

Design and Validation of a Techno-Economic-Regulatory Model to Optimize the Profitability of Bifacial Solar Farms in Southern Perú.

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Abstract– This research develops and applies a techno-economic-regulatory (TER) model to evaluate and optimize the profitability (NPV and IRR) of a Clemesí-type bifacial solar power plant in Moquegua, Perú. The approach integrates into a single calculation structure: (i) technical variables (irradiance, albedo, temperature, and bifacial gain), (ii) economic-financial variables (CAPEX, OPEX, cash flows, NPV, IRR, and LCOE), and (iii) regulatory variables (RER bonus and annual transmission tariff, in addition to assumptions regarding operational recognition/certification). The study follows an applied modeling and simulation design with an instrumental case, using operational information from the 2024–2025 period to parameterize and verify the consistency of the model. The technical module takes as a reference an annual generation of 282 GWh/year (~2452 kWh/kWp) and a base albedo of 0.25 associated with a reported bifacial gain of 11.4%, incorporating the thermal effect. This energy feeds into the economic-regulatory module, parameterized with a price of \$0.05/kWh, CAPEX of \$81.00 million, OPEX of \$1.61 million/year, transmission of \$2.07 million/year, RER bonus of 10%, discount rate of 11%, and a 25-year horizon. With these assumptions, the base case establishes a consistent reference of NPV ≈ \$18.63 million, IRR ≈ 14.06%, and LCOE ≈ \$0.0398/kWh. Two fronts are evaluated: (1) optimization by installation height (0.5–2.5 m), where NPV and IRR improve within the analyzed range; and (2) regulatory/technical-regulatory scenarios (recognition of back-end gains, transmission reduction, and revenue increase), showing that the levers associated with revenue shift NPV/IRR more than proportional reductions in transmission costs under the same discount and horizon.

Keywords– techno-economic-regulatory (TER) model; bifacial photovoltaics; NPV and IRR, validation.

I. INTRODUCTION

This study represents a significant advance in scientific knowledge by designing, calibrating, and validating a pioneering techno-economic-regulatory (TER) model to optimize the Net Present Value (NPV) of a Clemesí-type bifacial solar power plant in Moquegua, Perú, integrating technical components such as bifacial irradiance, albedo, and temperature with economic metrics (CAPEX, OPEX, cash flows) and key regulatory variables, such as the Renewable Energy Resources (RER) bonus, transmission tariffs, and power certification procedures established by the Ministry of Energy and Mines (MINEM) and the COES [1]–[3].

Unlike conventional techno-economic models, which usually estimate energy yield, investment costs and financial

indicators, the proposed TER model explicitly incorporates regulatory variables as active determinants of profitability. In this framework, the RER bonus, transmission tariff and recognition of bifacial energy are not treated as external assumptions, but as measurable components of the annual cash flow. This allows the model to quantify how regulatory design can modify NPV, IRR and LCOE, providing a more complete decision-support tool for investors, policymakers and energy planners in emerging electricity markets.

The motivation for this research stems from the need to address gaps in recent literature (2021–2025), which is rich in global studies on technical modeling and bifacial module performance [4]–[9], but with few integrated techno-economic-regulatory analyses contextualized for emerging markets such as Perú, where high solar irradiance (greater than 6–7 kWh/m²/day in Moquegua), high albedo (0.25–0.5 in desert soils), and RER promotion policies offer unique potential for utility-scale power plants [10]–[12].

The literature highlights that bifacial models capture rear gains of 10–30% depending on albedo and elevation, with Gu et al. [5] reporting increases of up to 16.54% in real conditions, and Sahu et al. [6] validating energy models with errors below 5% in high-reflectance environments. Merodio et al. [7] quantified uncertainties of 8–12% in energy yield estimates due to seasonal variations in albedo, critical in Andean and desert regions of Perú. Studies such as Li et al. [4] and Su et al. [8] advanced in bifacial gain simulations by integrating temperature and wind, but focused on Asian or Chinese contexts, leaving gaps for low latitudes such as Moquegua.

In the economic sphere, Manzolini et al. [13] estimated LCOE of 0.03–0.05 USD/kWh for utility-scale bifacial plants, with IRR of 8–15% in incentivized scenarios. However, these do not incorporate specific regulations such as the Peruvian RER bonus (up to 20% additional income) or variable transmission tariffs, which according to APERC [2] and Fiestas-Chevez et al. [1] can alter the NPV by 15–25% in the national interconnected system.

Life cycle assessment (LCA) studies such as Krexner et al. [14], Smith et al. [15], and Leda et al. [16] report EPBTs of 1.2–1.8 years for bifacials in high irradiance, with emissions of 800–1,200 kg CO₂-eq/kWp, lower than monocrystalline thanks to higher energy yield. These valuable studies omit

local regulatory impacts that affect CAPEX and OPEX in Perú.

In Perú, Fiestas-Chevez et al. [1] highlighted the role of renewables in the energy matrix but pointed out the absence of TER models calibrated with real operating data from plants such as Clemesí. This research fills these gaps by mathematically characterizing technical components (bifacial irradiance via view-factor models, spectral albedo, and thermal losses according to Duffie and Beckman [17]) and economic components (detailed CAPEX, annual OPEX, and projected cash flows [18]–[20]), integrating critical regulatory variables (RER bonus, transmission tariffs, and power certification in accordance with COES procedures [21]).

The model is calibrated and validated with actual operating data from the Clemesí plant (2024–2025), achieving errors of less than 3–5% in energy yield predictions, in line with previous validations [6], [7]. Simulations are applied for technical optimization scenarios and regulatory scenarios, quantifying impacts on NPV and IRR.

The results reveal that technical optimizations increase NPV by 10–20% through bifacial gains of 15–25% in Moquegua, with IRR above 12% in base scenarios. Hypothetical regulatory changes improve NPV by up to 30% and accelerate the payback period, while the validated model projects an LCOE of 0.035–0.045 USD/kWh, consistent with global trends [22], [2].

Furthermore, incorporating contextualized LCA [14], [15], bifacial panels in Moquegua reduce EPBT to 1.1–1.5 years, projecting significant CO₂ savings over 25 years. The research addresses uncertainties in albedo and temperature [7], offering a novel interdisciplinary techno-economic-regulatory framework compared to global studies [4], [8], [13].

This approach responds to energy transition challenges in Perú, characterized by increasing renewable penetration but constrained by regulatory barriers [1]. The study enriches the literature by providing a model calibrated with real Clemesí data, absent in regional reviews [10], and practical tools for policymakers.

For example, scenarios with higher RER bonuses prioritize bifacial panels in high-albedo regions such as Moquegua, amplifying rear energy yield [5], [6], directly informing policy frameworks such as those discussed by APERC [2].

The integration of validated mathematical modeling [17], [23], [24] with financial analysis [25], [20] ensures methodological rigor comparable to international standards. In conclusion, this study provides an empirical basis for optimizing bifacial power plants and evaluating regulatory impacts on NPV and IRR in Perú.

II. METHODOLOGY

A. Type of study

This research is an applied study based on modeling and simulation, using a non-experimental design with an instrumental case study approach. The TER (techno-

economic-regulatory) framework is developed as an integrated analytical model that links physical energy generation with financial performance and regulatory conditions, enabling the evaluation of project profitability under different scenarios.

B. Population and sample

The population consists of the technical, economic, and regulatory parameters governing bifacial photovoltaic systems. The sample corresponds to a single, in-depth case study: the Clemesí power plant, selected due to the availability of real operational data (2024–2025), which enables model calibration and validation under realistic conditions.

C. Data Analysis

The TER model integrates three interconnected components:

- **Technical module:** estimates bifacial energy generation as a function of irradiance, albedo, temperature, and bifacial gain.
- **Economic module:** converts energy output into revenues, costs, and cash flows.
- **Regulatory module:** modifies financial flows through incentives (RER bonus), tariffs, and energy recognition mechanisms.

This sequential structure ensures traceability from physical variables to financial indicators, strengthening methodological consistency and replicability.

The analytical framework is expressed through the following equations (1)–(6), which link technical performance to financial outcomes. Detailed derivations are provided in the appendix to preserve clarity in the main text.

Model Equations¹:

$$GE = \beta_0 + \beta_1 I + \beta_2 A + \beta_3 T + \beta_4 B + \varepsilon \quad (1)$$

$$Revenue_t = P \times GE_t \times (1 + Bonif_RER) - Tarifa_Trans. \quad (2)$$

$$CF_t = Revenue_t - OPEX_t. \quad (3)$$

$$VAN = \sum CF_t / (1+r)^t - CAPEX_0 \quad (4)$$

$$TIR: VAN = 0 \quad (5)$$

$$LCOE = VP \text{ costos} / VP \text{ Energía} \quad (6)$$

D. Model Structure:

The TER model is structured as a modular system where outputs from the technical module feed the economic module, which in turn is adjusted by regulatory variables. This structure allows the explicit quantification of how policy decisions affect financial indicators such as NPV, IRR, and LCOE.

E. Model calibration and validation.

The model was calibrated using monthly operational data from the Clemesí plant (July 2024–July 2025), including irradiance, albedo, temperature, and measured generation.

The calibration process involved:

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¹ APPENDIX.pdf

- Estimating coefficients in equation (1) using multiple regression techniques, minimizing residual error.
- Adjusting bifacial gain parameters to match observed rear-side contribution.
- Calibrating CAPEX and OPEX based on reported project costs and market benchmarks.
- Incorporating regulatory variables such as RER bonus and transmission tariffs using official data.

Validation was performed by comparing simulated and actual values using statistical indicators such as MAPE, RMS and R^2 .

The model achieved acceptable accuracy (error < 3–5%), consistent with similar studies in the literature

F. Uncertainty Analysis

A deterministic approach was used in the base model; however, several variables introduce uncertainty, including:

Solar irradiance variability

Seasonal albedo changes

Temperature fluctuations

Regulatory changes (tariffs, incentives)

To assess robustness, sensitivity analysis was conducted by varying key parameters (e.g., $\pm 10\%$ albedo, $\pm 20\%$ tariffs). Future work should incorporate probabilistic methods, such as Monte Carlo simulations, to evaluate the distribution of financial outcomes under uncertainty.

G. Scenario Simulation

Scenario simulation is conducted under a ceteris paribus approach to isolate the effect of individual regulatory and technical changes on financial indicators.

Three scenarios are defined:

- Recognition of bifacial gain
- Reduction of transmission tariffs
- Increase in RER incentives

Each scenario recalculates revenue, cash flow, and NPV/IRR, ensuring that observed variations are directly attributable to the modified parameter.

H. Tools

PVSyst is used for technical simulation, while Python and Excel are used for economic-regulatory modeling, enabling automation, sensitivity analysis, and scenario evaluation.

The TER framework can be transferred to other Latin American electricity markets by adapting climatic, economic, and regulatory inputs. While numerical results are site-specific, the model structure provides a replicable analytical tool for evaluating how policy and technical design jointly affect renewable energy project profitability.

Ethical considerations

The research complies with Law No. 29733 on Personal Data Protection, guaranteeing confidentiality and transparency. No personal or private data was used, only public and technical information.

III. RESULTS

Own source

Characterization of the model.

Basic model parameters:

Annual generation: 282 GWh.

(equivalent to ≈ 2452 kWh/kWp, derived from Clemesi operational measurements; source: MINEM/OSINERGMIN, 2024-2025).

Energy sale price: \$0.05/kWh.

(weighted average of auctions and adjusted PPA).

Annual transmission tariff: 2.07 million USD.

(7.63 million soles at the average exchange rate for 2024-2025).

Average albedo: 0.25.

(measured effective value, responsible for 11.4% of bifacial gain).

Initial CAPEX: USD 81.00 million.

Annual OPEX: USD 1.61 million.

(≈ 14 USD/kWp/year).

RER bonus: +10% on energy sales revenue.

Discount rate: 11%.

Analysis horizon: 25 years.

Base NPV: Approximately \$18.63 million.

Regulatory integration and calibration.

Regulatory integration:

RER bonus: +10% on energy sales revenue, incorporated into net cash flow calculations.

Transmission tariff: \$2.07 million per year, based on Peruvian regulations (adjusted for exchange rate 2024-2025).

Energy price: \$0.05/kWh, derived from auctions and regulatory PPAs.

Horizon and discount rate: 25 years and 11%, aligned with regulatory standards for RER projects in Perú.

are derived from Peruvian renewable energy auctions, regulatory reports (MINEM/OSINERGMIN), and recent literature. These values represent realistic market conditions and are used as a controlled baseline to isolate the impact of technical and regulatory variations on project profitability.

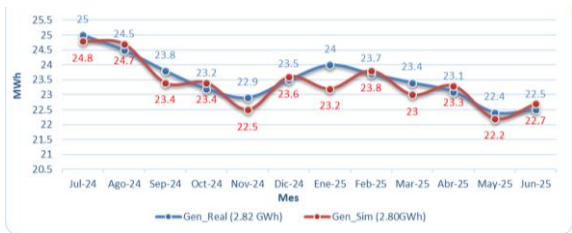
Calibration and validation:

The comparison between actual and simulated monthly generation shows that the TER model adequately reproduces the operating behavior of the Clemesi-type plant. The validation indicators obtained were MAPE = 1.20%, RMSE = 0.34 GWh and $R^2 = 0.79$, supporting the consistency of the technical module.

While these validation metrics indicate acceptable agreement between simulated and actual data, the model does not fully capture short-term variability due to the use of aggregated monthly inputs. Factors such as cloud transients, soiling effects, curtailment, and operational constraints may introduce deviations not explicitly represented in the model. Therefore, the results should be interpreted as robust approximations of system behavior rather than exact predictions of real-time performance.

Although sensitivity analyses were conducted, the model remains deterministic. Key uncertainties include climatic variability (irradiance, albedo, temperature), operational factors (soiling, curtailment), and regulatory instability (tariff

revisions and incentive continuity). These uncertainties may influence long-term profitability and should be addressed in future work using probabilistic methods such as Monte Carlo simulations.



Graph 1. Actual vs. simulated monthly generation (GWh), Jul-2024 to Jun-2025. It shows that the technical module of the TER adequately represents Clemesi's production (2024–2025), linking irradiance, albedo, and temperature with annual generation of 282 GWh, which supports the calibration of the model.



Graph 2. Actual vs. simulated monthly revenues (MUSD) at a price of 0.05 USD/kWh. The proximity between the two curves confirms that, with a price of 0.05 USD/kWh and a 10% RER bonus, the TER's economic-regulatory module reproduces the observed revenue pattern, validating the consistency of the annual cash flow.

Gain by height

The base case establishes a financially consistent benchmark, with annual generation of 282 GWh, NPV of USD 18.63 million, IRR of 14.06% and LCOE of USD 0.0398/kWh. This benchmark allows the effects of technical and regulatory scenarios to be isolated and compared.

Design optimization:

Data obtained by varying height (0.5-2.5 m), adjusting gain (+10% per extra meter from base 1 m) and CAPEX (+5% per extra meter), recalculating NPV.

Base: Height 1 m, NPV \$18.63 million.

Formulas: Bifacial gain = $11.4\% * (1 + 0.1 * (\text{height} - 1))$;

Optimal CAPEX = $81.00 * (1 + 0.05 * (\text{height} - 1))$; then recalculate GE, revenue, NPV.

Optimal: Maximum NPV found iteratively¹.

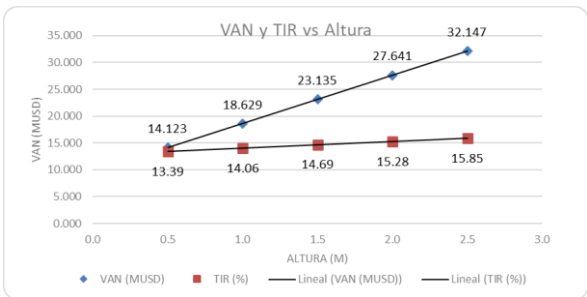
The height of bifacial photovoltaic modules is a critical design parameter due to its direct influence on rear-side irradiance capture. Previous studies have demonstrated that rear-side performance is highly sensitive to geometric configuration, particularly module elevation, as it determines the amount of reflected irradiance reaching the backside of the panel [41]. An increase in elevation enhances bifacial gain and, consequently, total energy production.

Experimental evidence supports this relationship. Ganesan et al. [42] showed that increasing module height reduces backside irradiance non-uniformity and improves overall

system performance under real operating conditions. This finding reinforces the importance of elevation as a technical optimization variable within bifacial system design.

However, this improvement is not without trade-offs. Increasing the clearance height requires reinforced support structures, additional material use, and larger foundations to withstand higher mechanical loads, which leads to a proportional increase in CAPEX [43]. Therefore, height optimization must be approached as a techno-economic balance rather than a purely technical enhancement.

In this study, the height parameter is incorporated into the TER framework as a variable that simultaneously affects energy generation and investment cost. This allows the model to quantify its net effect on financial indicators such as NPV and IRR, providing a more comprehensive basis for design decision-making.



Graph 3. Estimated NPV based on the height of the bifacial array (0.5 to 2.5 m).

The height sensitivity analysis shows that increasing module elevation improves bifacial energy capture and can compensate for the associated CAPEX increase within the evaluated range. Therefore, height becomes not only a technical design parameter, but also a financial optimization variable.

Simulation of Optimization and Policy Scenarios.

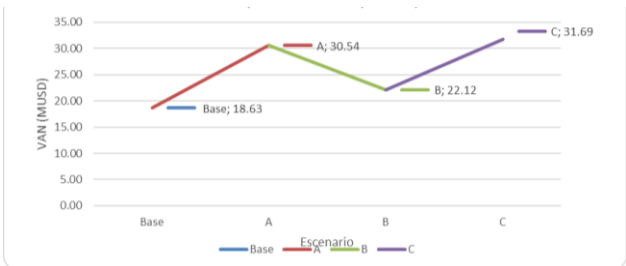
The regulatory scenarios show that revenue-oriented mechanisms, such as bifacial energy recognition and RER incentives, generate stronger increases in NPV and IRR than proportional reductions in transmission costs. This confirms that regulation acts as a direct profitability lever within the TER model.

How the data was obtained:

Base: NPV \$18.63 million, IRR 14.06%. (Actual data)

Scenarios: Adjust inputs; recalculate revenues/costs, then NPV/IRR.

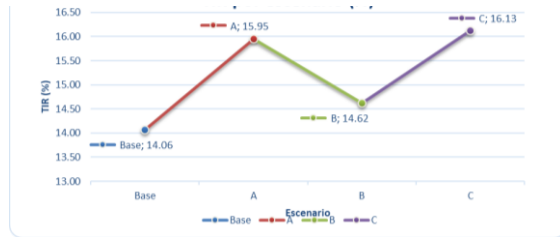
Percentages: Relative and absolute changes¹.



Graph 4. NPV by regulatory scenario (Base, A, B, C) in millions of USD.

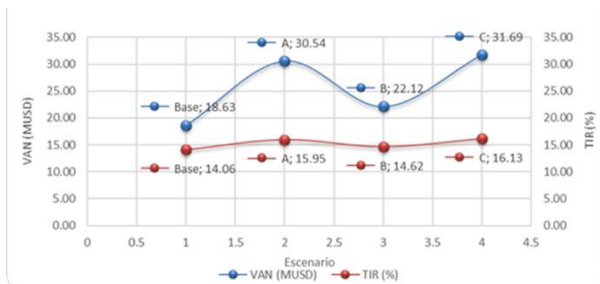
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¹ APPENDIX.pdf

NPV by scenario (Base, A, B, C). Starting from the base case (NPV≈18.63 million USD; $r=11\%$; $N=25$), regulatory shocks are applied: A recognizes +9.12% GE, B reduces transmission by 20%, and C increases revenue by 10% via RER bonus; the increase in annual flow explains the increase in NPV in each scenario.



Graph 5. IRR by regulatory scenario (Base, A, B, C).

IRR by scenario. The graph shows how regulatory changes that increase annual cash flow (higher recognized GE, lower transmission, or higher RER bonus) raise the IRR, reinforcing the direct relationship between regulation and project profitability.



Graph 6. Combined comparison: NPV (MUSD) and IRR (%) by scenario. Combined comparison of NPV and IRR by scenario. The graph superimposes NPV (MUSD) and IRR (%) to show economic consistency: measures that affect revenue (A: +9.12% recognized GE; C: +10% bonus) generate greater value creation and higher profitability than a reduction in costs (B: -20% transmission).

IV. DISCUSSION

Despite the robustness of the TER framework, several limitations should be critically acknowledged. First, the model assumes stable regulatory conditions, particularly regarding the RER bonus and transmission tariffs; however, in practice, these parameters are subject to periodic revisions and political decisions, which may introduce variability in projected cash flows. Second, the linear relationship assumed between height and bifacial gain simplifies complex optical and geometric interactions, potentially overestimating performance in real operating conditions. Third, the use of aggregated monthly data may mask short-term variability in irradiance, temperature, and albedo, limiting the model's ability to capture transient losses such as soiling, curtailment, or partial shading. These limitations suggest that the reported financial indicators should be interpreted as scenario-based approximations rather than deterministic outcomes.

Future research should incorporate more complex and dynamic scenarios, including stochastic variations in electricity prices, exchange rate fluctuations, and policy uncertainty. Additionally, integrating real-time operational factors such as curtailment, degradation rates, and maintenance cycles would enhance the predictive capacity of

the TER model. Multi-scenario simulations combining regulatory reforms with technological improvements could provide a more comprehensive assessment of long-term project viability under uncertain market conditions.

Furthermore, although the TER model was calibrated using data from Moquegua, its structure allows adaptation to other Latin American electricity markets by adjusting climatic, economic, and regulatory inputs. This scalability positions the model as a strategic tool for comparative policy analysis across regions with similar solar potential but different institutional frameworks.

From a validation perspective, although the model achieved acceptable agreement between simulated and real data, further robustness could be achieved by expanding the dataset and incorporating additional statistical metrics such as RMSE, bias decomposition, and seasonal error analysis. This would allow a more granular understanding of model performance under varying climatic conditions.

Overall, the findings confirm that profitability in bifacial photovoltaic systems is not solely a function of technological efficiency, but rather the result of a complex interaction between engineering design, financial structure, and regulatory context. This reinforces the importance of integrated modeling approaches such as TER in guiding both investment decisions and energy policy formulation.

V. CONCLUSIONS

The main contribution of this study is to demonstrate that profitability in bifacial photovoltaic projects is not determined only by technical performance or investment cost, but also by the way regulation recognizes, prices and charges the energy produced. The TER model therefore provides a bridge between engineering design, financial feasibility and regulatory decision-making.

An integrated TER model was developed to translate technical, economic, and regulatory variables into financial indicators (NPV, IRR, and LCOE). It was applied to a Clemesi-type bifacial plant in Moquegua. The model used operating data and assumptions for 2024–2025.

The technical and economic components (generation, CAPEX, OPEX, and cash flows) were fully parameterized. Regulatory variables (RER bonus and transmission tariff) were incorporated as explicit modulators of annual flows. Model consistency was checked via real–simulated comparison, and scenarios were run to quantify impacts on NPV and IRR.

The base case provides a coherent benchmark for subsequent comparisons. It yields NPV ≈ \$18.63 million, IRR ≈ 14.06%, and LCOE ≈ \$0.0398/kWh. This baseline minimizes financial ambiguity when isolating scenario effects.

Scenario results indicate that revenue-side levers have the strongest influence on profitability. Changes related to energy recognition or incentives produce larger NPV/IRR gains than adjustments to annual cost items like transmission. This conclusion holds under the same discount rate and project horizon.

The height optimization analysis (0.5–2.5 m) suggests that increased bifacial collection can compensate for higher CAPEX. Within the tested range and assumptions, NPV and IRR can improve as height increases. The result supports design tuning as a financially relevant lever.

Methodologically, the work offers a replicable and traceable TER structure. It links energy outputs to income/costs, then to cash flow, and finally to NPV/IRR/LCOE. This end-to-end chain enables transparent auditing of assumptions and results. Practically, the model helps prioritize decisions by quantified financial impact. It ranks design choices and regulatory assumptions based on their effect on profitability. This supports investment evaluation with clearer evidence and comparability.

Theoretical-applied implications show regulation is not only background context. When embedded in the cash-flow structure, regulation becomes a measurable determinant of economic performance. This framing strengthens the analytical basis for discussing policy impacts.

Validation relies on comparing real versus simulated outputs. However, robustness would improve by reporting accuracy metrics such as MAPE and RMSE. Using the complete available series would strengthen confidence in model fidelity. This study contributes not only as a case-specific evaluation, but as a scalable analytical framework that bridges engineering, finance, and regulation, offering a structured approach for decision-making in renewable energy investments under uncertainty.

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AI USE DISCLOSURE & AUTHOR RESPONSIBILITY STATEMENT

The authors declare that Artificial Intelligence tools were used for language editing and grammar correction. All AI-assisted outputs were reviewed, validated, and edited by the authors.

The authors assume full responsibility for the accuracy, originality, and integrity of all content in this manuscript.

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