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Original Article

Break-Even Carbon Price for Reliable Photovoltaic-Battery Electric Vehicle Charging Stations in Indonesia: A Monte Carlo Assessment

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Abstract *- Carbon incentives may support Photovoltaic (PV) and Battery Energy Storage System (BESS) deployment at public electric vehicle charging stations, but the carbon price required to close the financing gap under service constraints remains unclear. This study determines the Break-Even Carbon Price (BECP) of a grid-connected PV-BESS charging station in Bandar Lampung, Indonesia. A price-independent hourly dispatch model evaluates 8,525 configurations over a 25-year demand horizon subject to a 66 kW grid-import limit. Transport-displacement and renewable-displacement crediting routes are evaluated using discounted creditable emissions, while a 3,000-draw Monte Carlo analysis quantifies uncertainty in costs, tariffs, financing, emission factors, and crediting parameters. At market capital costs without export remuneration, the lowest BECP satisfying an LPSP target of 0.10 and a mean waiting time below 5 min is IDR 4.46 million/tCO₂e. The Monte Carlo median is IDR 4.43 million/tCO₂e, with zero viability at the benchmark carbon prices considered. A 50% export-remuneration fraction eliminates the need for carbon revenue, whereas a 15-year crediting period increases the threshold to IDR 7.40 million/tCO₂e. Carbon incentives therefore act more effectively as a complement to export remuneration than as a standalone mechanism for reliable solar-assisted charging.*

Keywords *- Carbon pricing, Energy storage, Policy frontier, Reliability assessment, Uncertainty analysis.*

1. Introduction

Road transport electrification can reduce direct vehicle emissions, but its climate benefit depends on the electricity used for charging. In Indonesia, the electricity mix remains carbon intensive [1], and the grid emission factor adopted for the study site is 0.943 kg CO_2e/kWh [2]. Consequently, Photovoltaic (PV) generation and Battery Energy Storage Systems (BESSs) can improve the environmental performance of electric vehicle charging while reducing dependence on a constrained grid connection [3-7].

The financial challenge is that a PV-BESS system transfers part of the station cost from electricity purchases to upfront capital expenditure. The resulting viability depends strongly on renewable self-consumption, storage utilization, electricity tariffs, and the treatment of surplus PV energy [8, 9]. Indonesia's rooftop-PV framework also changed in 2024, making export remuneration an important policy variable for the economics of distributed PV [10]. In parallel, Indonesia has developed carbon-market instruments and expanded carbon-market infrastructure, creating a potential additional revenue stream for emission-reduction projects [11-14].

Previous studies have examined the economics of PV-assisted EV charging, the value of storage, and the effect of electricity-market or feed-in-price structures [15-18]. Monte Carlo methods have also been applied to quantify uncertainty in PV and battery-storage economics [19], while recent studies have examined feed-in tariffs and policy support for solar and EV-charging systems [20, 21].

These studies generally evaluate discrete policy or carbon-price scenarios. They do not directly quantify the minimum carbon price required to close the financing gap of a service-constrained charging station while accounting for alternative crediting routes, export remuneration, crediting duration, and MRV costs.

Four analytical gaps are therefore addressed. First, the carbon incentive is solved as a break-even threshold rather than imposed only as a discrete scenario. Second, the

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threshold is explicitly linked to charging-service reliability. Third, transport-displacement and renewable-displacement crediting are compared using a common discounted-credit framework, while crediting-period and MRV effects are included.

Fourth, carbon incentives are evaluated jointly with export remuneration and uncertainty. The analysis is designed as a policy-oriented electrical-energy assessment of a grid-connected PV-BESS charging station in Bandar Lampung. The main contributions are: (i) exhaustive enumeration of 8,525 PV-BESS-charger configurations with price-independent dispatch; (ii) closed-form calculation of BECP for every configuration; (iii) mapping of BECP against reliability targets and export remuneration; and (iv) Monte Carlo estimation of viability probabilities under uncertain techno-economic and crediting parameters.

The study therefore asks: what carbon-credit price makes a reliable grid-connected PV-BESS charging station financially viable, and how does the required price change with reliability, export remuneration, crediting route, crediting period, MRV cost, and uncertainty? Market-based capital costs are used as the base case, while a low-cost sensitivity case is retained to show the effect of capital-cost assumptions.

2. Literature Review

2.1. Techno-Economics of PV and Storage-Supported EV Charging

The economics of solar-assisted charging have now been studied for more than ten years. Early feasibility studies concerning workplace and urban charging stations gave figures for net present value, the cost of energy, and emission reductions for particular sites [15, 16]. Later work broadened the scope to cover solar carports, charging stations on highways, and optimal planning when storage is involved [7, 17, 18].

Analyses of load management and the combined advantages of Photovoltaic (PV) systems and storage show that improvements in both cost and emissions occur when charging demand matches up with solar supply [5, 6]. Research carried out on stations in Vietnam showed that the optimal configuration and investment efficiency are greatly affected by irradiation and rooftop feed-in tariffs [22]. Taken together, this body of literature shows that PV-BESS charging is technically feasible, even though the financial results are very much dependent on capital costs, tariff structures, and the specific conditions of the site.

2.2. Carbon Pricing and Carbon Crediting

In most PV-assisted charging studies, the carbon price enters as a scenario input. A study of a solar-powered station in Shenzhen reported that carbon pricing promotes renewable supply only above about USD 20/t [16], and a solar-carport study in Kaohsiung found that higher carbon-tax scenarios improve the viability of the station [17]. For PV with storage supplying EV charging, a stricter carbon tax raised the installed storage capacity and self-consumption, although carbon neutrality remained unattainable because of area limits [23]. A carbon-credit saving of about USD 8,787 per year was reported for a hybrid renewable charging system on Yas Island, Abu Dhabi [24], and an application of the VM0038 methodology to a charging station in India estimated about 191 credits per year, with a value of up to about 31% above the annual profit [25, 26].

For Indonesia, power-sector modeling indicates that carbon prices of about USD 2-25/tCO_2e can start a coal-to-gas switch without changing the generation profile significantly, which changes substantially only above USD 35/tCO_2e [27], while a RETScreen study found that an emission incentive of USD 10/t would make a proposed 26 MW solar plant financially viable for independent power producers [28].

The integrity and cost of crediting also matter. An assessment of carbon crediting projects estimated that less than 16% of the credits issued to the investigated projects represented real emission reductions [29]. Monitoring requirements in the Clean Development Mechanism were found to add a cost per tonne that varies widely with project type [30], and transaction costs of low-carbon technologies were found to vary with technology type and size, with project bundling named among the measures that can reduce them [31].

2.3. Export Remuneration and Rooftop PV Policy

Export and feed-in policy has a strong effect on PV-based charging economics. A highway charging station study found that allowing grid sales reduced the net present cost by 40% in 2030 and by 35% in 2050 [18], and further work has examined retail and feed-in prices, feed-in tariff viability, and policy options for PV with storage [8, 9, 20, 21]. In Indonesia, the export rate under the 2018 rooftop PV policy was set at 65% of the retail tariff and was identified as the main obstacle in interviews with officials, private-sector representatives, and experts [32], and net metering alone was found insufficient to make residential rooftop PV economically viable in the cities studied unless an installation incentive was added [33].

2.4. Service Reliability and Uncertainty

Service quality is typically quantified using the Loss of Power Supply Probability (LPSP) or queueing models. LPSP has been employed to determine the appropriate size of PV-based charging stations and hybrid systems with electric vehicles [34, 35]. Queueing analysis has been utilized for charging control [36], for sizing charging ports to meet a maximum allowable waiting time in network planning studies that incorporate PV and Battery Energy Storage Systems (BESS) [37], and for profit-maximizing PV and storage planning that includes penalties for waiting and rejected

vehicles [38]. In these studies, service quality is generally treated as a design objective or incorporated as a penalty term. Uncertainty has been handled by Monte Carlo analysis for PV-battery investment in commercial buildings [19] and in a probabilistic framework for smart energy hubs for EV charging [39].

An uncertainty-propagation study of the levelized cost of electricity in renewable energy communities identified electricity purchase and selling prices, yearly load, and self-consumption and shared-energy rates as the crucial inputs [40]. The cost of avoided CO_2 has also been used as a decision metric, for example, a minimum of about 35 €/t reported for grid-connected, PV-supported refueling infrastructure serving a mixed battery-electric and hydrogen fleet [41].

2.5. Research Gap and Novelty

Three primary gaps emerge from the studies reviewed above. First, carbon price is typically treated as an input scenario or as an output of a fixed design [16, 17, 23, 24], rather than as a variable determined by the requirement for a charging station to achieve break-even. Second, service quality is generally addressed as an objective or as a penalty term [37, 38], rather than as a prerequisite that each candidate design must fulfill prior to economic comparison.

Third, export remuneration, crediting route, crediting period, MRV cost, and parameter uncertainty are often examined in isolation [18, 20, 25], which obscures how these factors may substitute for one another in addressing the financing gap.

The novelty of the present work follows from these gaps. The study provides (i) a closed-form break-even carbon price evaluated for each of 8,525 PV-BESS-charger designs from a price-independent dispatch; (ii) a service-admissibility screen based on LPSP and M/M/c waiting time that is applied before the threshold is computed; (iii) a policy substitution frontier between export remuneration and carbon price; and (iv) a Monte Carlo estimate of the probability of viability, together with the effect of crediting period and MRV cost. A comparison with representative earlier studies is given in Table 6 (Section 4.7).

3. Materials and Methods

3.1. Case Study and Input Data

The case is a public charging station in Bandar Lampung, Sumatra. An observed hourly load profile of one year (8,760 values) serves as the demand input; it totals 17,029.66 kWh, contains 1,133 non-zero hours, and peaks at 95.2 kW.

Hourly global horizontal irradiance (annual sum 1,869 kWh/m²) and ambient temperature (annual mean 27.1 °C) for the same site drive the PV model. Future demand follows a stepwise growth path that yields a year-25 demand multiplier of 7.93 relative to the first-year demand and 1,858 MWh of requested energy over the project life.

A doubled-utilization case (UF2.0), in which additional charging sessions are added at hours consistent with the observed pattern, is used as a demand sensitivity. The same load and weather series are used throughout the present analysis. Model outputs are evaluated consistently for the full enumerated design space.

Table 1 lists the technical and economic inputs. The market base case uses IDR 12 million/kWp for PV and IDR 4 million/kWh for BESS. A low-cost sensitivity case uses IDR 1.2 million/kWp and IDR 2 million/kWh. The PV reference cost is deliberately conservative relative to recent global cost trends [42], while the battery-cost sensitivity is consistent with the continuing decline in battery-storage costs reported by the IEA [43].

Table 1. Technical, economic, and crediting inputs (Base case and Monte Carlo ranges)

Parameter	Base value	Monte Carlo range
PV capital cost (IDR/kWp)	12.0×10^6 (low case 1.2×10^6)	Triangular 9-12-16 × 10^6
BESS capital cost (IDR/kWh)	4.0×10^6 (low case 2.0×10^6)	Triangular 2.5-4.0-6.0 × 10^6
AC / DC charger (IDR/unit)	25×10^6 / 500×10^6	Fixed
O&M (% of CAPEX per year)	1	Fixed
BESS / inverter replacement	Years 10, 20 / years 12, 24	Fixed
Discount rate	5%	Triangular 4-5-10%
EV charging tariff (IDR/kWh)	2,466	Triangular 2,200-2,466-2,700
Grid purchase tariff (IDR/kWh)	1,699	Triangular 1,550-1,699-1,900
Reference export price (IDR/kWh)	1,669.53	φ = 0, 0.30, 0.65 (frontier: 0-1)
Grid emission factor (kg/kWh)	0.943, constant	Decline 0-2.5% per year
ICEV fuel economy (km/L)	12 (2.31 kg CO_2/L; EV 0.18 kWh/km)	Triangular 10-12-14
Credit haircut	0	Uniform 0-20%
Carbon price escalation	0% per year	Uniform 0-5% per year
PV system efficiency / temperature coefficient	0.90 / -0.004 $°C^{-1}$	Fixed
BESS efficiency / depth of discharge / C-rates	0.95 / 80% / 0.5 charge, 0.8 discharge	Fixed
Charger ratings / grid-import limit	22 kW AC, 150 kW DC / 66 kW	Fixed

3.2. Design Enumeration and Price-Independent Dispatch

Instead of searching the design space with an optimizer, all combinations of PV capacity (0 to 300 kWp in 10 kWp steps), BESS capacity (0 to 600 kWh in 25 kWh steps), and eleven charger sets (one DC charger with one to nine AC chargers, or two DC chargers with one or two AC chargers, all within a 350 kW connection) are evaluated. The 350 kW figure limits the total rated charger power, whereas the 66 kW grid-import limit applies to the power drawn from the grid; the difference is covered by PV and BESS. This yields 8,525 configurations and includes the grid-only station (no PV and no BESS) for every charger set, which serves as the counterfactual for incremental abatement costs.

The PV output at hour t is,

$$P_{PV}(t) = P_r \frac{G(t)}{G_{ref}} \eta_{PV}[1 + \alpha(T_a(t) - 25)] \quad (1)$$

Where Pr is the rated capacity, G(t) the irradiance, Gref = 1 kW/m², ηPV the system efficiency, α the temperature coefficient, and Ta the ambient temperature. Charging demand above the installed charger power is rejected.

Accepted demand is served first by PV, then by BESS discharge within the state-of-charge and C-rate limits, and finally by the grid up to the import limit; the BESS is charged only from PV surplus, and any remaining surplus is exported when export is permitted and curtailed otherwise. The grid import is therefore

$$P_g(t) = \min\{P_g^{\max},\ \max[0,\ P_{acc}(t) - P_{PV\to EV}(t) - P_B^{dis}(t)]\} \quad (2)$$

Where Pacc is the accepted demand, PPV→EV the PV power used directly, and PBdis the BESS discharge. Accepted energy that none of the three sources can supply is recorded as unmet. Because none of these rules contains a price, the annual energy flows of each configuration (served, imported, exported, unmet, and rejected energy) are computed once for all 25 years and then reused for every economic, policy, and Monte Carlo evaluation. This separation is what makes a closed-form break-even price possible.

3.3. Service Admissibility

Service quality is imposed as a screen rather than as an optimization objective. The service-loss indicator includes both charging energy rejected because the installed charger capacity is insufficient and accepted charging energy that cannot be supplied by the PV-BESS-grid system. This definition is used consistently in the admissibility screen and is distinct from a power-system-only unserved-energy metric:

$$LPSP = \frac{\sum_{y=1}^{25}(E_{un,y} + E_{rej,y})}{\sum_{y=1}^{25} E_{req,y}} \quad (3)$$

The mean waiting time Wq is obtained from two parallel M/M/c queues for the AC and DC chargers. The design arrival rate is derived from the 95th percentile of hourly charging demand after conversion to session arrivals using a mean session energy of 19.6 kWh/session; 30% of arrivals are routed to DC chargers. For a queue with c chargers, arrival rate λ and service rate μ,

$$W_q = \frac{C(c, \lambda/\mu)}{c\mu - \lambda} \quad (4)$$

Where C(·) is the Erlang C probability of waiting. A configuration x is admissible for a reliability target L* if

$$x \in \mathcal{A}(L^*) \Leftrightarrow LPSP(x) \le L^* \ \wedge\ W_q(x) \le 5 \text{ min} \quad (5)$$

The target L* is varied from 0.04 to 0.23, and L* = 0.10 is used as the reference level.

3.4. Net Present Value without Carbon Revenue

All costs and revenues are expressed in constant Indonesian rupiah and discounted at rate r over N = 25 years. The fixed life-cycle cost C_{fix} collects the initial investment, BESS replacements in years 10 and 20, inverter replacements (15% of PV capital) in years 12 and 24, annual O&M, and a salvage credit for the half-used last battery.

The net present value without any carbon cash flow is,

$$NPV_0 = \sum_{y=1}^{N} \frac{E_{s,y}\,\pi_{EV} + \varphi\,\pi_{ex}\,E_{ex,y} - E_{g,y}\,\pi_g}{(1+r)^y} - C_{fix} \quad (6)$$

Where Es,y, Eex,y, and Eg,y are the served, exported, and imported energy in year y; πEV, πex, and πg are the charging tariff, the reference export price, and the grid tariff; and φ ∈ [0, 1] is the export remuneration fraction. φ = 0 represents the current rule for rooftop PV [10], and φ = 0.65 and 1.0 correspond to the partial and full net-billing variants examined in the present study.

3.5. Carbon Crediting Routes

Creditable reductions are computed from metered quantities, as an MRV system would do, and embodied emissions of PV and BESS are therefore outside the crediting boundary. Two alternative routes are considered, and a project may claim only one of them. Route T (transport displacement) credits the delivered charging energy against the petrol vehicles it replaces and deducts the emissions of imported grid electricity:

$$CR_{T,y} = \frac{1}{1000}\max[0,\ E_{s,y}\,\kappa_{ICEV} - E_{g,y}\,EF_y] \quad (7)$$

Where κICEV = fCO2/(eEV FE) is the petrol-vehicle emission avoided per kWh delivered; with fCO2 = 2.31 kg CO2/L, eEV = 0.18 kWh/km, and FE = 12 km/L it equals 1.069 kg CO2/kWh. Route R (renewable displacement)

credits only the on-site renewable energy delivered to vehicles or exported:

$$CR_{R,y} = \frac{1}{1000}\max\left[0,\ \left(E_{s,y} - E_{g,y} + E_{ex,y}\right)EF_y\right] \quad (8)$$

The grid emission factor follows EFy = EF0(1 - d)y-1 with EF0 = 0.943 kg/kWh and a decline rate d. With a crediting period Yc, a haircut h for buffer or quality deductions, and a carbon price that starts at p in year 1 and escalates at gc per year, the discounted creditable tonnes are

$$D = \sum_{y=1}^{Y_c} \frac{(1-h)\,CR_y\,(1+g_c)^{y-1}}{(1+r)^y} \quad (9)$$

3.6. Break-Even Carbon Price, Policy Frontier, and Uncertainty

The net present value is linear in the carbon price:

$$NPV(p) = NPV_0 + p\,D - \sum_{y=1}^{Y_c} \frac{M}{(1+r)^y} \quad (10)$$

Where M is the annual MRV cost. The break-even carbon price of a configuration is the value of p at which NPV(p) = 0:

$$BECP = \max\left\{0,\ \frac{-NPV_0 + \sum_{y=1}^{Y_c} M(1+r)^{-y}}{D}\right\} \quad (11)$$

The carbon price required by a reliability target is the lowest BECP in the admissible set, BECPmin(L*) = minx∈ □(L*) BECP(x). Repeating this minimization for φ from 0 to 1 gives a policy substitution frontier p*(φ) that separates viable from non-viable combinations of export remuneration and carbon price.

The carbon-price equivalent of a given export remuneration is also reported for each admissible design as the ratio of the export-driven NPV gain to D.

Uncertainty is propagated with 3,000 joint Monte Carlo draws of the nine inputs whose ranges appear in Table 1. For every draw s, NPV0, s and Ds are recomputed for all 2,136 configurations admissible at L* = 0.10, and the probability of viability at a carbon price p is,

$$P_v(p) = \frac{1}{S}\sum_{s=1}^{S} 1\left[NPV_{0,s} + p\,D_s \geq 0\right] \quad (12)$$

The robust design for each policy case is the admissible configuration with the lowest median BECP across draws. A one-at-a-time tornado analysis and Spearman rank correlations identify the inputs that drive the threshold. The complete workflow is summarized in Figure 1.

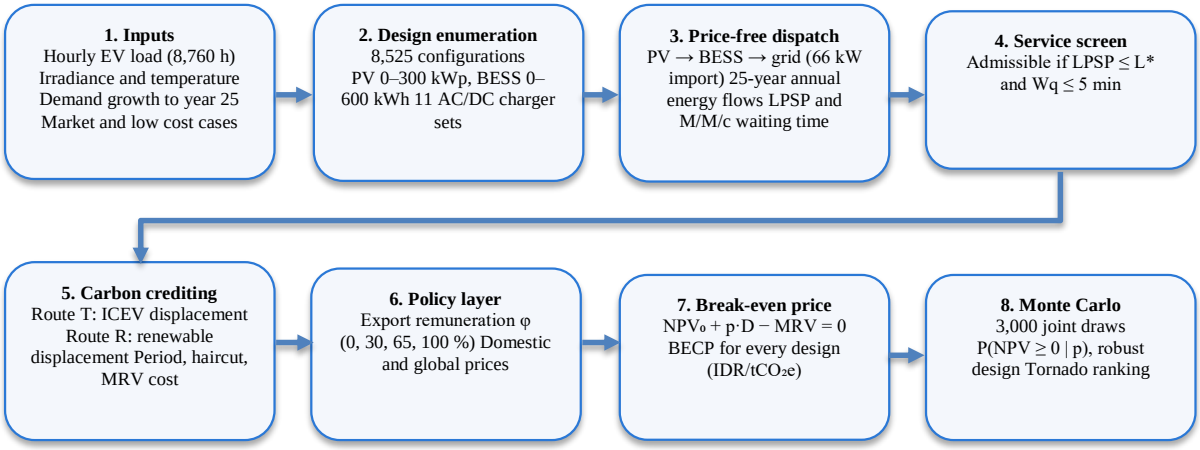

Fig. 1 Workflow of the break-even carbon price assessment. Steps 1-4 are price-independent and are computed once; Steps 5-8 reuse the stored energy flows.

The carbon-price benchmarks against which the thresholds are judged are listed in Table 2. Rupiah values of foreign prices use IDR 16,500 per USD and IDR 19,000 per EUR.

Table 2. Carbon-Price benchmarks used in this study

Benchmark	IDR/tCO₂e	USD/tCO₂e
Indonesian statutory carbon-tax benchmark, Law 7/2021 [11]	30,000	1.8
IDXCarbon average price, September 2025 (1,234 tCO₂e traded) [12]	67,047	4.1
IDXCarbon IDTBSA-RE closing price, 28 November 2025 [13]	144,000	8.7
Global average price of implemented instruments, 2025 [44]	313,500	19
EU ETS allowance, December 2025 (EUR 83.79 adopted; futures about EUR 85 at expiry) [45]	1,592,010	96

4. Results and Discussion

4.1. Economics of Reliable Configurations without Carbon Revenue

Without export remuneration and at market capital costs, none of the configurations that meet the reference service screen has a positive NPV0. The screen at L* = 0.10 admits 2,136 configurations, and their NPV0 ranges from -IDR 8.44 billion to -IDR 3.53 billion. The grid-only station with nine AC chargers and one DC charger (D-G in Table 3) loses less money, -IDR 0.40 billion, but its LPSP of 0.423 shows that the 66 kW import limit leaves 42% of the requested energy unserved once demand has grown. PV and BESS are therefore not optional additions at this site; they are the only means of serving the growing load under the existing connection, which is why reliability and financial viability are coupled. The least-BECP admissible configuration, D-R, combines 130 kWp of PV, 325 kWh of BESS, nine AC chargers, and one DC charger. It serves 87.9% of the delivered energy from PV and BESS, keeps the LPSP at 0.099 and Wq at 0.073 min, and requires IDR 3.59 billion of initial investment. Its NPV0 of -IDR 3.53 billion is the financing gap that carbon revenue has to close.

Table 3 also reports the D-C configuration (264.1 kWp and 152.2 kWh) for comparison. Under the low-cost sensitivity case, D-C has a positive NPV0 of IDR 17.2 million; at market cost, its NPV0 falls to -IDR 4.21 billion and its LPSP of 0.132 does not meet the reference screen. The capital-cost assumption therefore reverses the financial result and motivates the use of market costs as the base case.

Table 3. Reference configurations at market cost (L* = 0.10 screen; BECP in million IDR/tCO$_2$e)

Indicator	D-R	D-C	D-65	D-G
PV (kWp) / BESS (kWh)	130 / 325	264.1 / 152.2	280 / 275	0 / 0
AC / DC chargers	9 / 1	5 / 1	4 / 1	9 / 1
LPSP / W_q (min)	0.099 / 0.07	0.132 / 0.07	0.099 / 0.09	0.423 / 0.07
Renewable share of served energy	87.9%	83.4%	91.5%	0%
Initial investment (IDR billion)	3.59	4.40	5.06	0.73
NPV_0, φ = 0 (IDR billion)	-3.53	-4.21	-5.24	-0.40
Creditable tonnes, route T (25 years)	1,600	1,472	1,655	136
Discounted tonnes D, route T / R	790.6 / 688.0	729.0 / 629.7	811.0 / 708.4	69.8 / 0
BECP, φ = 0, route T / R	4.46 / 5.13	5.78 / 6.69	6.46 / 7.40	5.79 / n.a.
BECP, φ = 0.30, route T	3.03	2.03	2.92	5.79
BECP, φ = 0.65, route T	1.37	0	0	5.79
BECP, low-cost case, φ = 0, route T	0.57	0	0.38	5.79

D-C and D-G do not meet the L = 0.10 screen and are shown for comparison; n.a.: no renewable energy to credit.*

4.2. The Carbon Price of Reliability

Figure 2 shows how the minimum BECP depends on the reliability target. Under route T and market cost, the threshold falls from IDR 7.31 million/tCO2e at L* = 0.04 to IDR 4.46 million at L* = 0.10, IDR 3.41 million at L* = 0.15, and IDR 2.40 million at L* = 0.23.

Every step towards a more reliable station therefore raises the carbon price that has to be paid for it by roughly IDR 0.2 million/tCO2e for each 0.01 reduction in LPSP between L* = 0.15 and 0.10, and by roughly IDR 0.5 million between 0.10 and 0.04. At L* = 0.10 the required price is about 149 times the legislated carbon tax, 67 times the 2025 IDXCarbon average, 31 times the IDXCarbon renewable-energy product price, 14 times the global average of implemented instruments, and 2.8 times the EU allowance price of December 2025 (Table 2). Even the loosest target in the sweep needs 1.5 times the EU price. `Route R gives thresholds 14-20% higher than route T across the reliability targets, reaching IDR 5.13 million/tCO$_2$e at L* = 0.10, because it credits only the renewable share of delivered energy, whereas route T also credits the fuel displacement associated with grid-supplied charging.

The route T credit of the grid-only station (69.8 discounted tonnes) confirms that most creditable tonnes are attributable to the PV-BESS system. The incremental abatement cost of D-R relative to D-G is IDR 4.33 million/tCO$_2$e under route T and IDR 4.54 million/tCO$_2$e under route R.

Doubling the utilization (UF2.0) roughly halves the threshold: the best configuration at L* = 0.10 (200 kWp, 425 kWh, nine AC chargers, one DC charger) needs IDR 2.12 million/tCO$_2$e because twice as much energy is served and credited per unit of capital.

In the low-cost sensitivity case, the threshold at L* = 0.10 is only IDR 0.26 million/tCO$_2$e, below the global average price, and it drops to zero for L* ≥ 0.13. Without incentives, the station therefore approaches viability only under the low-cost assumptions.

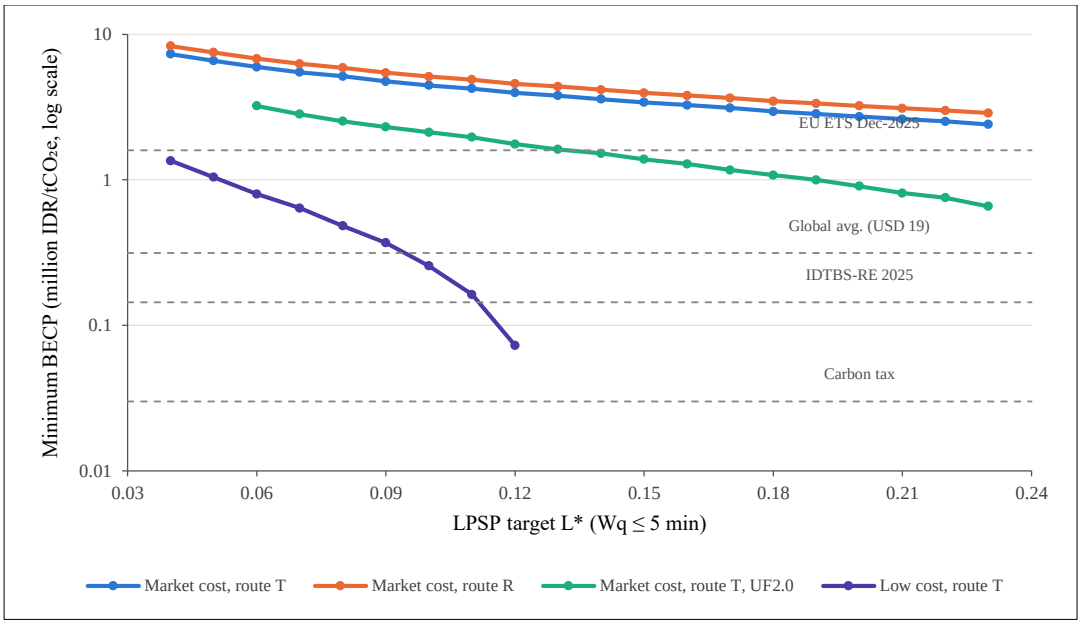

Fig. 2 Minimum break-even carbon price of admissible configurations as a function of the LPSP target without export remuneration. Missing points of the low-cost curve correspond to a zero threshold (viable without carbon revenue); UF2.0 cannot reach L* below 0.06 within the enumerated capacities.

Figure 3 maps the lowest BECP over the PV-BESS plane among the charger sets that pass the reference screen.

An admissible station needs at least 90 kWp of PV, and at 90 kWp it needs 600 kWh of storage; the storage requirement falls as PV capacity increases. The threshold is lowest, IDR 4.46-4.66 million/tCO2e, in a narrow band of 120-160 kWp combined with 275-375 kWh, and it rises in both directions: towards smaller PV because more storage is needed to hold the screen, and towards larger PV because the extra capacity is mostly curtailed in the early, low-demand years and earns no credits. At 300 kWp the lowest threshold is IDR 6.60 million.

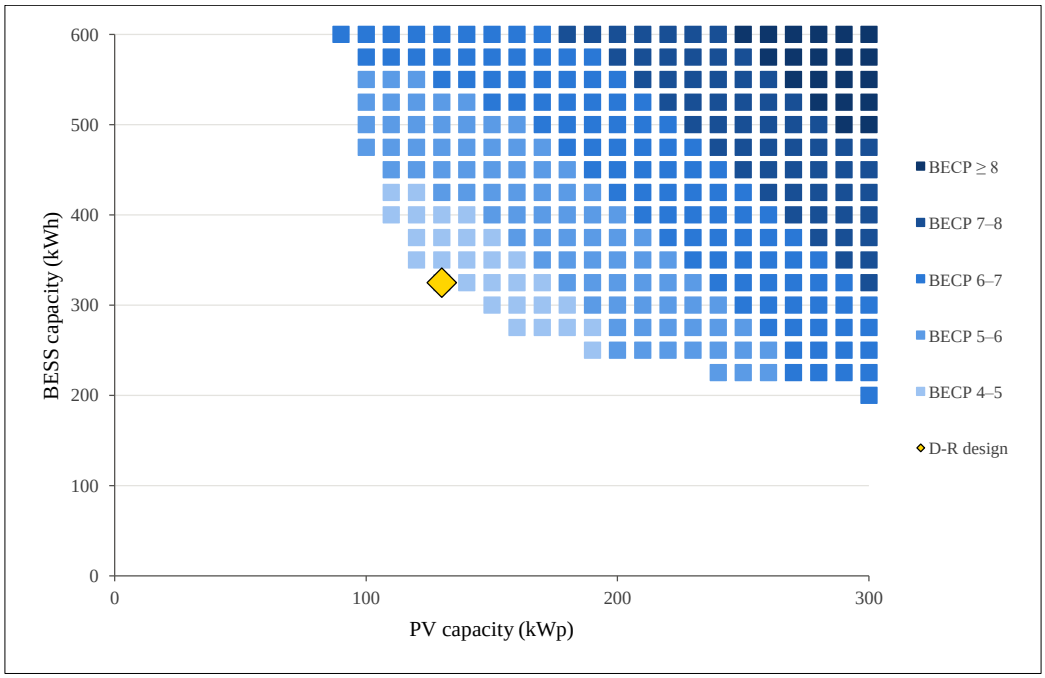

Fig. 3 Lowest break-even carbon price (Route T, market cost, φ = 0) over PV and BESS capacity among charger sets with LPSP ≤ 0.10 and $W_q \leq 5$ min; blank areas have no admissible charger set, the square color indicates the lowest break-even carbon price in each PV-BESS cell, and the diamond marks D-R.

A further observation concerns design guidance. The discounted creditable tonnes of all 2,136 admissible configurations lie within a narrow band of 779 to 904 tonnes, because route T credits are dominated by delivered energy, which every admissible design delivers in similar amounts. As a result, the NPV-maximizing admissible configuration without export remains D-R for every carbon price between zero and IDR 8 million/tCO2e.

A carbon incentive changes whether the station is viable, but it hardly changes what should be built. Export remuneration behaves differently: with φ = 0.30 the NPV-maximizing design moves to 240 kWp and 225 kWh at zero carbon price, and with φ = 0.65 to 300 kWp and 200 kWh, since each exported kilowatt-hour now carries a price.

4.3. Substitution between Export Remuneration and Carbon Price

Figure 4 presents the policy substitution frontier. At L* = 0.10 the minimum BECP declines almost linearly from IDR 4.46 million at φ = 0 to IDR 2.53 million at φ = 0.30 and IDR 1.26 million at φ = 0.40, which is below the December 2025 EU allowance price, and it reaches zero at φ = 0.50. The IDR 2.53 million figure is the minimum over all admissible designs at φ = 0.30; D-R alone requires IDR 3.03 million (Table 3), and the Monte Carlo median of the robust design is IDR 2.90 million (Section 4.4). The corresponding export fraction that removes the need for carbon revenue is 0.55 for L* = 0.08 and 0.45 for L* = 0.15. Expressed the other way round, the NPV gain from 65% export remuneration is equivalent, per admissible configuration, to a carbon price with a median of IDR 5.38 million/tCO2e (interquartile range 3.95-6.66 million), and full remuneration is equivalent to a median of IDR 8.27 million. For the regulator, restoring even half of the pre-2024 export credit (φ ≈ 0.33) is thus worth far more to reliable solar-assisted charging than any carbon price currently traded in Indonesia. When exports are remunerated, route R changes character, because exported renewable energy also becomes creditable. The route R threshold at L* = 0.10 then drops from IDR 5.13 million at φ = 0 to IDR 0.70 million at φ = 0.05. This result, however, relies on the same exported kilowatt-hour earning both an export payment and a carbon credit, and on the grid, operator not claiming the same reduction in its own inventory. Without clear rules against double counting under the new national framework [14], route R with export crediting should be treated as an upper bound on carbon revenue rather than a planning value.

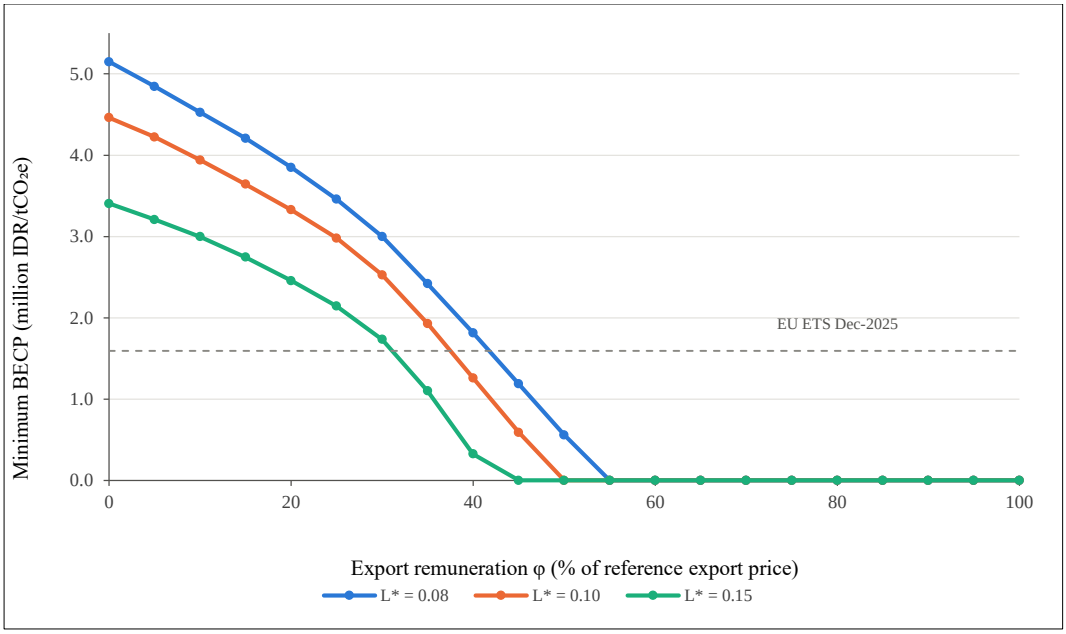

Fig. 4 Policy substitution frontier: minimum break-even carbon price (Route T, market cost) versus the export remuneration fraction for three LPSP targets. Combinations above each line are viable.

4.4. Probability of Viability under Uncertainty

Figure 5 and Table 4 summarize the Monte Carlo results. Without export remuneration, the BECP of D-R has a median of IDR 4.43 million/tCO₂e and a 90% interval of IDR 2.66-7.17 million/tCO₂e. D-R is also the robust design in this case. Its probability of viability is zero at the domestic benchmarks, the global average price, and the EU allowance benchmark. A carbon price of IDR 4.45 million/tCO₂e is required for a 50% viability probability and IDR 6.45 million/tCO₂e for a 90% probability. With 30% export remuneration, the robust design (190 kWp, 250 kWh, nine AC chargers, one DC charger) has a median threshold of IDR 2.90 million/tCO₂e and a 7.5% viability probability at the EU benchmark. With 65% remuneration, the robust design (D-65 in Table 3) is viable without carbon revenue in 55.9% of the draws, and the EU benchmark increases this share to 92.4%.

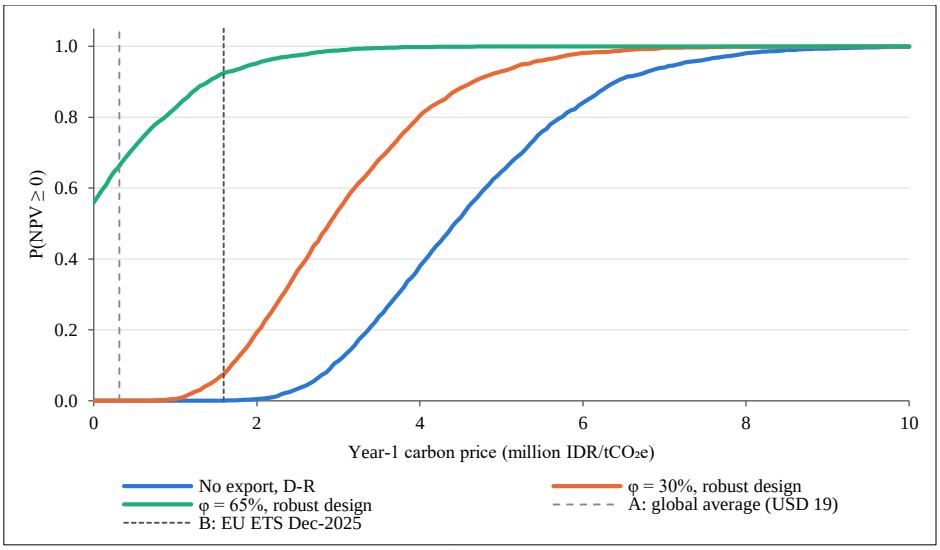

Fig. 5 Probability of a nonnegative NPV versus the year-1 carbon price from 3,000 Monte Carlo draws (Route T, L* = 0.10). Line A marks the global average price, which lies above the carbon tax and the IDXCarbon prices; line B marks the EU allowance benchmark of December 2025.

Table 4. Monte Carlo break-even carbon price and probability of viability (route T, L* = 0.10)

Policy case/design	BECP P10	BECP P50	BECP P90	P_v at IDR 144k benchmark	P_v at EU ETS
φ = 0, D-R	2.93	4.43	6.40	0.000	0.000
φ = 0.30, robust (190/250)	1.69	2.90	4.65	0.000	0.075
φ = 0.65, robust D-65 (280/275)	0	0	1.41	0.608	0.924

BECP in million IDR/tCO₂e; the robust design minimizes the median BECP across draws.

The rank correlations with the BECP of D-R identify carbon-price escalation (ρ = -0.59) and the discount rate (ρ = +0.55) as the dominant drivers, followed by BESS cost (+0.38), ICEV fuel economy (+0.23), credit haircut (+0.23), and PV cost (+0.19). Tariffs and the decline of the grid emission factor have little influence (|ρ| ≤ 0.05). The tornado diagram in Figure 6 confirms this ranking: a 10% discount rate raises the threshold of D-R to IDR 8.08 million, whereas a 5% annual escalation of the carbon price lowers the year-1 threshold to IDR 2.32 million. Because the credits of a growing station are back-loaded, from 18 tonnes in year 1 to 93 tonnes in year 25 for D-R, any mechanism that raises the value of later credits, such as a published price floor with an escalation path, is more effective than a higher initial price.

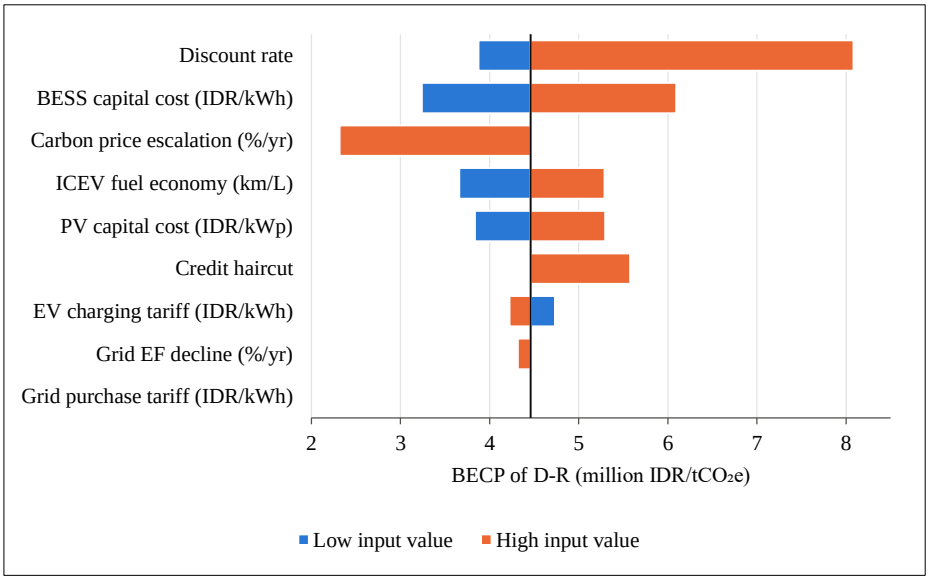

Fig. 6 One-at-a-Time sensitivity of the break-even carbon price of D-R (Route T, market cost, φ = 0) to the Monte Carlo input ranges of Table 1

4.5. Crediting Period and Transaction Costs

The back-loading of credits makes the crediting period decisive (Table 5). If D-R could credit only its first 7 years, its threshold would rise to IDR 19.4 million/tCO_2e, and a 10-year period would still require IDR 12.1 million, compared with IDR 4.46 million for full 25-year crediting. With 65% export remuneration, the corresponding values are IDR 5.96, 3.72, 2.27, and 1.37 million. An annual MRV cost of IDR 50 million adds between IDR 0.9 and 1.6 million/tCO_2e, because D-R generates only about 64 creditable tonnes per year on average.

A standalone project of this size therefore cannot absorb conventional validation and verification costs, which points towards grouped registration in which many charging sites share one MRV system [26].

Table 5. Break-even carbon price of D-R by crediting period and annual MRV cost (Million IDR/tCO_2e, route T)

Crediting period	φ = 0, MRV 0	φ = 0, MRV 25 M	φ = 0, MRV 50 M	φ = 0.65, MRV 0	φ = 0.65, MRV 50 M
7 years	19.42	20.22	21.02	5.96	7.55
10 years	12.12	12.78	13.45	3.72	5.04
15 years	7.40	7.94	8.49	2.27	3.36
25 years	4.46	4.91	5.35	1.37	2.26

4.6. Implications and Limitations

Three policy implications follow. First, at market capital costs, carbon revenue alone is insufficient to finance a reliable PV-BESS charging station at this site because the required BECP is far above domestic carbon-market benchmarks. Second, partial export remuneration is a more efficient economic lever: a 50% export-remuneration fraction closes the financing gap without carbon revenue, while 30-40% remuneration substantially reduces the remaining carbon-price requirement.

Third, crediting design matters alongside price: longer crediting periods, predictable price escalation, and pooled MRV can materially reduce the required year-1 carbon price. These results should be interpreted within the model limitations.

The 66kW import limit is an assumption about the existing connection; a grid upgrade was not costed. Demand growth is scenario-based, PV degradation and BESS capacity fade are not modeled, and the queueing screen relies on Markovian arrival and service assumptions.

The two crediting routes are simplified representations and would require additionality, baseline, MRV, and double-counting tests under an applicable crediting framework. In this study, MRV is shown only as a fixed annual cost that is discounted over the crediting period. There is no real monitoring, reporting, or third-party verification by an accredited body. As a result, the emission reductions that can be credited are based on model estimates from simulated energy flows.

The MRV cost should be seen as a planning assumption, not an actual verification fee. Benchmark prices are time-sensitive and should therefore be updated when the framework is applied to future investment decisions.

4.7. Comparison with Previous Studies

The results agree in direction with earlier work but differ in magnitude, and the differences can be traced to the scope of each study. The BECP of IDR 4.46 million/tCO_2e (about USD 270/tCO_2e at IDR 16,500 per USD) is far above the USD 20/t at which carbon pricing was found to favor solar charging in the Shenzhen case [16], above the USD 10/t incentive reported to make a proposed 26 MW solar plant viable in Indonesia [28], and above the USD 35/t level beyond which the Indonesian power-sector model shows a significant change in the generation profile [27].

Three features of the present problem help to explain the gap. First, those studies address different systems and do not impose the present service requirement, whereas the admissible designs here must combine at least 90 kWp of PV with storage to reach LPSP ≤ 0.10, which raises the capital to be recovered. Second, the station is small, and D-R generates only about 64 creditable tonnes per year, so carbon revenue per unit of capital is limited. Third, the observed demand of 17.0 MWh in year 1 is low relative to the installed capacity, and the projected growth to 7.93 times the year-1 level is reached only at the end of the 25-year period.

The finding that export remuneration is the more effective lever is consistent with the large reduction in net present cost reported when grid sales are allowed [18], with the identification of the export rate as the main barrier to rooftop PV in Indonesia [32], and with the observation that net metering alone leaves residential economics negative [33].

The present analysis adds a quantitative exchange rate between the two instruments: at $L^* = 0.10$, an export remuneration of 50% removes the need for carbon revenue, whereas 30% lowers the threshold from IDR 4.46 to 2.53 million/tCO_2e.

The modest role of credits also contrasts with the VM0038 case in India, where the credit value was estimated at up to about 31% above the annual profit [25]. That estimate relates credits to the profit of an operating station, while here they are compared with a financing gap of IDR 3.53 billion in the D-R design. The comparison is indicative, because the studies differ in cost base, tariffs, accounting boundary, and year of analysis. Table 6 summarizes the reported scope of representative studies and the aspects that are treated differently in the present work.

Table 6. Comparison of this study with representative earlier studies

Study	Scope and carbon-price treatment	Treated differently in this study
[16]	Solar-powered charging station in Shenzhen; carbon price as sensitivity, with a threshold near USD 20/t	Break-even price solved per design; service screen; export and crediting routes
[17]	Solar carport in Kaohsiung; carbon-tax scenarios applied to driver economics	No fixed tax scenario; threshold solved under a service constraint
[23]	PV with storage for EV charging; carbon tax scenarios raise storage and self-consumption	Break-even price solved; LPSP and queue screen; export remuneration and MRV cost analyzed
[18]	Highway solar charging; grid sale and carbon price as future scenarios	Carbon price is solved, not assumed; crediting route and MRV added
[24]	Hybrid renewable charging in Abu Dhabi; carbon-credit saving reported as an annual value	Credits give a required price instead of a resulting value
[25]	Carbon-credit potential of a charging station under VM0038	Credits compared with the financing gap, with period, haircut and MRV cost
[28]	Proposed 26 MW solar plant in Indonesia (RETScreen); USD 10/t incentive makes it viable	Small PV-BESS charging station with service constraint and Monte Carlo
[38]	Fast-charging PV and storage planning; waiting and rejection penalties in cost	Service quality as admissibility condition; carbon price solved
This study	Break-even carbon price for each of 8,525 designs, service screen, two crediting routes, export remuneration, 3,000 Monte Carlo draws	-

Scope as reported by the cited studies; USD values as stated in the sources.

5. Conclusion

This study quantified the carbon price at which a service-reliable PV-BESS charging station in Bandar Lampung becomes financially viable. By separating price-independent dispatch from the economic layer, the BECP of 8,525 configurations was obtained in closed form and evaluated against reliability targets, crediting routes, export remuneration, and uncertainty. At market capital costs, without export remuneration, and for $L^* = 0.10$ with waiting times below 5 min, the minimum threshold is IDR 4.46 million/tCO_2e, with a Monte Carlo median of IDR 4.43 million/tCO_2e and zero viability at the benchmark carbon prices considered. The threshold rises with stricter reliability, is 14-20% higher under renewable-displacement crediting than under transport-displacement crediting, and approximately halves when utilization doubles. Under the low-cost sensitivity case, the threshold falls to IDR 0.26 million/tCO_2e.

Export remuneration of 50% removes the need for carbon revenue, while 65% remuneration makes the robust design viable in 55.9% of draws without carbon revenue and in 92.4% at the EU benchmark. Crediting periods of 15 years or less increase the threshold to at least IDR 7.4 million/tCO_2e, and an annual MRV cost of IDR 50 million adds up to IDR 1.6 million/tCO_2e. Carbon incentives are therefore better interpreted as a complementary policy instrument to export remuneration rather than as a standalone mechanism for reliable solar-assisted charging. Future work should cost grid-connection upgrades as an alternative, include component degradation, and extend the analysis to multiple sites and formal crediting methodologies.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author Contributions

H.G.: conceptualization, methodology, software, formal analysis, and writing-original draft. A.S.S.: electrical-system methodology, supervision, and critical review. D.D.: power-system modeling, validation, and critical review. F.D.: techno-economic and carbon-pricing analysis, critical review, and editing. All authors reviewed and approved the final manuscript.

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