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Initializing Future Scenarios of Sustainable Infrastructure for Charging EV Smart Buses Powered by Hybrid Renewables

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Abstract

The University of the Philippines Los Baños operates twelve electric minibuses (eLBeep), whose removable 5.4 kWh lithium iron phosphate battery packs are charged off-board. This case study uses HOMER Grid to compare five grid-connected combinations of solar photovoltaics (PV), a 10 kW wind turbine, and a battery energy storage system (BESS) for a dedicated charging station against a grid-only base case over 25 years and under a flat energy tariff of USD 0.24/kWh. The charging load is 52.0 MWh per year with a 17.4 kW peak. Without compensation, 40 kW of PV with 72 kWh of storage has the lowest net present cost (NPC; USD 123,919, 34% below the grid-only base), meets 78% of the load on site, and reduces gross grid-related CO_2 emissions by 78%. Solar-only at the same PV size costs USD 17,794 more. Wind adds cost at this site, where the turbine's capacity factor is 7.7%, and storage without PV did not provide returns under either tariff tested. Under the flat tariff, the ranking depends on export credit: at the net-metering rate of about USD 0.13/kWh, solar-only becomes least-cost. Under the MERALCO General Service B tariff, which adds a demand charge, solar–BESS is the least-cost, with or without export credit. Solar–BESS remains least-cost across the tested ranges of the component cost, discount rate, project lifetime, tariff, and fleet size. The findings are specific to the modeled tariff, costs, and site.

Keywords: sustainable mobility; hybrid renewable energy system (HRES); electric vehicle charging stations (EVCS); levelized cost of electricity (LCOE); net present cost (NPC); battery energy storage; net metering

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1. Introduction

An increasing share of electric vehicle (EV) sales worldwide is linked to much higher energy demand forecasts over the next decade. Currently, Chinese automakers and companies such as BYD, Geely, and SAIC account for over 50% of global electric car sales [1] (p. 16), according to the International Energy Agency (IEA) 2026 Global EV Outlook (see Figure 1). Beyond passenger cars and electric bikes (including four-, three-, and two-wheeled vehicles), the shift toward electric transportation and mobility also includes public utility vehicles, especially in emerging markets such as ASEAN, South America, and Africa. Higher levels of air and noise pollution, along with rising fossil fuel costs in most markets, strengthen the case for electrification in public transportation networks. Moreover, most recent EV-related scientific publications call for more renewable-powered mobility modes [2,3]. This includes not only the aforementioned vehicles, but also public

works and infrastructure related to charging, such as EV-dedicated public chargers, parking spaces, e-bike sharing racks, and EV special privileges on highways—aligning with decarbonization and a broader reduction in the transportation sector's carbon footprint. Publicly available charging infrastructure across multiple regions is also projected to triple by 2035 [1] (p. 244). Specifically, in the Philippines, policy and development roadmaps for public EV charging infrastructure are aligned with a target of around 20,400 charging stations. This number is intended to account for about half (127,000 public charging points) of ASEAN's electric light-duty vehicle (LDV) stock, along with Malaysia, Singapore, and Thailand [1] (pp. 244–245). The International Energy Agency (IEA) also notes the Philippines' EV incentives, including excise tax exemptions for EVs and trade policies such as import tariff exemptions running until 2028 [1] (p. 211).

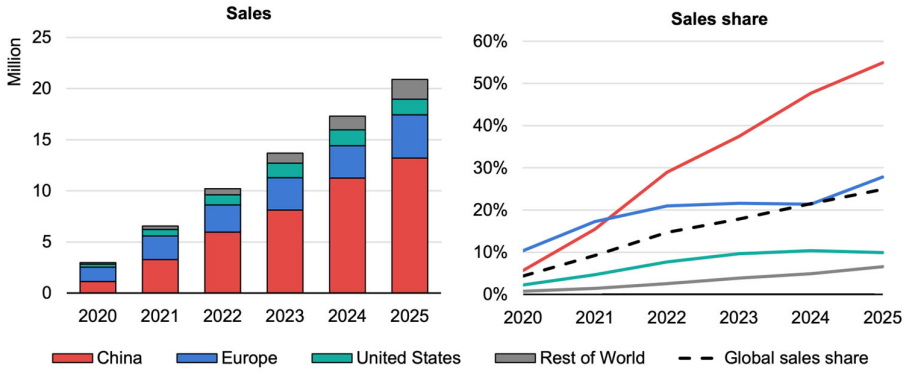


Figure 1. Electric car sales for 2020–2025, reported in IEA's Global EV Outlook [1] (p. 16).

This research focuses on the University of the Philippines Los Baños (UPLB) and its deployment of a fleet of smart bus (or EV minibus) units as part of its Green Mobility Initiative, known as eLBeep, which stands for Electric Light Bus for the Environment and Economy Partnership [4], as EVs for use as a public utility vehicle (PUV) service in the Philippines. A subsection in the next chapter provides detailed information on the smart bus under consideration and its serviced routes, along with other variables essential for evaluating the theoretical EVCS needed to charge the smart bus model.

2. Materials and Methods

2.1. General Objectives

Building on the growing demand for enhanced EV charging infrastructure and the UPLB Green Mobility Initiative's goals for sustainable transportation, this preliminary study systematically investigates and theoretically compares grid-connected scenarios for different EVCS configurations powered by renewable microgrids that utilize more than one energy resource. This paper focuses on developing HRES-based EVCS scenarios using UPLB and eLBeep as a case study. Specifically, this preliminary study also aims to:

1. Apply hybrid optimization techniques to identify scenarios with the most favorable economic outcomes for EVCS using HRES;
2. Test the robustness of the scenario ranking through sensitivity analyses of export credit, tariffs, component costs, discount rates, project lifetime, and fleet sizes;
3. Provide a detailed profile of the economics, emissions, and EV charging schedule of the least-cost scenario for the eLBeep service in Los Baños.

2.2. Scope and Limitations

This study uses data from the current operation of the eLBeep smart buses at the University of the Philippines Los Baños, including the battery and charger nameplates, the operator's published timetable, the published MERALCO tariff, and a site measurement from satellite imagery. The charging schedule is constructed from the fleet size and the ridership peaks and is not a measured load. This study does not address the battery health or degradation of the LFP packs in service, nor does it consider supplementing the battery energy storage system used by the existing Tipaklong EVCS.

Furthermore, this study does not include other currently available AssemblePoint SmartBus SB configurations or alternative charging systems that the smart bus model's LFP batteries may use.

2.3. Definition of Key Terms and Literature Review

This paper discusses a hybrid energy system, defined as a generation setup that combines two or more distinct energy sources or technologies to produce electricity, and occasionally heat, in a complementary and dependable manner. In essence, a hybrid energy system integrates multiple energy technologies to improve reliability, sustainability, and efficiency beyond what a single source can provide. A hybrid system may combine two or more energy sources or technologies (for example, solar and diesel, solar, battery and biomass, wind and hydro, etc.). For context in the following chapters, HRES stands for a hybrid renewable energy system, and EVCS stands for an electric vehicle charging station. The widespread adoption of various EV types plays a vital role in global efforts to reduce carbon emissions. Nonetheless, scaling up EV usage poses significant challenges for the current power grid infrastructure, especially in managing peak loads and ensuring capacity in remote or underdeveloped areas, such as the current eLBeep routes in Los Baños and Bay. As a result, this paper focuses on mainstream on-grid and hybrid renewable energy solutions for EV charging, with notable research and publications increasing in recent years. The following subsections consolidate recent studies emphasizing renewable energy integration, energy storage technologies, and prototype system designs tailored for HRES-powered EV charging applications.

2.3.1. Renewable Energy Hybrid Systems

A primary focus of current research is decoupling electric vehicle (EV) charging from fossil fuel-dependent utility grids by integrating renewable energy sources (RES), particularly solar photovoltaic (PV) and wind power systems [5]. Given the virtually infinite combinations of renewables available for consideration and simulation in this preliminary study, this paper explores using solar PV and wind as primary energy sources to charge the EV smart bus units currently operating on the UPLB–Jubileeville route. Recent studies have also demonstrated the effectiveness of solar PV systems in providing sustainable charging solutions [6,7]. EV adoption is increasing globally across sectors; diversifying energy sources to power charging systems is essential, and a one-size-fits-all solution may be neither viable nor a feasible research avenue. Yan et al. (2018) noted the rapid development of electric vehicle charging networks; however, research assessing their business value remains scarce [8]. Their study investigates the business valuation of electric vehicle charging networks within the Internet of Vehicles framework. By analyzing relevant evaluation metrics, system constraints, and available technologies, the study supports this paper in initializing scenarios anchored in a comprehensive three-dimensional value/cost system that encompasses economic, social, and environmental benefits to improve EVCS network operational performance. Table 1 presents the available resources and corresponding system constraints for powering the HRES-EVCS scenarios considered in this research.

Table 1. System constraints for technologies and resources for HRES-EVCS scenarios.

Resource Category	Screening Threshold or Input	Data Sources	Description
Solar resource	Solar capacity factor at ≥15%; global horizontal irradiation (GHI) at 4.57 kWh/m² per day in UP Los Baños	NASA POWER [9], PAGASA-DOST [10]	Annual average solar radiation data at 1 km spatial resolution
Battery energy storage system (BESS)	USD 18.55/kW-year commercial rate	US NREL [11] (now NLR)	NREL SETO O&M benchmark for commercial applications
Wind resource	Wind capacity factor at ≥20%	NASA POWER [9] Global Wind Atlas [12]	Annual average wind speed data at 1 km spatial resolution
Main electric grid with simple tariff	Philippine tariff rates and MERALCO average power prices	MERALCO [13]	Current per kilowatt hour price of electricity in UPLB
EV charging load	Power rating and LFP battery capacity	AssemblePoint SmartBus SB data specifications sheet [14]	Status quo with UPLB eLBeep service

2.3.2. Electric Vehicle Charging

Electric vehicles are integral to transitioning to energy-efficient transportation and sustainable mobility. The IEA reported in 2024 that lithium batteries and their derivatives accounted for nearly 50% of the global electric vehicle (EV) battery market, supporting manufacturers' efforts to reduce EV prices and production costs to maintain or grow their market share amid rising competition. China led LFP (lithium iron phosphate, or $LiFePO_4$) battery adoption, meeting almost three-quarters of its domestic battery demand that year. Its market share continued to rise, reaching 80% of batteries sold in November and December 2024 [15]. Moreover, as this paper also mentions LFP battery use in eLBeep, we highlight this trend and underscore the importance of optimizing EV charging schedules to improve battery technologies, including efficiency and performance. Most of this paper's cited literature offers concise overviews and aligns with the rapidly evolving electrified transportation sector, where the emphasis is shifting from feasibility to optimization and hybridization.

Standalone solar or wind systems are increasingly seen as inadequate for reliable off-grid EV charging, prompting the adoption of more sophisticated grid-connected hybrid solar–wind architecture, supported by advanced tracking algorithms and control systems. As technologies improve, EVs and charging stations continue to adapt to site-specific battery storage solutions. While lithium-ion and LFP batteries currently dominate stationary storage systems, ongoing research into flow batteries and hydrogen storage suggests future diversification. Additionally, this paper builds on previously cited literature [16–18] reporting successful prototyping of hybrid renewable energy systems (HRES) and electric vehicle charging stations (EVCS), with results validated through MATLAB R2026b simulations and hardware models. These findings support the hypothesis that HRES-powered electric vehicle charging is techno-economically feasible, provided intelligent control systems effectively manage variability in renewable sources.

2.3.3. EV Smart Bus Considered in This Research

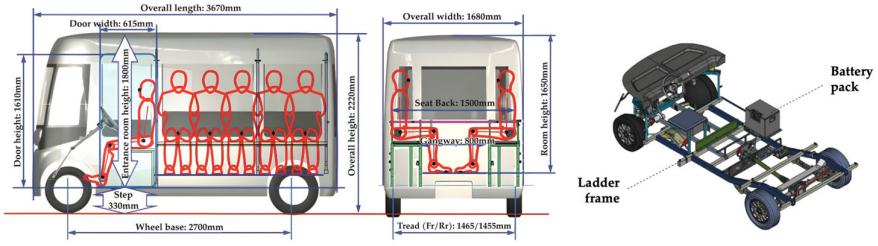
For consistency and brevity, we refer to the EV considered in this study as a "smart bus." Recognized as the first electric transportation system at any university in the Philippines, eLBeep is a hybrid name combining the colloquial term for Los Baños (Elbi) and the common designation for the Filipino jeepney (jeep). Deploying and integrating eLBeep units into the university's existing transport systems aims to promote environmental sustainability and eco-friendly transportation on the UPLB campus. Figure 2a shows the

smart bus in this study as an eLBeep service at the Jubileeville passenger terminal in Bay, Laguna, Philippines.

The smart bus model is classified as a commercial low-speed vehicle (LSV) manufactured by AssemblePoint Philippines Inc., the Philippine subsidiary based in Carmona City, Cavite, Philippines, whose parent Japanese company (AssemblePoint Co. Ltd.) is headquartered in Minato, Tokyo, Japan. Figure 2c displays the orthographic and chassis views of the smart bus PUV configuration, while Table 2 presents its technical specifications as a PUV. Aside from UPLB, as of August 2026, the AssemblePoint SmartBus SB model is also serving local government units in the region, as well as private companies and public institutions for similar MaaS (mobility-as-a-service) initiatives [19]. As of October 2026, no literature, publications, or scientific articles address this specific EV or any of its other configurations.



(**a**)



(**b**) (**c**)

Figure 2. (**a**) The EV smart bus model (AssemblePoint SmartBus SB) at the Jubileeville passenger terminal in Bay, Laguna, Philippines, which mainly serves the UP Rural High School community; (**a**) photo taken in February 2025 by the authors, (**b**) orthographic views, and (**c**) chassis frame view of the AssemblePoint EV smart bus showing an 11-passenger, 1-driver PUV configuration [20].

From November 2024, the SNODLOB (an acronym for Samahan ng Nagkakaisang Drivers at Operators ng Los Baños in the Tagalog language, or the Los Baños United Drivers and Operators Association in English) is the official operator and franchise holder of the eLBeep service, which initially facilitated transit between the main campus of UPLB and the University of the Philippines Rural High School (UPRHS) in Paciano Rizal, Bay, Laguna. This eLBeep route is approximately six kilometers long (6.0 km), as shown in Figure 3, which illustrates the spatial connection between UPLB and UPRHS. The route is referred to here as the UPLB–Jubileeville route, after its two terminals: the UPLB main campus terminal at the old Maquiling School campus, and the Jubileeville terminal in Bay. Primary users/passengers include students, faculty, and staff from both institutions, as well as residents of Jubileeville—a nearby residential subdivision primarily inhabited by UPLB personnel and the location of the eLBeep terminal (Figure 2a). Historically, traditional jeepneys served this transportation link, each powered by a single diesel internal combustion engine (ICE). As of October 2026, the SNODLOB is awaiting new

AssemblePoint smart bus units and will deploy them on additional routes outside the UPLB main campus, including a loop route to and from UPRHS in Bay.



Figure 3. The 6 km UPLB–Jubileeville route of the eLBeep service between the UPLB main campus terminal (old Maquiling School campus, Los Baños) and the Jubileeville terminal (Bay), both in the province of Laguna, Philippines.

The smart bus prototyping and design complied with the United States Low Speed Vehicle standard (FMVSS 500). As of this paper's writing, the smart bus operator still lacks dedicated EV charging infrastructure to support smart bus operations and the eLBeep service. By comparison, private users of this smart bus model rely on off-board, on-grid charging, either powered exclusively by solar panels or by non-renewables. The smart bus' rechargeable, removable (and interchangeable) $LiFePO_4$ battery system is currently recharged at a battery charging station in Baker Hall on the UPLB campus (see Figures 3 and 4). This station presently has eight solar photovoltaic panels rated at 0.5 kW each and serves as a 100% solar-powered electric vehicle charging station (EVCS) for the Tipaklong electric bike-sharing service, another venture integral to the UPLB Green Mobility Initiative, along with eLBeep. This EVCS connects directly to UPLB's main electrical grid, which mainly sources power from the nearby Makiling–Banahaw Geothermal Power Plant. This power plant is part of the Luzon Island grid's renewable energy mix. As a smart bus operator, SNODLOB reimburses Tipaklong for charging its eLBeep batteries. Since early 2025, eLBeep, as a service, has paralleled an urgent need to develop a reliable EVCS to improve operational sustainability, reduce dependence on third-party charging services, and achieve self-sustaining electricity generation for EV charging. Figure 4 shows the solar-powered Tipaklong EV battery charging station. The station charges four battery packs simultaneously using 2.9 kW chargers (58.4 V and 50 A DC output, with at least 93% efficiency) on standard 220 V A sockets. Each smart bus carries one pack, and the fleet holds no spare packs.

Although this paper focuses on the AssemblePoint SmartBus SB, the EV model is used not only by UPLB but also by other institutions in the Philippines across the public and private sectors [21], including the Philippine Congress in Manila and the International Rice Research Institute (also located in the municipality of Los Baños). The objectives of this study also align with diversifying possible EV charging infrastructure scenarios that future EV smart bus models may use, which is significant for empowering the Philippine public transportation sector. Moreover, the same AssemblePoint smart bus model is

currently operating in Accra, Ghana, as a campus transportation minibus service for the University of Ghana [22]. A possible demonstration of this AssemblePoint smart bus configuration is also planned in Makassar City, Indonesia, for the 2027 fiscal year as part of a collaboration project with the Yokohama City government, Japan [23].



Figure 4. Solar PV panels of the Tipaklong e-bike and battery charging station at the UPLB Baker Hall (photo taken in February 2025 by the authors).

Table 2. Technical specifications of the smart bus considered for this paper.

Specifications [1]	Parameter	Values
Crew constant	Passenger + driver count	11 on board (10 + 1)
Dimensions	Length	3670 mm
	Width	1680 mm
	Height	2220 mm
	Room height	1650 mm
	Entry/exit height	1815 mm
Wheelbase		2700 mm
Tread	Front wheels (2)	1466 mm
	Rear wheels (2)	1455 mm
Curb weight		600 kg (empty bus)
Tire	Front	165/65/R14
	Rear	165/65/R14
Minimum turning radius		5.3 m
Battery	Capacity	5.376 kWh (51.2 V, 105 Ah; removable)
	Format: $LiFePO_4$	48 V class (51.2 V nominal)
	Charging time (20% to full, 2.9 kW charger)	About 90 min
	Charger	58.4 V, 50 A DC (2.92 kW); efficiency ≥ 93%; input ≤ 14.5 A at 200–240 V AC
Performance	Maximum speed (with speed limiter)	40 km/h
	Electricity consumption	12.1 km/kWh
	Cruising range (manufacturer statements)	50 to 60 km typical; 70 km maximum
Window material		Resin

[1] Specifications and corresponding values are listed as of November 2026. Battery and charger values are from the equipment nameplates; the cruising range is from the manufacturer's published statements [24,25].

2.4. Objective Functions

This study mainly follows published documentation for hybrid optimization and simulation. The aim is to determine the minimum net present cost (NPC) and levelized cost of electricity (LCOE) for theoretical EVCS-HRES scenarios through hybrid optimization. Equations (1) and (2) define the NPC and LCOE. Generally, the NPC is the

summation of all system costs over the project lifespan, minus the present value of all revenue the HRES earns over its lifespan. $C_{0,i}$ is the capital expenditure (CAPEX) of the HRES component i at year 0.

$$NPC = \sum_{HRES\ components} \left[C_{0,1} + \sum_{n=1}^{t} \frac{C_{n,i}}{(1+r)^n} \right] \quad (1)$$

$C_{n,i}$ is the cost of component i in year n, comprising operation and maintenance (O&M), replacement, and grid purchase costs, less the salvage value and any export revenue. The variables r and t are the discount rate and the project lifetime, respectively. In this paper's energy system analysis, LCOE (levelized cost of energy, as used in other literature) is defined in Equation (2).

$$LCOE = \frac{C_{ann,tot} - C_{boiler} H_{served}}{E_{served}} \quad (2)$$

The LCOE is the average cost per kWh of energy served. $C_{ann,tot}$ is the system's total annualized cost (USD/yr), and E_{served} is the energy served (kWh/yr). HOMER Grid counts both the charging load and the energy exported to the grid as energy served. Because exports earn nothing in the baseline, this study also reports the cost per kWh of the charging load, which divides the same annualized cost by the charging load alone. NPC is used to rank the scenarios and assess long-term financial viability, and LCOE is used to compare the cost per unit of energy. Emissions are simulated to measure the environmental effect of each scenario.

Using hybrid microgrid simulation software (HOMER Grid), this study aims to optimize system configurations for grid-connected EV charging stations partially supplied by on-site renewable sources. The NPC is defined as the sum of all energy system expenses over the EVCS-HRES project lifespan, minus the present value of all revenue generated by the hybrid system during this period. Key variables influencing the NPC include the CAPEX, annualized costs, discount rate, and total component count. We evaluate these variables across multiple simulation scenarios. Additionally, the LCOE is a key performance metric representing the average cost per kilowatt-hour of delivered energy. For the analysis, we set the parameters specific to hybrid systems supporting both electrical and thermal loads to the default values in the hybrid optimization software. Figure 5 illustrates the methodological framework underpinning this research.

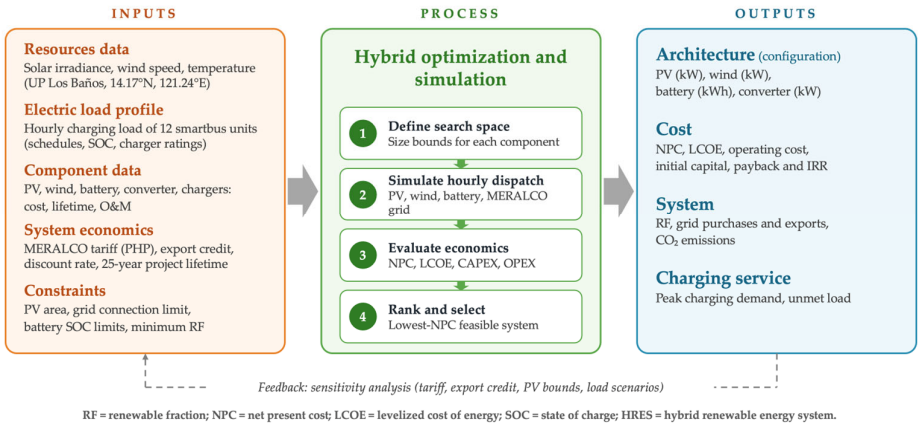


Figure 5. Methodological framework of this study.

Figure 6 visualizes recent studies anchored in HOMER optimization and simulation [26–30] with concrete NPC and LCOE values. Roslan et al. simulated a grid-connected HRES with solar PVs, wind, batteries, hydrogen, and fuel cells across potential locations in Malaysia, and recommended extending their research by using load-forecasting

algorithms for recharging to enable multiyear analyses [26]. In the same year, Das et al. assessed grid-integrated EVCS powered by solar–wind HRES as a case study [27] for coastal cities in Bangladesh and used a derivative-free algorithm for comprehensive analysis. Similarly, Guven et al. conducted their 2025 study [28] on a university campus in Turkey using meteorological data and minimizing the LCOE and NPC across simulated scenarios by benchmarking four metaheuristic algorithms under identical conditions. In contrast, they proposed a replicable optimization framework that was adaptable to areas with high utility tariff rates and renewable integration targets. In 2024, Palanisamy et al. also simulated six standalone HRES configurations using solar, wind, and biomass, including a grid-tied HRES in Chennai, India, that used a single EVCS with hydrogen refueling [29]. Lastly, the 2026 study by Akram et al. compared urban and remote scenarios for HRES-EVCS architecture in Canada, finding that a fully renewable, zero-emission off-grid charging station was feasible, though remote sites cost more. The study also noted that site-specific design matters more than economics, and that certain parameters can improve HRES performance. Their sensitivity analysis found that taller wind turbine hub heights and longer solar PV panel lifespans improved HRES performance [30].

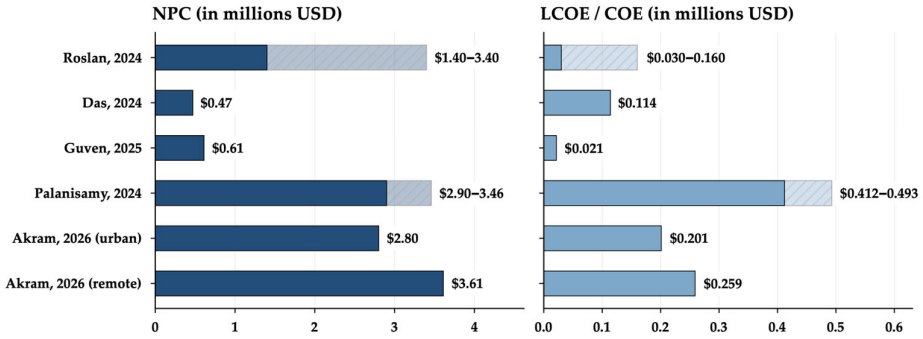


Figure 6. Comparison of NPC and LCOE values of six recent and significant HOMER-based HRES-EVCS studies [26–30].

Generally, NPC (life cycle cost in some literature) is the present value of all installation and operating costs over the HRES lifetime, minus the present value of all revenue earned over the project lifetime. LCOE is the average cost per kWh of useful electrical energy produced by the HRES. In optimization, the calculated operating cost is the annualized value of all costs and revenue, excluding the initial capital costs. IRR, or the internal rate of return, is the discount rate at which the base case in HOMER optimization and the current system have the same NPC. HOMER calculates the IRR by finding the discount rate that makes the present value of the difference between the two cash flow sequences equal to zero.

The initial selection of the HRES-powered EVCS location for the eLBeep units considered the current and future sites identified and projected by the UPLB Green Mobility Initiative. As of September 2026, the eLBeep units' removable batteries are still charged off-board via the dedicated Tipaklong solar-powered charging station shown in Figure 4, which is grid-connected at UPLB Baker Hall. In HOMER Grid, the exact location (14°09′55.72″ N 121°14′37.38″ E) on the UPLB campus served as the default geolocation pin upon initialization. Other inputs include a nominal discount rate of 8%. This is a reasonable assumption for a private/academic EVCS project and reflects typical benchmark rates and a small risk premium that is consistent with the guidelines set by the Bangko Sentral ng Pilipinas (BSP, or the Philippine Central Bank in English). The expected inflation rate is set to 3.5% for long-term planning and aligns with the BSP inflation bracket [31]. Together, these provide a real discount rate of 4.35%. No tax incentive, grant, or

depreciation benefit is applied. Costs are in US dollars; peso-denominated tariff components are converted at PHP 59.41 per USD, the BSP monthly average for March 2026 [32], and exclude value-added tax. Appendix A lists every model input.

For the project lifetime, this study uses a typical PV lifetime of 25 years, with converters (15 years) and battery storage (up to 15 years) replaced once during the project lifetime. Section 3.9 reports 20-year and 30-year cases. Table 3 separates the measured and published inputs to the model from the synthetic ones, and Table 4 summarizes the operator's timetable, which is used to check that the charging schedule is compatible with the service.

2.5. Hybrid Optimization Processes

This paper's research approach simulated the optimal system for an HRES-powered EVCS for eLBeep using HOMER Grid version 1.11.7 [33]. Future electricity costs (as a monthly utility bill) were based on SNODLOB's projected payments for electricity used in EV charging. The significance of using HOMER Grid as the primary optimization tool in this paper stems from its generator and converter modeling, which supports peak shaving, energy efficiency, and scheduling. Guven et al. [34] used HOMER Grid to propose an economic optimization framework for campus-scale HRES integrated with EVCS, evaluating nine HRES configurations and five EVCS profiles using LCOE and annual CO_2 emissions. In comparison, Yadav et al. [35] assessed 26 sites for the viability of solar PV, wind, and BESS-based EVCS and found solar–battery configurations to be the most cost-effective in terms of LCOE. Other studies [36–39] in the Middle East also use hybrid optimization for various site-specific system architectures and energy resources in HRES-EVCS sizing, project economics, and sensitivity analyses. Table 5 lists the most recent HOMER-based studies and significant research as references for this paper's methods.

Table 3. Measured, published, and synthetic inputs to the model.

Input	Basis	Source
Battery pack: 51.2 V, 105 Ah, 5.376 kWh	Measured	AssemblePoint SmartBus SB battery pack nameplate
Charger: 58.4 V, 50 A DC (2.92 kW), efficiency ≥ 93%	Measured	AssemblePoint SmartBus SB charger nameplate
Service timetable: 69 one-way trips per day	Measured	SNOBLOB timetable (September 2025)
Site area: 531 m^2 (1032 m^2 with the adjoining court)	Measured	Satellite imagery (March 2026) [40]
Tariff, export credit, and exchange rate	Published	MERALCO [13,41]; BSP [32]
Grid emission factor	Published	Philippine Department of Energy [42]
Charging schedule: 36 sessions per day in three blocks	Synthetic	Constructed from fleet size and ridership peaks
Solar, wind, and temperature series	Synthetic	Hourly series generated by HOMER Grid from NASA POWER monthly means [9]
PV, storage, converter, and wind turbine	Generic	HOMER Grid library models with cited costs

Table 4. Summary of the UPLB–Jubileeville timetable (1–5 September 2025) and the buses needed in service.

Window	One-Way Trips	Typical Headway per Direction	Buses Needed in Service [1]
06:00 to 08:59	18	10 to 20 min	4 to 5
09:00 to 15:59	28	30 min	2
16:00 to 20:00	23	15 to 30 min	3–4
Whole day	69	-	5 at most

[1] Assumes a 50 min round trip on the 6 km route, including a layover.

Table 5. Most recent HOMER-based studies and prior relevant research on HRES-EVCS.

Year	Country	Title or Theme	Key Findings or Significance	Reference
2026	Turkey	Techno-economic optimization of renewable-integrated EV charging in campus microgrids with heterogeneous charging behaviors	Optimization of nine configurations across 45 scenarios; most current multi-technology HOMER Grid study	[34]
2026	India	Techno-economic and policy analysis of solar–wind powered EV charging for sustainable e-mobility	Its literature review is also a useful map of earlier HOMER-based EVCS studies	[35]
2025	Egypt	Design and techno-economic feasibility study of a solar-powered EV charging station in Egypt	Authors reported that the optimal configuration is about USD 10.23M over 25 years, with annual utility-bill savings of roughly USD 409,326	[36]
2025	Turkey	Sustainable hybrid systems for EV charging infrastructures in regional applications	Used HOMER to raise the renewable share in local EVCSs and buildings and cut CO_2 emissions	[37]
2024	Saudi Arabia	Evaluating the techno-economic viability of a PV–wind–battery hybrid system for an EVCS in Khobar, Saudi Arabia	Paper employed HOMER to evaluate the sizing, cost, and control strategy of the hybrid system	[38]
2025	Jordan	HOMER Grid study of solar-powered EVCS along Jordanian highways	Addresses gap in planning renewable-powered EV charging stations along Jordanian highways	[39]

Two features distinguish the present study from those in Table 5. First, it is a case-specific planning study of a minibus fleet with removable battery packs, scaled up from an existing 4 kW solar charging station. The battery, charger, timetable, and site inputs are drawn from nameplates and operating records. Second, it tests the results against the utility's tariff structure and net-metering credit, as well as component costs. It claims no methodological advance. Separate lines of work plan charging infrastructure at the network level and include vehicle-to-grid (V2G) capability. Alizadeh et al. [43–45] jointly optimize the location, sizing, and operation of charging stations and battery storage across a distribution network, with power losses, operating costs, and reliability as objectives. The present study works at a different level: it sizes supply for one station whose location and fleet are given. It asks which combination of on-site generation and storage yields the lowest lifetime cost.

The charging load is modeled using the HOMER Grid EV charger component [33,46]. The station has six charging points rated at 3 kW. Each charging point is a 2.9 kW charger (58.4 V and 50 A DC output, efficiency of at least 93%) on a standard 220 V AC socket, the same unit used at the existing Tipaklong station. A session draws 2.9 kW for 90 min, or 4.35 kWh at the plug, which, at 93% charger efficiency, returns 4.05 kWh or 75% of the 5.376 kWh pack (from 25% to full). Thirty-six sessions are scheduled per day, three for each of the twelve buses, in three blocks placed between the ridership peaks: 8 to 11 AM, 1 to 4 PM, and 8 PM to 2 AM. Six charging points cannot always serve consecutive batches of 90 min sessions without overlap; therefore, the simulated year contains 11,952 sessions (32.7 per day, about 91% of those scheduled) and 51.98 MWh. No generic HOMER charger profile was used.

Each bus carries one 5.376 kWh pack, and the fleet holds no spare packs; therefore, a bus is out of service while its pack recharges. With six charging points, half of the fleet charges for 90 min while the other half remains in service, and the two groups switch places within each three-hour block. The timetable (Table 4, Figure 7) requires, at most, about five of the twelve buses at once; therefore, every timetabled trip can be run while half of the fleet charges. One session returns 75% of the pack, which, at the typical range of 50 to 60 km per full charge [24], covers about 38 to 45 km, or six to seven one-way trips on the 6 km route. The packs are removable, but the model does not rely on swapping: a spare pack inventory would allow charging to move into the solar hours and be left for future work. The modeled load of 36 sessions per day represents full use of the fleet, which is equivalent to about 3.3 buses on every timetabled trip, and is therefore an upper bound. Section 3.9.4 tests a lower level of demand derived from the timetable.

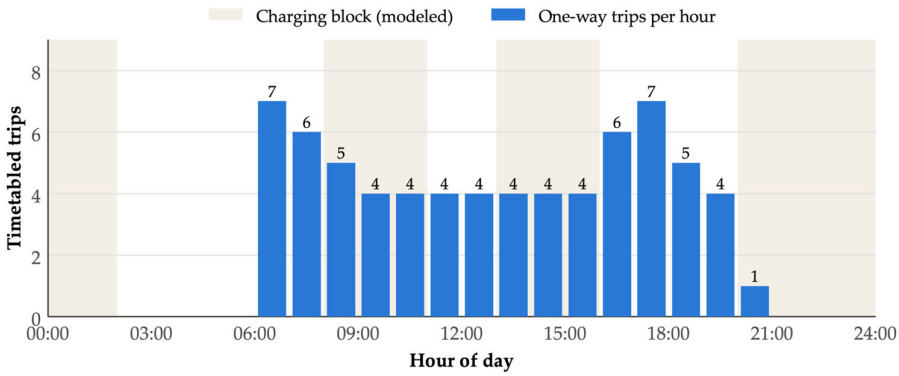


Figure 7. Timetabled one-way trips per hour on the UPLB–Jubileeville route (1–5 September 2025) and the three charging blocks of the modeled schedule (shaded).

Figure 8 shows the schematic of the grid-connected system. PV and storage are on the DC bus; the wind turbine, charging points, and the grid connection are on the AC bus; and a bidirectional converter links the two buses. HOMER Grid simulates the system at a 60 min time step using its peak-shaving dispatch and ranks all feasible configurations in the search space by NPC. Section 3 presents the results.

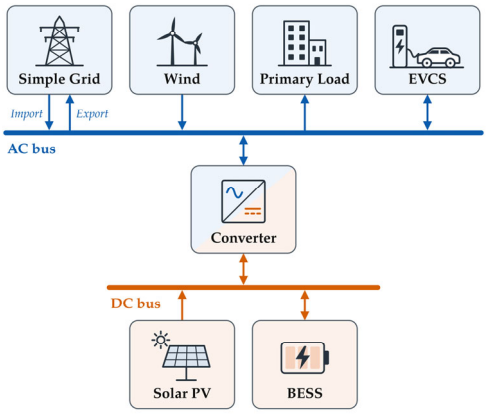


Figure 8. Schematic diagram for a grid-connected HRES-powered EVCS.

The PV search space is limited to 60 kW. This is a site constraint, not an economic one. At a module efficiency of about 20%, 60 kWp requires about 300 m² of module area. The former basketball court beside the UPLB main campus terminal, at the old Maquiling School campus, measures 531 m² (Google Earth Pro, imagery of 10 March 2026 [40]) and can host a ground-mounted array of this size at the 14º design tilt. The limit also keeps the system under the 100 kW ceiling for net-metering eligibility in the Philippines [41,47–49]. The constraint does not bind in the baseline, where NPC is lowest at 40 kW and is USD 629 higher at 50 kW and USD 4881 higher at 60 kW. It binds when exports are credited and for a 16-bus fleet. A larger array could extend onto the adjacent volleyball court, bringing the open area to 1032 m²; tree cover around the court means that shading losses would require a site survey, or a new passenger terminal location would need to be chosen.

3. Results and Discussion

This chapter presents all simulation and optimization results for an EVCS serving the eLBeep smartbus units at UPLB. This section presents the smartbus fleet charging and

HRES scenarios, generating project economics and emissions for parametric analysis. An initial characterization of the charging load is necessary to establish the grid-only baseline and to provide a techno-economic comparison of the five optimized grid-connected configurations as HRES-EVCS scenarios. This section also highlights the operating behavior of the least-cost system in terms of NPC and utility savings, its environmental performance (CO_2 emissions), and the main reasons for underperformance in select scenarios. The section closes with the limitations of the present analysis, considering the current count of 12 AssemblePoint SmartBus SB units and a proposed EV charging station at the UPLB main campus terminal (the old Maquiling School campus).

3.1. Charging Load Characteristics

The simulated charging load averages 142.4 kWh/day (4332 kWh/month) and totals 51.98 MWh/year (Table 6). Six charging points serve 32.7 of the 36 scheduled sessions per day (91%); the remaining sessions queue beyond the end of a charging block. The annual peak demand of 17.4 kW occurred on 17 January, and Figure 9 shows the load profile for that day, along with the annual mean by hour. The charging blocks fall within eLBeep's peak ridership hours (6–8 a.m., 11 a.m.–1 p.m., and 4–8 p.m.; compare Figure 7). Figure 10 shows the load as a heat map. The mean demand is 5.93 kW, yielding a load factor of 0.34 and a crest factor (peak over root mean square demand) of 2.05.

Table 6. Site and charging load summary.

Parameter	Value
Location	UPLB, Los Baños, Laguna, Philippines
Coordinates	14°09.95′ N, 121°14.63′ E
Average daily consumption	142.4 kWh/day
Average monthly consumption	4332 kWh/month
Annual consumption	51.98 MWh
Session served	11,952 per year (32.7 of 36 scheduled per day)
Annual peak demand	17.40 kW (17 January)
Mean demand	5.93 kW
Load factor	0.34
Crest factor (peak/RMS)	2.05

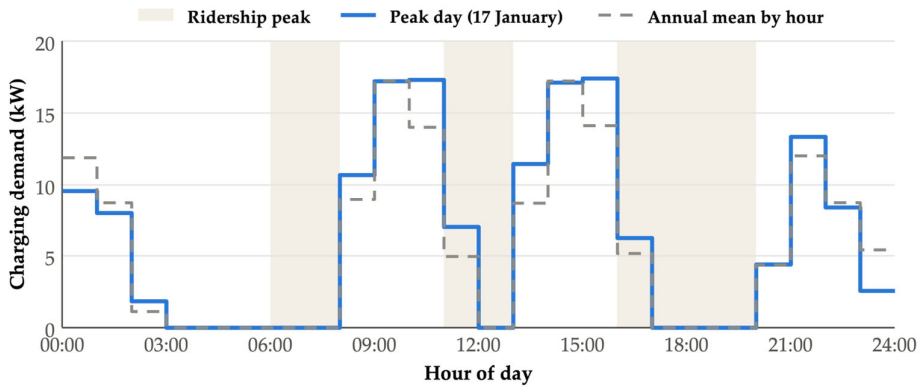


Figure 9. Charging load on the annual peak (17 January) and the annual mean by hour; shaded bands mark the weekday ridership peak of the eLBeep service.

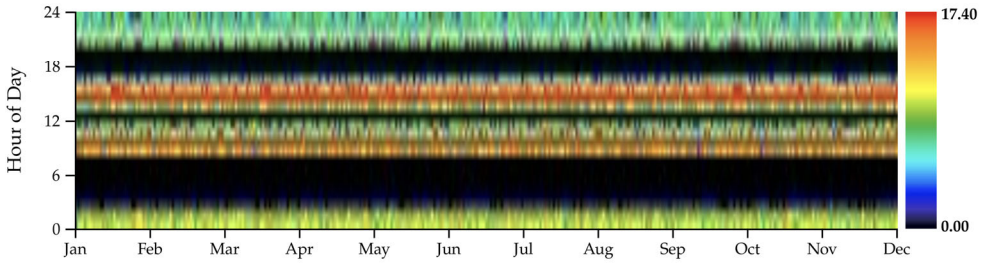


Figure 10. Heat map showing energy consumption patterns of the EVCS.

Table 7 outlines the five grid-connected scenarios compared with the grid-only base case. In each scenario, the optimizer sizes the listed components within the specified search space and selects the configuration with the lowest NPC. The main grid is MERALCO, the distribution utility serving the UPLB campus, which draws power from the Luzon grid.

Table 7. Scenario definition: architecture, components sized by the optimizer, and search space.

Scenario Number	Architecture	Schematic	Components Sized	Search Space
Base case	Grid		None	–
1	Solar–BESS–grid		PV, BESS, converter	PV 0–60 kW; BESS 0–150 kwh; converter 0–40 kW
2	Solar grid		PV, converter	PV 0–60 kW; converter 0–40 kW
3	Solar–wind–BESS–grid		PV, wind, BESS, converter	As Scenario 1, with 10 kW turbines (0–2)
4	BESS–grid		BESS, converter	BESS fixed at 30 kWh; converter 0–40 kW
5	Solar–wind–grid		PV, wind, converter	As Scenario 2 with 10 kW turbines (0–2)

The daily profile (Figure 9) consists of three charging blocks: a morning block from 8 to 11 AM, an afternoon block from about 1 to 4 PM, and a night block from about 8 PM to 2 AM the following day. Demand is nearly zero from 3 to 7 AM and from 5 to 7 PM, when the buses are in service. Each block delivers about 47 kWh at the plug on average. The heat map in Figure 10 shows the same three-block pattern every day of the year, and monthly consumption varies only between 4006 kWh (February) and 4486 kWh (August), which largely reflects the number of days per month. Two of the three blocks coincide with daylight hours, which favors direct solar supply, while the night block can be served only by storage or the grid.

3.2. Grid-Only Baselining

Under the grid-only base case, annual electricity costs were USD 12,475, with monthly bills from USD 962 (February) to USD 1077 (August). The baseline tariff is a flat energy charge of USD 0.24/kWh with no demand charge, fixed charge, or export credit. This is a simplification: a customer with 5 to 40 kW of demand is billed by MERALCO under General Service B, which carries demand and fixed charges [13]. The flat tariff is kept as the baseline because it isolates the energy value of on-site generation, and Section 3.9.3 repeats the optimization under the General Service B schedule. Gross emissions of the base case are 38.7 t CO_2/yr, from 51.98 MWh of purchases at the Philippine Department of Energy grid emission factor of 0.7446 t CO_2/MWh [42]. Under the flat tariff, on-site resources have one source of value, which is displacing purchased kilowatt-hours; peak shaving and energy arbitrage have no monetary value (Scenario 4).

3.3. Optimized Configurations and Techno-Economic Comparison

Hybrid optimization returned the optimal sizing for the five grid-connected scenarios (Table 8, hereafter denoted Scenario 1 (solar–BESS), Scenario 2 (solar only), Scenario 3 (solar–wind–BESS), Scenario 4 (BESS only), and Scenario 5 (solar–wind), where BESS denotes the simulated lithium-ion battery energy storage system. All scenarios keep the energy systems connected to the grid under the same tariff. Table 8 lists their component sizes and capital costs, and Table 9 summarizes their economic and environmental indicators over the 25-year project lifetime.

Table 8. Scenario comparison table for the HRES configuration, NPC, and LCOE.

Scenario Number	Architecture	NPC (USD)	LCOE, HOMER (USD/kWh)	PV (1 kW)	Wind (10 kW Long Rotor)	Battery (1 kWh Li-ion)	Converter (kW)	CAPEX (USD)	Component O&M (USD/yr)
Base case	Grid only	187,919	0.240	—	—	—	—	0	—
1	Solar–BESS	123,919	0.138	40	0	72	20	57,600	1032
2	Solar only	141,713	0.130	40	0	0	20	36,000	600
3	Solar–wind–BESS	173,196	0.183	40	1	71	20	97,300	1826
4	BESS only	206,038	0.263	0	0	30	10	11,500	220
5	Solar–wind	192,210	0.186	30	1	0	15	67,250	1250

Table 9. Economic and environmental indicators of the optimized configurations for a 25-year project lifetime.

Indicator	Base Case	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
CAPEX (USD)	0	57,600	36,000	97,300	11,500	67,250
Annual OPEX (USD/yr)	12,475	4403	7018	5039	12,915	8296
Annual utility bill (USD/yr)	12,475	2771	6330	2129	12,475	6528
Component O&M (USD/yr)	0	1032	600	1826	220	1250
Replacement net of salvage (USD/yr)	0	600	88	1084	219	518
Annual bill savings (USD/yr)	—	9704	6145	10,347	0	5947
Net annual savings (USD/yr)	—	8073	5457	7437	−439	4180
Simple payback (yr)	—	6.6	6.5	11.4	Not available	14.7
Discounted payback (yr)	—	8.0	7.8	16.3	Not available	Not reached
IRR (%)	—	14.6	14.8	6.7	Not available	3.7
LCOE, HOMER (USD/kWh)	0.240	0.138	0.130	0.183	0.263	0.186
Cost per kWh of charging load (USD/kWh)	0.240	0.158	0.181	0.221	0.263	0.245
Net present cost (USD)	187,919	123,919	141,713	173,196	206,038	192,210
Gross CO_2 emissions (t/yr)	38.7	8.6	19.8	6.6	38.7	20.3
Net CO_2 emissions (t/yr)	38.7	3.0	4.3	−1.5	38.7	7.9

All scenarios use generic flat-plate PV modules at USD 800/kW installed, with an O&M of USD 13/kW per year. Wind scenarios use a generic 10 kW turbine at USD 40,000, and storage scenarios use generic 1 kWh lithium-ion units at USD 300 kWh, with replacement at USD 200 kWh and an O&M of USD 6/kWh per year. Converter costs range from USD 2500 for 10 kW to USD 7350 for 40 kW. The itemized installed costs sum to the reported CAPEX; for Scenario 1, these are USD 32,000 for PV, USD 21,600 for storage, and USD 4000 for the converter. Annual OPEX is the utility bill plus component O&M plus

the annualized replacement cost net of salvage (Table 9), and the net annual savings are the base-case OPEX minus the scenario OPEX. Appendix A lists all inputs.

Ranked by NPC, Scenario 1 is the least-cost configuration at USD 123,919, 34.1% (USD 64,000) below the base case (Figure 11). Scenario 2 ranks second at USD 141,713 (24.6% below), and Scenario 3 is 7.8% below. Scenarios 4 and 5 have NPCs above the grid-only case by 9.6% and 2.3%, respectively. HOMER's LCOE divides the annualized cost by the load served plus the energy exported; therefore, the configurations that export more appear cheaper per kilowatt-hour: Scenario 2 has the lowest HOMER LCOE (USD 0.130/kWh, against USD 0.138/kWh for Scenario 1), although its NPC is higher. Per kilowatt-hour of charging load, Scenario 1 costs USD 0.158 and Scenario 2 USD 0.181, and all scenarios rank in the same order as by the NPC (Table 9). Scenario 1 recovers its USD 57,600 investment in 6.6 years (8.0 years discounted), with an IRR of 14.6%; its bill savings of USD 9704 per year have a present value of about 146,000 over the project lifetime.

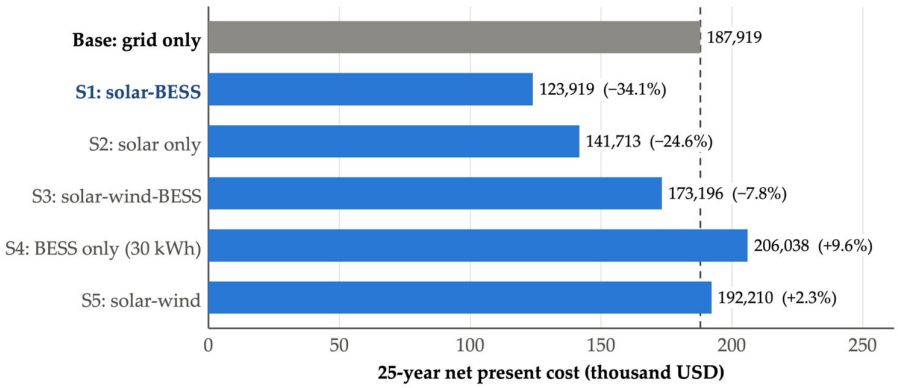


Figure 11. The 25-year NPC for each scenario; the dashed line marks the grid-only base case; and the percentages provide the differences.

3.4. Solar Only vs. Solar–BESS

The optimizer selects the same 40 kW array for Scenarios 1 and 2; therefore, the two differ only by the 72 kWh battery. Adding the battery raises the capital cost by USD 21,600 and net annual savings by USD 2616, yielding a simple payback of 8.3 years on the incremental investment and lowering the NPC by USD 17,794. Storage also lowers the NPC at every other PV size tested between 10 and 60 kW. Scenario 2 has a marginally higher IRR (14.8% against 14.6%) and a slightly shorter payback because it requires less capital. For mutually exclusive projects of different scale, where capital is not rationed, the present-value criterion is the appropriate basis for selection; therefore, Scenario 1 is preferred under the baseline assumptions. The battery's value lies in increasing on-site use of solar energy. Table 10 summarizes the annual energy exchanged with the grid.

Table 10. Annual grid exchange, on-site supply, and CO_2 emissions of each scenario.

System	Grid Purchases (MWh/yr)	Grid Exports (MWh/yr)	Load Met on-Site (%)	Gross/Net CO_2 (t/yr)
Base case	51.98	0	0	38.7/38.7
Scenario 1	11.55	7.47	77.8	8.6/3.0
Scenario 2	26.38	20.58	49.3	19.6/4.3
Scenario 3	8.87	10.89	82.9	6.6/−1.5
Scenario 4	51.98	0	0	38.7/38.7
Scenario 5	27.20	16.61	47.7	20.3/7.9

The base case grid purchases (51.98 MWh/yr) equal the charging load. Scenario 2 exports 20.6 MWh/yr, 38% of its PV generation, because much of its midday output exceeds the charging demand. Scenario 1 exports 7.5 MWh/yr from the same array and supplies 77.8% of the load on site, compared with 49.3% for Scenario 2. The share of load met on site is one minus purchases over load; HOMER's renewable fraction, which also counts exports, is 80.6% for Scenario 1. Because the baseline tariff has no export credit, the reduction in the utility bill equals the share of load met on site. The 40 kW array produces 54.1 MWh/yr, a capacity factor of 15.5% (1354 kWh/kWp).

3.5. Operating Behavior of the Least-Cost Scenario (Solar–BESS)

Figure 12 shows the dispatch for Scenario 1 on the peak day, 17 January. Solar output covers the morning block and charges the battery by noon. The battery then supplies most of the afternoon block and the first two hours of the night block before reaching its 20% floor at 10 PM. Afterward, the grid supplies the remaining load until about 2 AM. About 2.5 MWh/yr (4.7%) of the PV output is lost at the 20 kW converter limit. Over the year, the battery completes 226 equivalent full cycles and has an expected life of 13.2 years; therefore, one replacement falls within the project. About 65% of the remaining grid purchases occur between 9 PM and 2 AM. Monthly bills under Scenario 1 range from USD 66 (April) to USD 329 (August), against USD 962 to 1077 for the base case (Figure 13a). Bills are lowest from February to May and highest from July to December, consistent with the dry season and the cloudier southwest monsoon season in Luzon [10]. The system exports between 419 and 1006 kWh each month, with the largest exports in March and April (Figure 13b).

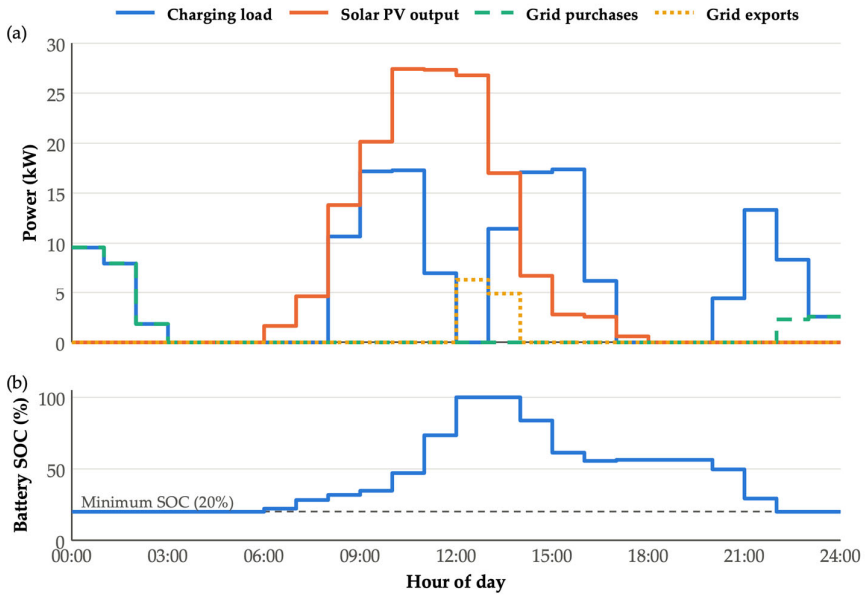


Figure 12. Dispatch of Scenario 1 on the annual peak day (17 January): (**a**) charging load, PV output, grid purchases, and grid exports; (**b**) battery state of charge.

Exports earn nothing in the baseline. Under the Philippine net-metering program for systems up to 100 kW, exports are credited against the consumer's bill [41,46] at the utility's blended generation cost, not the retail rate. Crediting exports would increase savings across all solar configurations, with the largest gains in Scenario 2, which exports nearly three times as much as Scenario 1; Section 3.9.1 quantifies this effect. The peak grid draw under Scenario 1 remains 17.2 kW because the night block still runs partly on grid

power after the battery is empty. Without a demand charge, the dispatch has no incentive to reduce peaks; Section 3.9.3 shows that under a tariff with a demand charge, the same battery earns additional value.

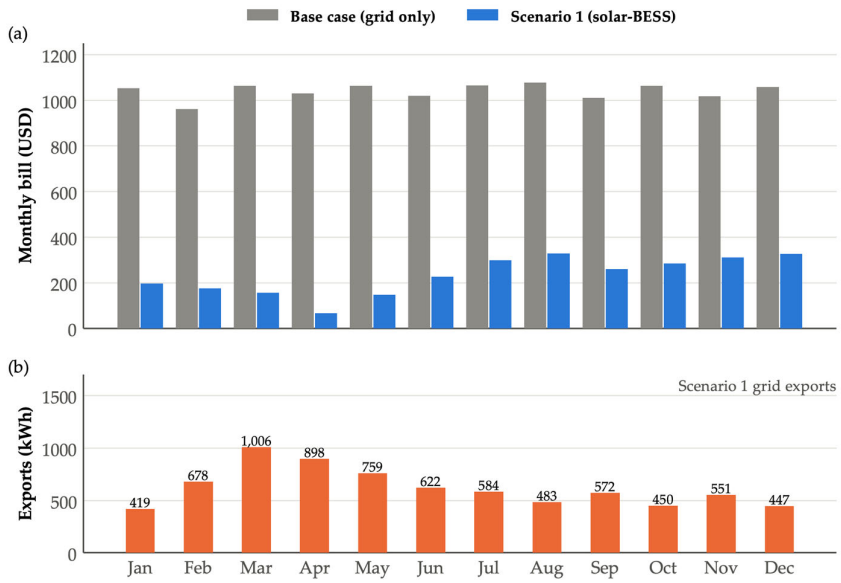


Figure 13. (**a**) Monthly utility bills for the grid-only base case and Scenario 1; (**b**) monthly grid exports of Scenario 1.

3.6. Emissions Scenario Profiling

Emissions are calculated with the Philippine Department of Energy's National Grid Emission Factor for the Luzon-Visayas grid for 2022 to 2024, using the combined margin for wind and solar projects (0.7446 t CO_2/MWh) [42,50]. The operating margin for the same period (0.7310 t CO_2/MWh) would lower every figure by 1.8%. Gross emissions count grid purchases only. Net emissions also credit exports as displaced grid generation at the same factor. Scenario 1 reduces gross emissions from 38.7 to 8.6 t/yr (78%) and net emissions to 3.0 t/yr (92%) (Figure 14). The net reduction exceeds the 78% of load met on site because the 7.5 MWh exported each year is credited. Scenario 2 reaches 49% gross and 89% net; therefore, most of its net reduction comes from exported energy and not from the charging station's own supply. Scenario 3 has the lowest emissions (6.6 t/yr gross; −1.5 t/yr net), and Scenario 4 leaves emissions unchanged. We treat the gross figure as the station's footprint and report the net figure for comparison with other studies.

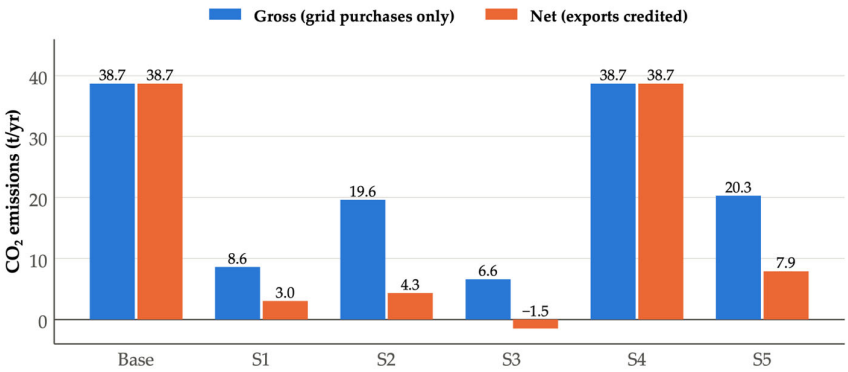


Figure 14. Annual gross and net CO_2 emissions for each scenario.

Because Scenario 1 has lower costs and lower emissions than the base case, its abatement cost is negative. Scenario 3 removes a further 2.0 t CO_2/yr of gross emissions at an NPC of USD 49,277 higher than Scenario 1, equivalent to roughly USD 1000 per tonne over the 25-year project lifetime (based on undiscounted tonnes), far above typical carbon price benchmarks.

3.7. Underperformance of Wind and Standalone Storage

The two wind configurations have the highest capital costs and the lowest returns (IRR of 6.7% for Scenario 3 and 3.7% for Scenario 5). The 10 kW turbine costs USD 40,000, or USD 4.00/W, five times the installed cost of PV. It produces 6753 kWh per year, yielding a capacity factor of 7.7%, well below the 20% screening threshold in Table 1. Output is concentrated from November to March, consistent with the northeast monsoon prevailing in Laguna [10]. Adding the turbine to the solar–BESS system (Scenario 3 Vs. Scenario 1) increases capital costs by USD 39,700, increases annual bill savings by USD 642, and increases the NPC by USD 49,277. Scenario 3 remains below the grid-only NPC only because of its solar and storage components, whereas Scenario 5 is above it. Small wind turbines are therefore not economic at this inland site under the assumed resources and costs.

A battery without PV cannot reduce the bill under a flat energy tariff: energy bought from the grid and stored is bought at the same price and partly lost in conversion. The optimizer therefore selects the smallest battery in the search space, and Scenario 4 is reported at a fixed 30 kWh for comparison, where it adds USD 18,119 to the base-case NPC and makes net annual savings negative (−USD 439/yr). Storage at the charging station creates value only when paired with PV, or under tariffs with demand or time-of-use charges; even under the General Service B tariff, a battery without PV does not provide returns (Section 3.9.3). Resilience during grid outages, which is not modeled, could add value to storage.

3.8. Limitations

Several modeling choices bound the generality of these results. First, the baseline tariff is a flat energy charge; Section 3.9.3 tests the General Service B schedule, but tariff components change monthly, and value-added tax is excluded. Prices are held constant in real terms; therefore, a sustained real escalation of the tariff would act in the same direction as the higher-tariff case in Section 3.9.2. Second, the charging schedule is constructed from the fleet size and the ridership peaks and is not a measured load; the modeled 90 min session is the charger's rated performance, and sessions in the field may run 10 to 20 min longer with the same energy. Six charging points serve 91% of the full-use schedule. Third, the PV, storage, converter, and wind components are generic library models with cited costs in USD; locally quoted costs would make the economics more directly applicable to Philippine decision-makers and other operators of the AssemblePoint SmartBus SB. Fourth, the model treats the grid as an unconstrained supply at the point of connection. It does not represent distribution network effects such as voltage deviation, feeder losses, or hosting capacity, which network-level planning and power distribution studies address [43–45] and which would matter if several such stations were connected to the same feeder. Fifth, the analysis is deterministic and does not model grid outages, battery degradation in the smartbus units, or shading at the site; backup supply to keep the eLBeep fleet operating during brownouts would add a resilience value that favors storage.

3.9. Sensitivity Analysis

Each input was varied on its own while the other stayed at the baseline values, and the full optimization was repeated for each case.

3.9.1. Export Credit

The baseline assumes that exported energy earns nothing. To test this assumption, the optimization was repeated with export rates from USD 0.06 to 0.24/kWh (Table 11, Figure 15). Under the Philippine net-metering program, exports are credited at the distribution utility's generation charge [41,46], which was PHP 7.8607/kWh in the March 2026 MERALCO schedule [13], or USD 0.132/kWh. Solar–BESS remains the least-cost system up to USD 0.09/kWh, although its margin over solar-only falls from USD 17,794 to USD 883. At USD 0.12 kWh/ and above, solar-only has the lower NPC and the optimal battery falls to the smallest size in the search space. Storage earns its return by moving surplus solar energy into the evening charging block; once that surplus can be sold for more than about 40% of the retail price, selling it is worth more than storing it. With any credit of USD 0.06/kWh or more, PV goes to the 60 kW site limit and the converter to its 40 kW limit because PV energy costs about USD 0.05/kWh and every added kilowatt earns a margin. At full credit, the NPC is negative: net-metering credits roll forward and are not paid out; therefore, that case is an upper bound only.

Table 11. Least-cost solar–BESS and solar-only systems at each export credit (flat tariff of USD 0.24/kWh).

Export Credit (USD/kWh)	Best Solar–BESS	NPC (USD)	Best Solar-Only	NPC (USD)	Least-Cost System
0 (baseline)	40 kW, 72 kWh	123,919	40 kW	141,713	Solar–BESS
0.06	60 kW, 69 kWh	108,029	60 kW	114,142	Solar–BESS
0.09	60 kW, 11 kWh	91,695	60 kW	92,578	Solar–BESS
0.12	60 kW, 1 kWh	71,045	60 kW	71,014	Solar-only
0.132 (MERALCO generation charge)	60 kW, 1 kWh	62,515	60 kW	62,388	Solar-only
0.24 (full retail)	60 kW, 1 kWh	−14,253	60 kW	−15,242	Solar-only

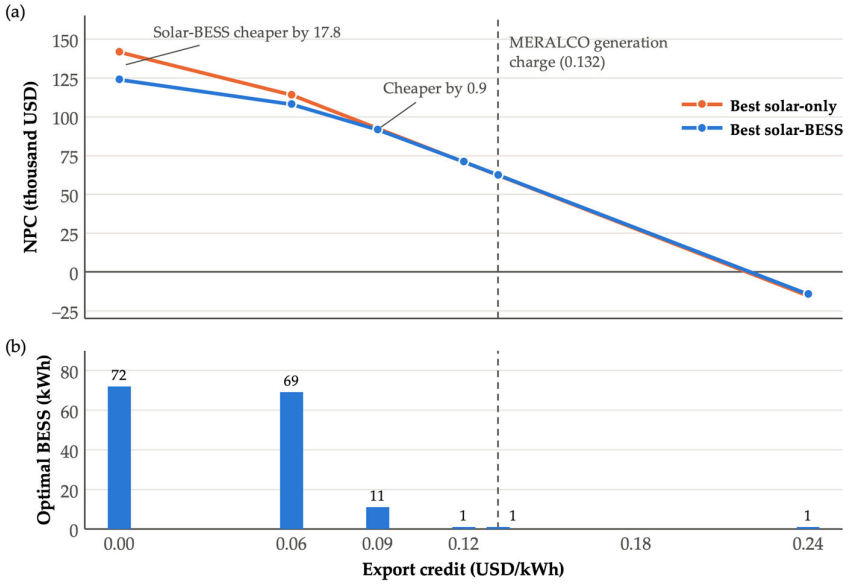


Figure 15. Sensitivity to export credit under the flat tariff: (**a**) the NPC of the best solar–BESS and solar-only systems; (**b**) optimal battery size. The dashed line marks the MERALCO generation charge.

3.9.2. Component Costs, Discount Rate, Project Lifetime, Tariff Level, and Fleet Size

Solar–BESS has the lowest NPC in every one of these cases (Table 12, Figure 16). Its advantage over solar-only is most sensitive to the energy price, falling to USD 5759 at USD 0.19/kWh and rising to USD 30,501 at USD 0.29/kWh, followed by the storage cost and the discount rate. A 20% change in PV costs over a five-year change in project lifetime leaves the optimal battery within 71 to 73 kWh. Fleets of 8 and 16 buses were modeled as 24 to 48 sessions per day, with six and eight charging points; the optimal system scales with the load and remains 34 to 35% cheaper than grid supply, and the 16-bus system reaches the 60 kW PV limit. No wind configuration is least-cost in any case. The run at a 10% discount rate, the rate used in an initial HOMER Grid optimization simulation, provides the same ranking.

Table 12. Sensitivity of the least-cost systems to costs, discount rate, project lifetime, tariff level, and fleet size. The margin is the NPC advantage of solar–BESS over solar-only.

Change from Baseline	Grid-Only NPC (USD)	Best Solar–BESS	NPC (USD)	Best Solar-Only	NPC (USD)	Margin (USD)
Baseline	187,919	40 kW, 72 kWh	123,919	40 kW	141,713	17,794
PV cost –20%	187,919	50 kW, 72 kWh	116,548	40 kW	135,313	18,765
PV cost +20%	187,919	40 kW, 72 kWh	130,319	30 kW	147,147	16,828
Storage cost −30%	187,919	40 kW, 73 kWh	115,132	40 kW	141,713	26,581
Storage cost +30%	187,919	40 kW, 61 kWh	132,207	40 kW	141,713	9506
Discount rate 6%	232,088	50 kW, 73 kWh	138,667	40 kW	166,578	27,911
Discount rate 10%	155,317	40 kW, 67 kWh	112,069	30 kW	122,467	10,398
Lifetime 20 years	164,439	40 kW, 71 kWh	111,710	40 kW	126,078	14,368
Lifetime 30 years	206,898	40 kW, 72 kWh	135,297	40 kW	155,551	20,254
Energy price: USD 0.19/kWh	148,769	30 kW, 34 kWh	114,516	30 kW	120,275	5759
Energy price: USD 0.29/kWh	227,069	50 kW, 73 kWh	131,077	40 kW	161,578	30,501
8 buses (24 sessions/day)	136,121	30 kW, 48 kWh	89,899	30 kW	104,388	14,489
16 buses (48 sessions/day, 8 charging points)	252,663	60 kW, 96 kWh	164,788	50 kW	188,194	23,406

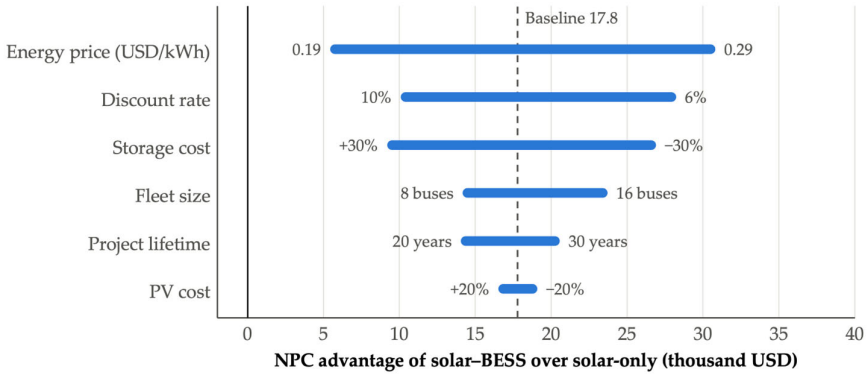


Figure 16. Range of the NPC advantage of solar–BESS over solar-only for each input varied; the dashed line marks the baseline.

3.9.3. MERALCO General Service B Tariff

The flat tariff omits the demand and fixed charges that apply to non-residential customers of this size. MERALCO bills customers with demand from 5 kW to under 40 kW as General Service B [13], so the optimization was repeated with that schedule for March 2026: USD 0.155/kWh for energy, USD 11.35 per kW of monthly peak demand, and USD 12.09 per month in fixed charges. The grid-only bill falls by 15% to USD 10.569 per year, of which the demand charges are 22%. Solar–BESS remains the least-cost option

(Table 13). Without export credit, the optimal system is 30 kW of PV with 32 kWh of storage (NPC USD 124,397, 22% below grid-only), against USD 141,043 for the best solar-only system; a 40 kW system with 42 kWh costs only 0.3% more. With exports credited at USD 0.132/kWh, the optimal battery falls to 11 kWh. However, solar–BESS still costs USD 5101 less than solar-only, whereas under the flat tariff, solar-only was marginally cheaper. The difference is the demand charge: the battery lowers the billed monthly peak and shifts solar energy, cutting the annual demand costs from USD 2367 to USD 873 in the case without export credit. A battery without PV still costs more than grid supply (the NPC is USD 162,879), and both wind configurations cost more than grid supply. The flat-tariff baseline therefore understates the value of storage at this site when exports are credited.

Table 13. Least-cost systems under the flat tariff and the MERALCO General Service B tariff, with or without export credit.

Tariff Case	Grid-Only NPC (USD)	Best Solar–BESS	NPC (USD)	Best Solar-Only	NPC (USD)	Margin (USD)
Flat USD 0.24/kWh, no export credit (baseline)	123,919	40 kW, 72 kWh	123,919	40 kW	141,713	17,794
Flat USD 0.24/kWh, export USD 0.132/kWh	187,919	60 kW, 1 kWh	62,515	60 kW	62,388	−127
General Service B, no export credit	159,207	30 kW, 32 kWh	124,397	30 kW	141,043	16,646
General Service B, export USD 0.132/kWh	159,207	60 kW, 11 kWh	62,820	60 kW	67,921	5101

3.9.4. Timetable-Based Demand

The baseline load assumes full use of the eLBeep smartbus fleet. To test a lower level of use, the optimization was repeated using demand from the September 2025 UPLB–Jubileeville timetable, which has 69 one-way trips per day (Table 4). At 0.098 kWh/km, one bus per trip would need about 10 charging sessions per day; 14 were modeled, one per hour from 7 AM to 9 PM, except at 1 PM, to allow for trips run by more than one bus. This yields 22.2 MWh per year, 43% of the baseline load, with every session served. The least-cost system is 20 kW of PV with 32 kWh of storage (the NPC is USD 55,266, 31% below the grid-only NPC of USD 80,360), compared with USD 60,786 for the best solar-only system. The optimal PV and storage sizes scale roughly with the load, and the ranking of the scenarios is the same as in the baseline. The preferred configuration therefore does not depend on whether all smart bus units operate near the timetable minimum or at full use.

3.10. Summary of Findings

The eLBeep fleet's regular, mostly daytime charging profile aligns well with solar PV generation. Under a flat tariff with no export credit, a grid-connected system with 40 kW of PV and 72 kWh of lithium-ion storage minimizes the 25-year NPC (USD 123,919, 34.1% below grid-only), meets 78% of the load on site, and reduces gross emissions by 78%, with a 6.6-year simple payback. Solar-only at the same array size costs USD 17,794 more over the project lifetime but requires USD 21,600 less capital. Small wind turbines and batteries without PV do not pay off under either tariff tested. The choice between solar–BESS and solar-only depends mainly on export compensation and whether the tariff includes a demand charge.

4. Conclusions

This study assessed five grid-connected renewable configurations for charging the twelve-unit eLBeep fleet at UPLB. Under a flat tariff with no export compensation, 40 kW of PV with 72 kWh of battery storage has the lowest 25-year NPC of USD 123,919 against USD 187,919 for grid supply alone and meets 78% of the charging load on site. The same array without storage costs USD 17,794 more because 38% of its output is exported without payment.

This ranking is conditional; under the flat tariff, when exports are credited at the current net-metering rate, solar-only becomes the least-cost design and the optimal battery falls to nearly zero. Across the other tested ranges (PV cost ±20, storage cost ±30%, discount rate 6 to 10%, lifetime 20 to 30 years, tariff USD 0.19 to 0.29/kWh, and 8 to 16 buses), solar–BESS stayed least-cost, with a margin over solar-only of between USD 5759 and USD 30,501. Under the General Service B tariff, which has a lower energy rate and a demand charge, solar–BESS is the least-cost option both without export credit (30 kW, 32 kWh) and with it (60 kW, 11 kWh) because the battery also reduced billed demand. Wind is not economic at any of the current eLBeep passenger terminal sites, and storage without PV did not provide returns under either tariff.

The accomplished work is a planning-level, theoretical case study that uses generic component models, a constructed charging schedule, and published tariffs, and does not model outages, battery degradation in the smart bus units, or measured load data. Its contribution is a first techno-economic profile of an EV minibus fleet with removable battery packs in the Philippines, with inputs taken from AssemblePoint equipment nameplates and the SNODLOB operating timetable, and a reusable set of inputs for operators of the same Smartbus SB model. The next steps are to validate the load against metered charging data, to include the resilience value of storage during grid interruptions, and to assess a spare pack inventory that would allow charging to move into the solar hours.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/wevj17120630/s1, HOMER Grid baseline scenario files, including sensitivity analysis and hourly charging load resource/time series are compressed as a ZIP file alongside this paper for reproducibility, validation, and verification support.

Author Contributions: J.M.L. and T.F. conceptualized the study and methodology. T.F. provided the software; J.M.L. conducted data acquisition, hybrid optimization, and scenario validation, and wrote the original draft. T.F. carried out the validation, review, editing, and supervision of the paper. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The secondary data used in this study are available online in the public domain. All model inputs are listed in Appendix A. The baseline HOMER Grid project file and the hourly load, resource, and dispatch series are provided as Supplementary Material to this paper. Further inquiries can be directed to the corresponding author.

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Nomenclature

The following nomenclature is used in this manuscript:

AC	Alternating current
BESS	Battery energy storage system
CAPEX	Capital expenditure
CO	Carbon monoxide
CO_2	Carbon dioxide
DOE	Department of Energy (Philippines)
eLBeep	Electric Light Bus for the Environment and Economy Partnership
ERC	Energy Regulatory Commission (Philippines)
EV	Electric vehicle
EVCS	Electric vehicle charging station
HDV	Heavy-duty vehicle
HOMER	Hybrid Optimization of Multiple Energy Resources
HRES	Hybrid renewable energy system
ICE	Internal combustion engine
IEA	International Energy Agency
IRR	Internal rate of return
LCOE	Levelized cost of electricity
LCV	Light commercial vehicle
LDV	Light-duty vehicle
LFP	Lithium iron phosphate ($LiFePO_4$)
LSV	Low-speed vehicle
MaaS	Mobility as a service
MERALCO	Manila Electric Company
NPC	Net present cost
NPV	Net present value
O&M	Operation and maintenance
PV	Photovoltaic
PUV	Public utility vehicle
RE	Renewable energy
RF	Renewable fraction
SDV	Software-defined vehicles
SNODLOB	Samahan ng Nagkakaisang Drivers at Operators ng Los Baños
SOC	State of charge
UPRHS	University of the Philippines Rural High School
UPLB	University of the Philippines Los Baños

Appendix A

Table A1 lists the inputs of the baseline model and of the General Service tariff case.

Table A1. Model inputs in this study.

Component	Parameter	Value
Software	Version; time step; dispatch	HOMER Grid version 1.11.7; 60 min; HOMER Peak Shaving;
Economics	Nominal discount rate; inflation; real discount rate; lifetime	8%; 3.5%; 4.35%; 25 years

Economics	Incentives; currency conversion	None; PHP 59.41 per USD (BSP March 2026), VAT excluded
EV charger	Charging points; charger rating	6 points at 3 kW; 58.4 V, 50 A DC (2.92 kW), efficiency ≥ 93%
EV charger	Session; schedule	2.9 kW for 90 min (4.35 kWh); 36 sessions/day: 6 each at 08, 09, 13, and 14 h; 3 each at 20, 21, 23, and 00 h
PV	Capital; O&M; lifetime; derating	USD 800/kW; USD 13/kW/yr; 25 years; 80%
PV	Search space	0 to 60 kW in 10 kW steps
Storage	Capital; replacement; O&M	USD 300, 200, and 6 per kWh
Storage	Lifetime; round-trip efficiency; minimum SOC	15 years or 3000 kWh throughput per kWh; 90%
Storage	Search space	0 to 150 kWh
Converter	Capital at 10, 20, 30, and 40 kW	USD 2500, 4000, 5700, and 7350
Converter	Lifetime; efficiency; search space	15 years; 96%; 0 to 40 kW
Wind turbine	Rating; capital; O&M; lifetime; hub height	10 kW; USD 40,000; USD 800/yr; 20 years; 30 m
Wind turbine	Search space	0 to 2 turbines
Utility (baseline)	Energy; demand; fixed; export	USD 0.24/kWh; 0; 0; 0
Utility (General Service B)	Energy; demand; fixed	USD 0.155/kWh; USD 11.35/kW/month; USD 12.09/month
Utility	CO_2 emission factor	744.6 g/kWh
Resources	Solar GHI; mean wind speed; mean temperature	4.57 kWh/m²/day; 4.59 m/s; 25.7 °C
Constraints	Unmet load	None allowed

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