies remain focused on simulation-based assessments or single-application analyses (Patel et al., 2024). This reinforces the importance of experimental investigations based on real operating systems, especially for small-scale PV-BESS applications intended for decentralized and off-grid contexts.

Small-scale experimental applications are particularly relevant as starting points for concept validation and the development of larger projects. To address this gap, the present work investigates three real small-scale implementations of SLB-based energy systems integrated with photovoltaic (PV) generation: (i) solar street lighting, (ii) a DC refrigeration unit, and (iii) an EV charging system. All setups are currently under operation in our laboratory and have potential applicability both in isolated areas and in grid-connected environments, with potential to also mitigate issues such as reverse power flow.

The remainder of this paper is organized as follows. Section 2 describes the general methodology adopted for the technical and economic analyses. Sections 3, 4, and 5 present the three case studies, focusing respectively on the solar streetlight system, the solar refrigerator system, and the EV charging station. Section 6 discusses the main findings through a comparative analysis of the results, highlighting the advantages and limitations of each configuration. Finally, Section 7 summarizes the key conclusions and outlines perspectives for future research on the application of second-life batteries in small-scale energy systems.

2. General Methodology

This study is based on the analysis of three experimental setups involving PV-BESS powered by SLBs. The experiments, summarized in Table 1, are described in detail in the following sections (3, 4 and 5), each focusing on a specific small-scale application: a solar-powered streetlight, a solar refrigerator, and an EV charging station. For all three cases, the methodological approach comprised the characterization and selection of SLB modules, the implementation and operational monitoring of each PV-BESS configuration, and the technical assessment based on measured performance data, along with the economic assessment conducted according to the assumptions adopted in each case study.

Table 1. Overview of the experimental setups

Application	Start date	Grid Connection	Monitoring System	PV System	Load	Initial Capacity
Solar streetlight	Nov 2024[1]	No	Microcontroller; 2x Temperature Sensors	1x PV module (255 Wp)	30 W DC LED lamp	3x battery modules @ 63% SOH = 0.95 kWh
Refrigerator	Jan 2022	No	Datalogger; Controller; 4x Temperature Sensors	1x PV module (255 Wp)	17.8 W DC Solar Refrigerator	3x battery modules @ 70.6% SOH = 1.08 kWh
EV Charger	Dec 2023	Yes	Solar Inverter; BMS; 8x Temperature Sensors	15 kWp; 128x PV modules (120 Wp)[2]	8 kW AC EV charger	56x battery modules @ 85.7% SOH = 24 kWh

The common foundation of the three case studies lies in their reliance on second-life battery modules repurposed from Nissan Leaf vehicles retired after approximately five years of taxi service in Brazil. Each module contained four LMO pouch cells, rated at 0.5 kWh, resulting in a pack-level capacity of 24.5 kWh across 48 modules, corresponding to a nominal driving range of 160 km when new (Nissan, 2012). Following decommissioning, the packs were dismantled, and each module was subjected to SOH and internal resistance tests using an NHR 9430-12 electronic load bank. The testing methodology, detailed by Hohmann et al. (2022), ensured the safe selection of modules for stationary integration. Figure 1 presents the battery pack configuration.

[1] The poles have been in operation since December 2019; however, the online monitoring system was installed in November 2024.
[2] The PV system was already in place and was not originally designed for the purpose of this experiment.

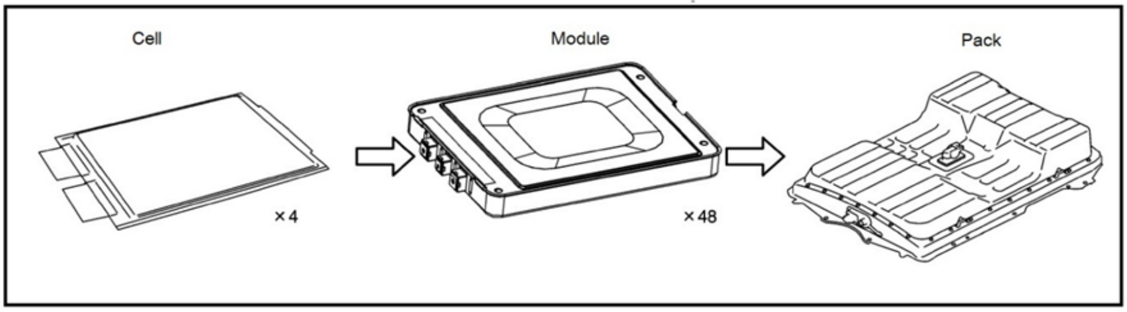

Figure 1. Composition of the lithium battery pack of Nissan LEAF, consisting of 48 modules, each containing four LMO pouch cells (Nissan, 2012)

Modules exhibiting acceptable SOH and electrical stability were selected and dimensioned according to the energy requirements of each experimental setup. Systems were configured for either off-grid (streetlight and refrigerator) or grid-connected (EV charger) operation. Each system was independently monitored through embedded instrumentation, which included sensors for voltage, current, temperature, and state of charge (SOC). These monitoring systems enabled real-time performance evaluation and long-term tracking of degradation indicators.

The data collected through these platforms supported a technical analysis of system performance and aging behavior. In addition, a complementary economic assessment was conducted for each system, based on the specific assumptions and indicators adopted in each case study. This analysis supported the evaluation of the economic feasibility of SLB-based systems in both off-grid and grid-connected contexts.

The two off-grid applications—the streetlight and refrigerator—are analyzed in terms of their relevance for remote or underserved locations, where conventional grid access is unavailable or unreliable. The grid-connected EV charging station, in contrast, is examined as a hybrid solution for urban areas, where SLBs can supplement PV generation and mitigate peak demand or grid instability. Together, these case studies provide a comprehensive view of the technical and economic potential of second-life batteries in diverse real-world energy scenarios.

3. Case Study 1 – Solar Streetlight System

The solar-powered streetlight is an autonomous DC system comprising a single PV module (255 Wp), a 30 W DC LED luminaire, and an SLB pack. The battery pack consists of three SLB modules with an average SoH of 63%, yielding a usable energy of 0.95 kWh. The system is designed to operate off-grid and sustain lighting during nighttime hours without external power. In the original 2019 configuration, the streetlight employed a PWM charge controller followed by a DC/DC converter, with the battery pack assembled from three modules connected in parallel to achieve a low bus voltage and high ampere-hour capacity. In November 2024, the system was modernized by adopting an MPPT charge controller and reconfiguring the battery into a three-module series string, thereby increasing the system voltage and simplifying the power path, as shown in Figure 2.

Figure 3 highlights the battery-centric diurnal cycle. From ~07:00 onward, under clear-sky conditions, PV generation charges the SLB, driving the SoC toward full by ~12:00. The pack then remains at high SoC through the afternoon with only minor regulation currents. After ~18:00, the battery transitions to discharge to supply the luminaire throughout the night, and the next morning the cycle repeats. On days with strong irradiance, the pack undergoes shallow cycling—low depth of discharge (≈10%, SoC ~90–100%)—a regime known to mitigate degradation and extend the lifetime of second-life modules.

In contrast, Figure 4 shows operation on a low-irradiance day: PV production is insufficient to fully recharge the battery, leaving the pack at a reduced state of charge and leading to deep overnight discharge. The resulting high depth of discharge (DoD) accelerates degradation and reduces the remaining useful life of the SLB.

Figure 2. Overview of the solar streetlight test system. (Left) Complete setup currently in operation, including the pole, PV module, and battery enclosure. (Center) First prototype version of the battery compartment and wiring layout. (Right) Updated configuration featuring the MPPT charge controller and improved instrumentation.

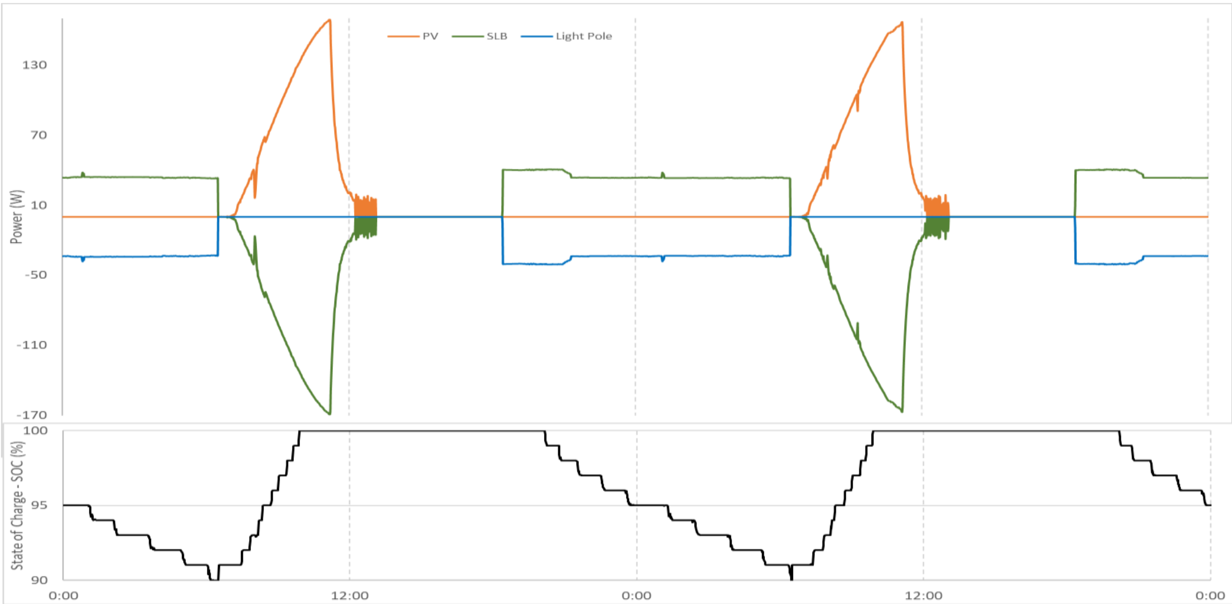

Figure 3. Real-time monitoring of the solar streetlight system. The upper panel shows instantaneous power measurements: the orange line represents the PV array output, the green line corresponds to the battery power—positive values indicate discharge and negative values indicate charging—and the blue line shows the load demand of the light pole. The lower panel presents the corresponding battery state of charge (SOC) throughout the observation period.

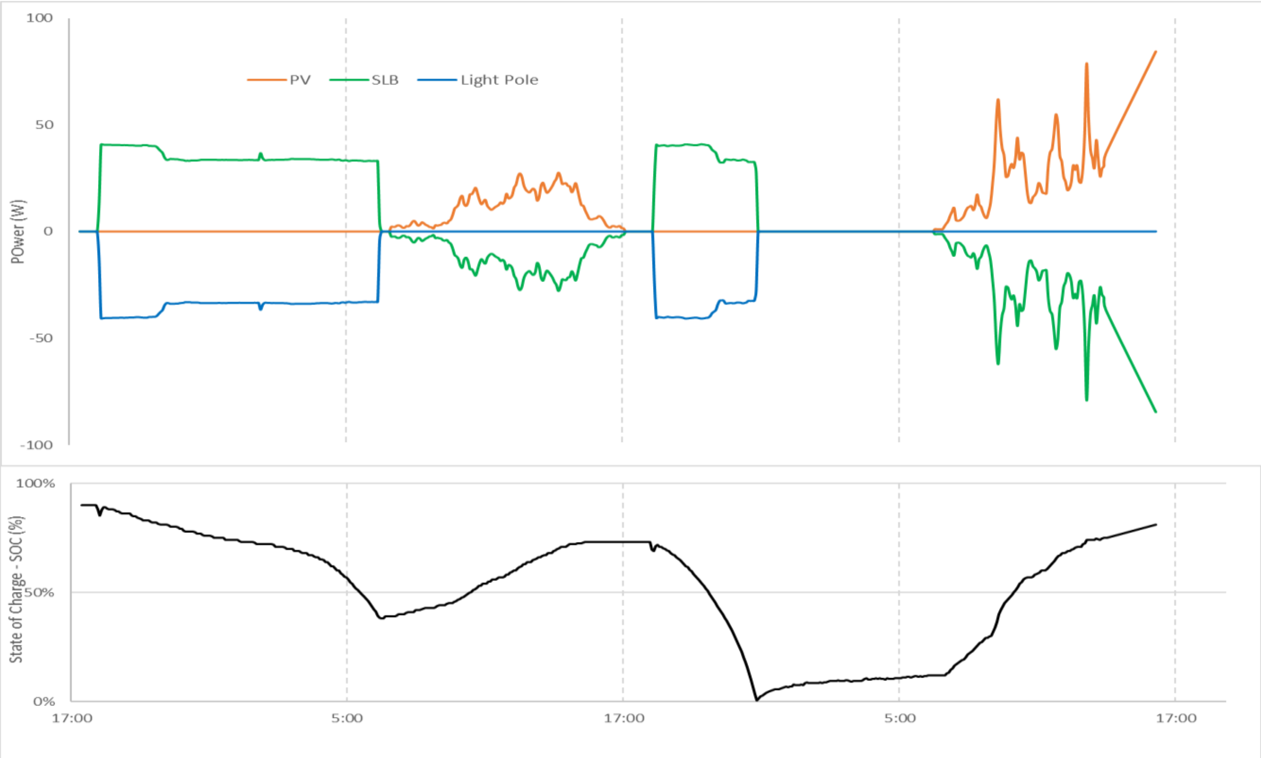

Figure 4. Real-time monitoring of the solar streetlight system during cloudy days, showing the effect of reduced solar generation on the battery's depth of discharge.

The monitored results show that the SLB-based streetlight system can reliably support autonomous nighttime lighting under favorable solar conditions. However, the system is strongly affected by daily irradiance variability, since low-solar-input periods lead to deeper battery discharge and greater stress on the storage system. These findings highlight the importance of proper system sizing and charge management to ensure stable operation and reduce long-term battery degradation.

4. Case Study 2 – Solar Refrigerator System

The solar refrigerator system was designed as an off-grid solution to provide reliable cooling capacity in remote or underserved communities without stable access to the electricity grid. The configuration comprised a single photovoltaic (PV) module rated at 255 Wp, coupled to three second-life battery (SLB) modules repurposed from decommissioned Nissan Leaf electric vehicles (Figure 5). The batteries exhibited an average State of Health (SOH) of 70.6%, corresponding to an available storage capacity of approximately 1.08 kWh. The system was dedicated to powering a direct-current solar refrigerator with a nominal load of 17.8 W.

The sizing of the system began with the assessment of the refrigerator's demand profile. Operating continuously under tropical conditions, the appliance was estimated to require an average daily energy supply of approximately 427 Wh. This baseline consumption was used as the reference point for defining both the storage capacity and the photovoltaic generation required to ensure stable performance. A key design criterion was the ability to sustain operation overnight and during periods of reduced solar irradiation, thereby avoiding service interruptions.

The photovoltaic generator was dimensioned to cover the daily energy demand while providing sufficient surplus for battery charging. A 255 Wp module was selected to guarantee reliable operation under seasonal and weather-related variability in solar resources. This configuration also provided a margin to compensate for conversion losses and other inefficiencies inherent to stand-alone PV systems.

The battery bank was designed to secure at least one full night of autonomy. The integration of three SLB modules with an average SOH of 70.6% provided a storage buffer well aligned with the daily load requirements of the refrigerator. The available capacity ensured that the system could continue to operate during consecutive cloudy periods without compromising cooling performance. System monitoring was implemented using a datalogger, a charge controller, and four temperature sensors. These instruments enabled continuous recording of current, voltage, temperature, and State of Charge (SOC).

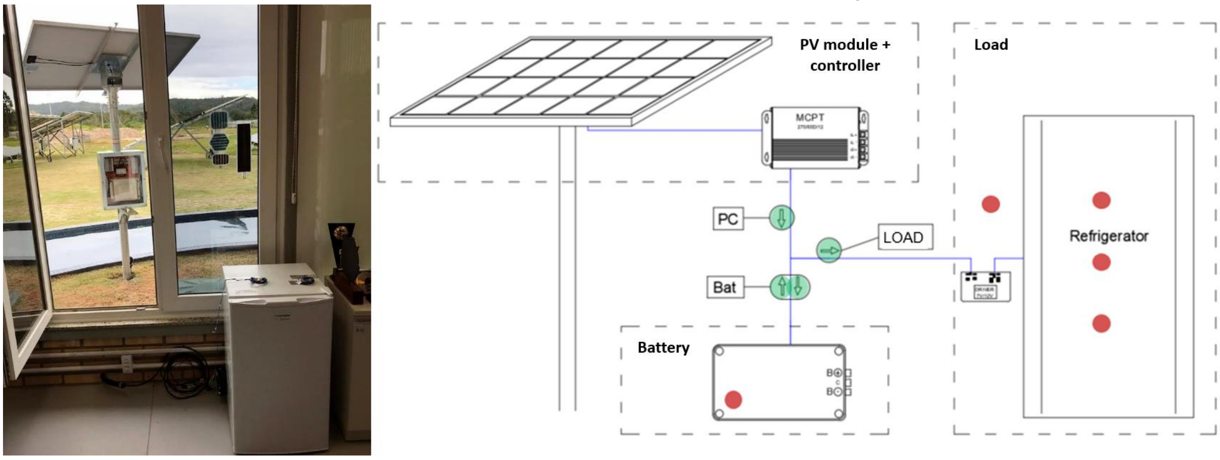

Figure 5. Solar refrigerator system: photograph of the experimental setup (left) and schematic showing electrical sensors in green and temperature sensors in red (right).

As illustrated in Figure 6, the refrigerator operates with a traditional on/off compressor: the appliance switches off at the thermostat setpoint and turns on when the internal temperature rises, producing a pulsed load profile. The battery power trace (orange) shows negative values during charging and positive values during discharge. Overnight, the battery profile nearly mirrors the refrigerator demand, indicating that the load is supplied entirely by the battery. During daylight hours, the PV array (blue) and the battery deliver power simultaneously; for much of the day PV generation is sufficient to both supply the refrigerator and charge the battery, while periods of lower irradiance are partially supplemented by the battery. The resulting cycling is very shallow (DoD ≈ 5%), a regime known to reduce cycle-induced degradation and thereby extend battery life.

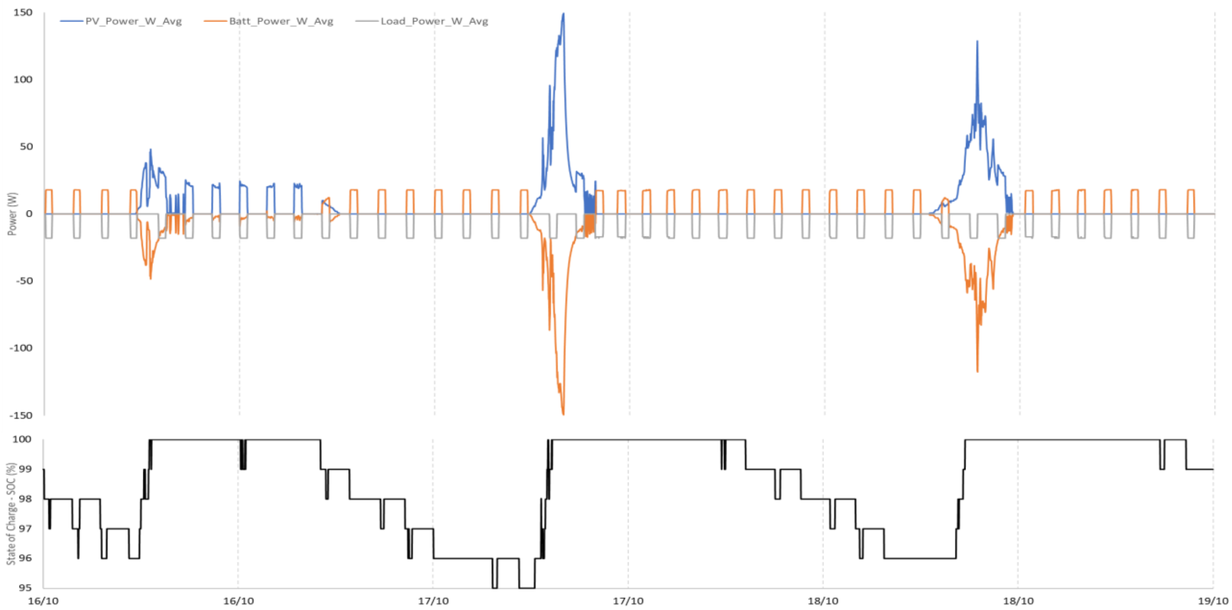

Figure 6. Real-time monitoring of the refrigerator system. The upper panel shows instantaneous power measurements: the blue line represents PV generation, the orange line corresponds to battery power—positive values indicate discharge and negative values indicate charging—and the gray line shows the refrigerator's cyclic load pattern. The lower panel presents the corresponding battery state of charge (SOC) throughout the observation period.

The monitored results indicate that the refrigerator system operated reliably under the proposed off-grid configuration, with the PV array and SLB bank adequately sized to meet the daily cooling demand. The shallow cycling observed throughout operation suggests reduced battery stress, which is favorable for extending the service life of second-life modules. These results support the technical suitability of SLBs for small autonomous refrigeration systems, especially in applications where the load profile is stable and predictable.

5. Case Study 3 – EV Charging Station

The experimental EV charging system, as shown in Figure 7, commissioned in December 2023, is a grid-connected hybrid architecture that integrates photovoltaic (PV) generation, a second-life battery energy storage system (BESS), and an AC EV charger. The BESS comprises 56 repurposed battery modules originally rated at 0.5kWh each (nominal pack =56×0.5=28kWh). At a measured state of health of 85.7%, the present usable energy is approximately 24 kWh, reflecting the reduced capacity typical of second-life deployments. The PV plant—pre-existing and not originally designed for this study—provides up to 15 kWp via 128 modules rated at 120 Wp each. A battery management system (BMS) with eight temperature sensors supervises safety and performance, and the EV supply equipment is an 8 kW AC unit, user-configurable to limit charging demand up to 7 kW for operational flexibility and reduced grid stress.

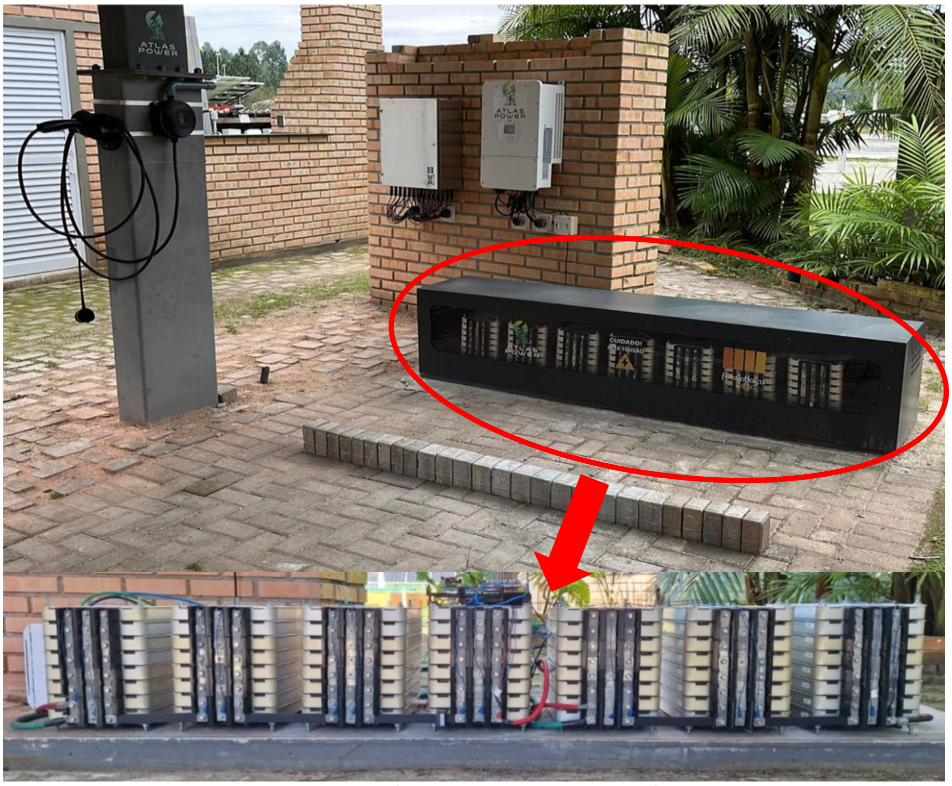

Figure 7. EV charging station equipped with a second-life battery bank composed of 56 repurposed Nissan Leaf modules. The upper panel shows the full installation, including the charger and battery enclosure. The lower panel provides a detailed view of the module arrangement, organized into seven parallel columns, each containing eight modules connected in series.

The inverter configuration ensures that the EV load is continuously supplied, with seamless sourcing from PV, battery, and/or the grid according to a predefined priority: (i) PV plus battery (preferred), (ii) PV plus grid (when the battery cannot contribute), and (iii) grid-only (e.g., rainy or low-irradiance periods). This hierarchy is designed to maximize on-site renewable utilization while preserving service continuity.

The control sequence proceeds as follows. The system prioritizes solar energy and, whenever the solar output is sufficient, the EV is powered exclusively from the photovoltaic array. If solar output is lower than the target charging power, the controller authorizes battery discharge to make up the difference, provided that battery safety and operating constraints are respected. Only when solar generation together with the allowable battery discharge is still inadequate does the controller import energy from the grid to meet the user's charging setpoint.

To visualize the system's behavior, Figure 8 depicts a representative day with an EV charging session starting at approximately 11:00. From around 07:30, the photovoltaic (PV) array ramps up and prioritizes charging the second-life battery; any surplus is exported to the grid (negative grid power). Once EV charging begins, the requested power—close to 7 kW—is supplied primarily by PV plus battery discharge, with negligible grid imports during this interval. By about 14:00, the battery state of charge (SoC) (red dashed line, right y-axis) falls to ~5%, constraining further discharge; supply therefore transitions to PV plus grid. As afternoon irradiance declines, grid import rises to maintain the charging setpoint until the session ends near 17:30. In accordance with the off-peak strategy, after 21:00 the battery is partially recharged from the grid at lower tariff, and the SoC increases until approximately 23:30, after which the system returns to near-idle operation overnight.

Figure 8. Real-time power flow at the EV charging station. The solid lines show the instantaneous AC/DC power contributions—red for grid power, green for battery power, yellow for PV power, and blue for charger power—each referenced to the left axis. The dashed red line represents the battery state of charge (SOC), shown on the right axis.

The monitored results indicate that the hybrid EV charging system can effectively increase the utilization of on-site PV generation by combining solar energy with second-life battery support during charging sessions. The SLB bank was able to reduce grid dependence during periods of high solar availability, while the grid ensured continuity of service whenever battery discharge limits were reached. These findings support the technical feasibility of using SLBs in grid-connected EV charging applications, particularly as a means of increasing self-consumption of PV generation and reducing grid imports during charging periods.

6. Discussion and Comparative Analysis

Section 6 is divided into two parts to reflect distinct application contexts and evaluation methods. Section 6.1 analyzes the refrigerator and the lighting circuit (solar streetlight) because their intended use is in isolated/off-grid systems, where autonomy and storage cycling are decisive. This analysis combines field measurements with HOMER©-based techno-economic modeling, including comparisons against a diesel-only counterfactual and a first-life battery baseline. Section 6.2 addresses the on-grid EV charger, for which we restrict the economic appraisal to estimating the crossover point and payback under predefined tariff and cost assumptions.

6.1 Refrigerator and Lighting Applications

The analysis presented in this Section considers the deployment of SLBs in off-grid applications, specifically targeting isolated communities where diesel generators are the predominant energy source. The intention is to assess the techno-economic viability of SLBs as a substitute for diesel-based systems in powering appliances such as refrigerators and solar lighting circuits. Given the limited availability of representative empirical data on the long-term degradation behavior of SLBs, it is not feasible to define a single, precise degradation model. Instead, three hypothetical degradation profiles—expected, high, and very high degradation—are proposed to represent a plausible range of SLB behavior under field conditions. Table 2 and Figure 9 summarize the simulated scenarios, combining degradation and pricing assumptions, and serve to facilitate the reader’s understanding of the comparative framework. Both the pricing and degradation profiles are expressed as percentages relative to the nominal price and expected performance of a new battery, thereby allowing a direct comparison between first-life and second-life configurations.

The model assumes a 9.1% (BACEN, 2024) discount rate and a 6.9% inflation rate (IBGE, 2024), consistent with national averages and financial conditions for rural energy projects. A 25-year project lifetime and a first-life battery cost of 200 USD kWh^{-1} (including accessories) are adopted as reference values (BloombergNEF, 2024) for the techno-economic analysis.

Table 2. Description of the scenarios analyzed, including the respective coding used to facilitate identification.

	Moderate	Aggressive		Expected	High	Very High
SLB Discount	20%	50%	SLB Degradation	60%	40%	20%
Price Code	P20	P50	Degradation Code	D60	D40	D20

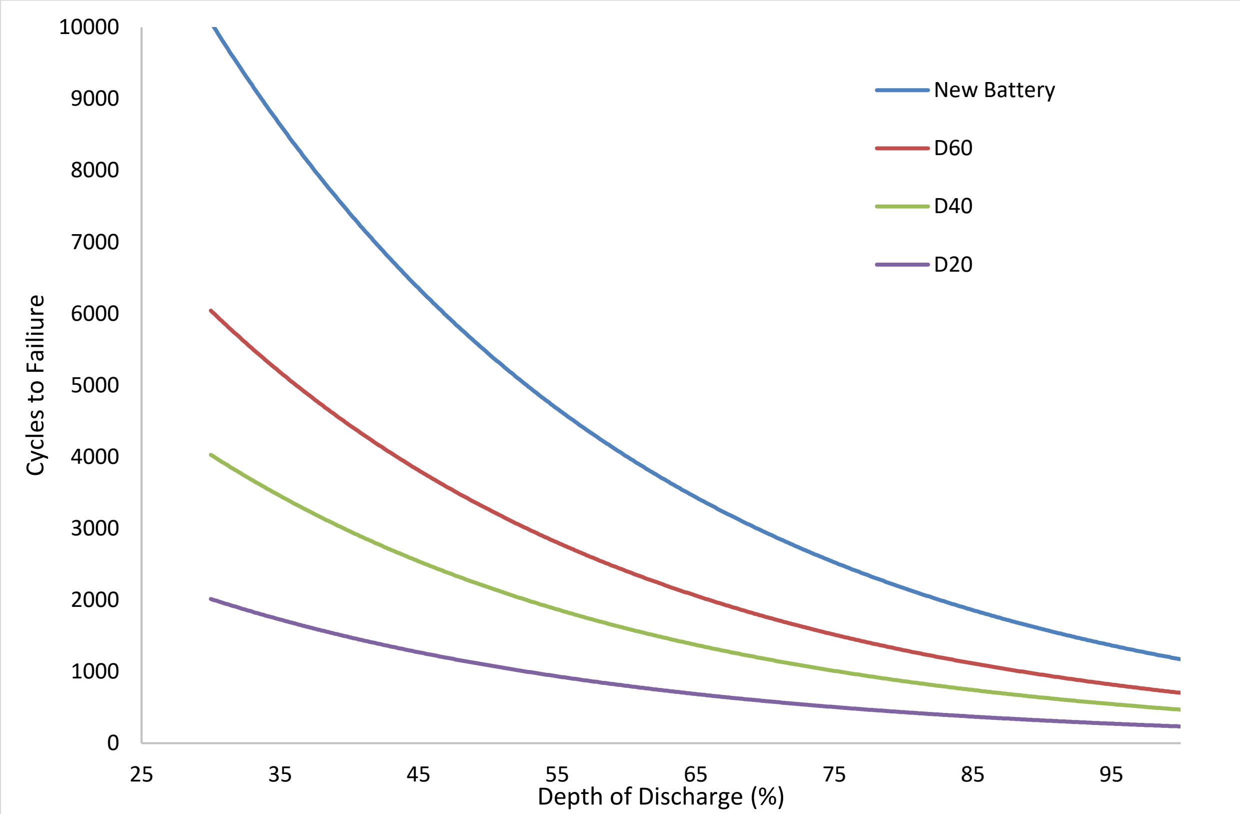

Figure 9. Degradation profiles considered for the simulations. The blue curve represents the new battery reference, while the red, green, and purple curves correspond to second-life batteries with remaining lifetimes of 60%, 40%, and 20% of the originally expected cycle life, respectively.

Due to the absence of a standardized market methodology for pricing SLBs, two pricing scenarios are assumed, based on discounts relative to the cost of new batteries: a moderate discount and an aggressive discount. By combining these two price points with the three degradation profiles, a matrix of six SLB scenarios is constructed. Additionally, a new battery system is simulated as a baseline reference for comparison. All simulations use real load profiles obtained through field monitoring of the refrigerator and lighting circuit. As a final benchmark, a diesel-only system is modeled as a counterfactual scenario, enabling direct comparison in terms of cost, performance, and fuel dependency.

As shown in Figure 10, which presents the simulation results for the lighting system, all configurations employing SLBs exhibit a lower Net Present Cost (NPC) compared to the diesel-based system. When comparing SLBs with first-life batteries (FLBs), favorable scenarios are observed in cases where higher price discounts are applied to the SLB cost per kWh, even under conditions of significant degradation (e.g., SLB P50-D40). Conversely, when only small price reductions are considered, SLBs lose their economic advantage. This behavior is primarily associated with the specific operational characteristics of the lighting circuit, which, during cloudy periods, often fails to fully charge the batteries. This results in frequent deep discharges (high Depth of Discharge, DoD), accelerating battery wear and consequently reducing system viability.

As shown in Figure 11, which presents the results for the refrigeration system, all SLB configurations exhibit a lower NPC than both the diesel-based and FLB systems. Even in the least favorable scenario—characterized by a low-price discount combined with very high degradation (SLB P50-D20)—the NPC remains nearly equivalent to that of the FLB configuration. This outcome is primarily attributed to the nature of the connected load, represented by a refrigerator with a cyclic operating profile. The system is equipped with an oversized battery capacity relative to the load demand, which results in low Depth of Discharge (DoD) values. Consequently, battery stress is minimized, extending the overall system lifetime and maintaining economic viability even under accelerated degradation conditions.

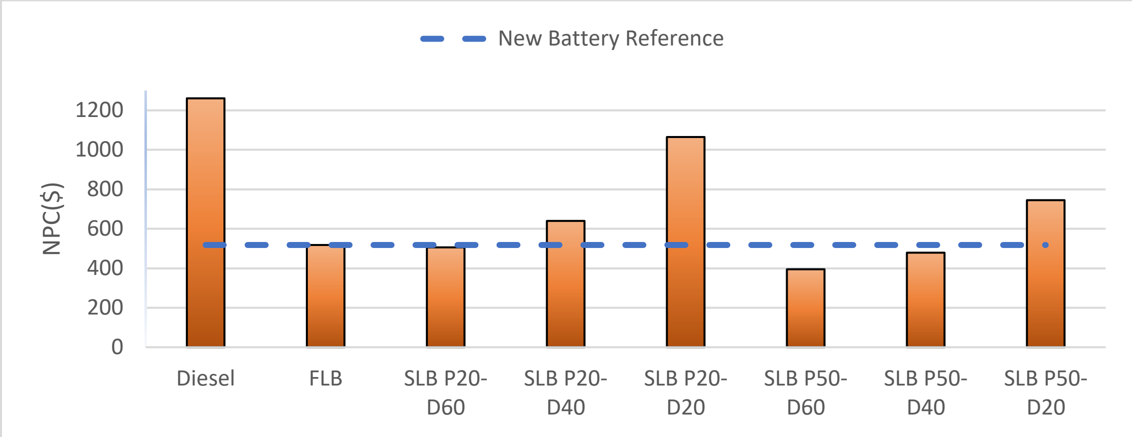

Figure 10. Comparative simulation results for the solar lighting system, showing the six second-life battery (SLB) scenarios according to the coding defined in Table 2. The dashed blue line indicates the net present cost (NPC) of the reference system using a new battery.

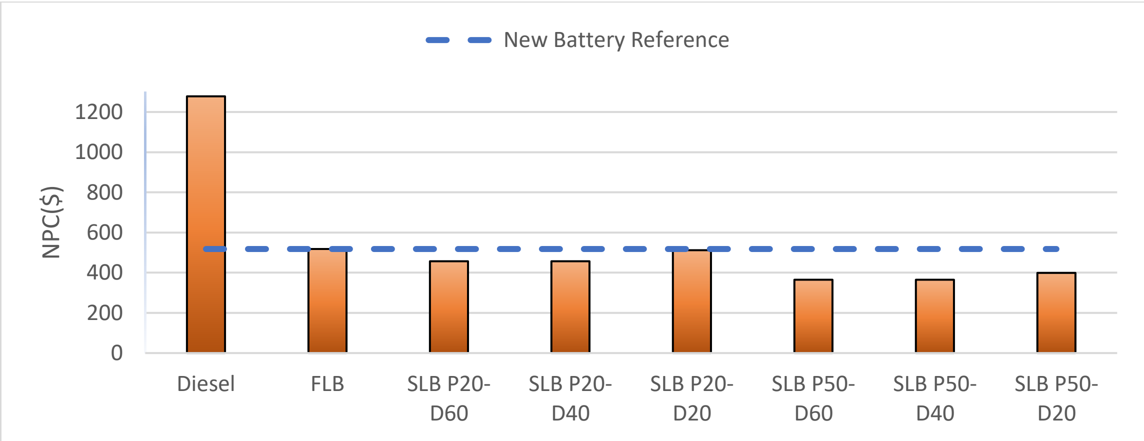

Figure 11. Comparative simulation results for the refrigerator system, showing the six second-life battery (SLB) scenarios according to the coding defined in Table 2. The dashed blue line indicates the net present cost (NPC) of the reference system using a new battery.

Overall, the results confirm that the economic viability of SLBs is highly dependent on both the load profile and the acquisition price of the storage system. Applications with stable, cyclic loads—such as refrigeration—tend to yield better economic performance than those with intermittent charging patterns, such as lighting systems. The findings also indicate that oversizing the battery capacity is a beneficial strategy to extend the operational lifetime of SLBs, as it helps maintain lower DoD levels and mitigates accelerated degradation. Notably, even when the diesel generator cost is assumed to be zero in the simulations, SLB-based systems remain economically advantageous under the least favorable conditions.

6.2 EV Charger Applications

In the context of EV charger applications, the economic analysis is simplified due to the high variability of potential system configurations that combine PV generation, battery storage, grid supply, and diverse charging strategies. The economic assessment for this application focuses on the payback time as the primary performance indicator. The payback time represents the period required for the cumulative savings generated by the hybrid system—comprising PV generation, SLBs, and power electronics—to offset the total initial investment cost. In this analysis, the fully on-grid configuration is used as the economic baseline. The payback period therefore corresponds to the time needed for the SLB-based system to recover its investment through avoided electricity purchases and potential feed-in revenues, becoming economically equivalent to continued grid dependence.

To evaluate the economic feasibility of the proposed system, an interactive tool was developed in Python using the Streamlit framework. This application enables users to input and adjust key techno-economic parameters, allowing real-time simulation of the financial performance of different EV charging configurations. The adjustable parameters include project lifetime, discount and inflation rates, and the capital (CAPEX) and operational (OPEX) costs of the system components, such as the PV array, SLB, and inverter.

For demonstration purposes, an illustrative dataset was defined with the following values: PV system CAPEX of USD 6,000, SLB CAPEX of USD 5,000, annual OPEX of USD 300, and a grid electricity price of USD 0.20 per kWh. Considering a discount rate of 9.1%, electricity inflation rate of 6.9%, and a project lifetime of 25 years, the simulation estimated a payback time of approximately 13 years. Although this study does not perform a detailed or fully optimized economic analysis, the results provide promising indications for the use of SLBs in EV charging applications. These results suggest that the economic attractiveness of this application depends strongly on local tariffs, component costs, and charging demand profiles.

7. Conclusion

This work evaluated three real-world applications of PV-BESS using SLBs: a solar streetlight, a DC refrigerator, and a grid-connected EV charging station. By combining field-monitored operation with techno-economic assessment, the study provided evidence of how SLBs can be integrated into both off-grid and grid-connected systems under different load profiles and operating conditions. The results showed that the technical performance of these systems is strongly influenced by solar availability, load regularity, and battery cycling depth.

For the off-grid applications, SLB-based systems consistently outperformed diesel-only counterfactuals in terms of net present cost, even under conservative assumptions. However, the results also showed that economic viability is application-dependent. In the lighting system, the intermittency of solar charging and the occurrence of deeper discharge cycles can reduce the advantage of SLBs relative to first-life batteries under less favorable pricing conditions. In contrast, the refrigerator system showed the most favorable performance, due to its stable cyclic load and shallow battery cycling, which reduce battery stress and support longer service life. For the grid-connected EV charging application, the monitored results demonstrated the ability of the SLB bank to increase self-consumption of PV generation and reduce grid imports during charging periods, while the economic analysis indicated a promising but context-dependent payback. Across all cases, the findings highlight battery oversizing and low depth of discharge as important strategies for improving durability and overall feasibility.

Despite these promising results, the conclusions should be interpreted in light of important uncertainties related to long-term SLB degradation and the absence of standardized pricing methodologies for second-life batteries. Future work should therefore focus on extended monitoring campaigns, the development of more robust degradation models under different thermal and cycling conditions, and improved economic analyses that account for market variability, tariff structures, and application-specific operating strategies. These advances are essential to strengthen the technical and financial assessment of SLBs and support their broader adoption in sustainable energy systems.

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