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Multi-Objective Techno-Economic and Environmental Assessment of Decentralized PV Integration in Conventional Distribution Networks under Uncertainty

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Abstract

This paper presents a comprehensive techno-economic and environmental assessment of decentralized photovoltaic (PV) injection into a conventional medium/low voltage (15 kV/0.4 kV) distribution network dominated by thermal generation. The study integrates deterministic and probabilistic approaches over a 25-year planning horizon. A mathematical framework incorporating PV degradation, generator failure rates, fuel cost variability, and policy-related uncertainties is developed. Economic performance is evaluated using Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Energy (LCOE), while environmental performance is assessed through CO_2 emission reduction. Monte Carlo simulations demonstrate that decentralized PV injection remains economically viable in more than 95% of simulated uncertainty scenarios. The results confirm the structural vulnerability of thermal generation and highlight the strategic role of decentralized PV systems in improving sustainability and economic resilience in developing power systems.

Keywords

Distribution Network, Techno-Economic Analysis, CO_2 Emissions, Renewable Integration, Uncertainty Modeling

1. Introduction

Distributed PV generation has rapidly expanded as costs decline and incentive policies emerge worldwide. However, integrating high PV penetration into conventional distribution networks introduces technical, economic, and environmental challenges [1]-[3]. Traditional grid systems often rely on thermal generation, creating high operational costs and greenhouse gas emissions. Integrating PV aims to reduce these burdens, but uncertainties such as PV degradation and generator reliability must be explicitly considered in planning studies [4].

Monte Carlo modeling and advanced techno-economic frameworks have been increasingly used to capture the impact of uncertainties on renewable integration [5]. While deterministic assessments provide baseline insights, stochastic approaches offer nuanced evaluation of performance under real-world variability [6]. Additionally, detailed LCOE analysis and comparative studies with storage components further inform sustainable deployment strategies [7]-[9].

This paper contributes a robust probabilistic analysis of decentralized PV integration under technical and economic uncertainties, evaluating impacts on energy production, cost structures, financial viability, and environmental emissions.

2. System Description

We consider a 15 kV/0.4 kV distribution network with 25 decentralized PV sites and 10 diesel generator units. The optimized PV capacity is 2024 kW across all sites. The diesel generators currently supply 77 MW nominally, with total installed thermal capacity of 158 MW. Annual operating hours are assumed at 3000 hours with a mean CO_2 emission factor of 483 kg/MWh [10]. The network currently produces approximately 111,573 tons of CO_2 annually.

3. Methodology

3.1. Input Data and Case Study Description

The input data used in this study were collected from various technical and scientific sources. The network demand is based on real operational data from the distribution network of N'Djamena for the reference year 2023, provided by the national electricity distribution operator.

The main parameters of the test distribution network are those presented in the following **Table 1**.

The calculated and retained values of PV production are presented in **Table 2** below.

The 25 photovoltaic sites were selected according to three criteria:

- proximity to existing distribution transformers;
- available land suitable for PV installation;
- high local electricity demand to maximize self-consumption and minimize feeder losses.

The solar resource potential was estimated using international climatic databases, namely NASA Surface Meteorology and Solar Energy (NASA SSE) [10] and PVGIS (Photovoltaic Geographical Information System) [11], indicating an average annual solar irradiation of approximately:

Table 1. Mains parameters of the test distribution network.

Parameters	Values
Network studied	MV/LV network of N'Djamena
Reference year	2023
Temporal resolution	Daily (24 H)
Number of transformer stations	90
Approximate length of feeders	0.8 Km
Maximum power demand	8 MW
Installed diesel power	4 MW

Table 2. Calculated and retained values of PV production.

Parameters	Calculated and retained Values
Measured PV power	638 kW
Optimised PV power	2024 kW
Annual Irradiation	2100 kWh/kW/year
Overall performance (Performance ratio)	0.80
Annual PV Production	3.40 GWh/year
Injection rate	80%
Injected energy	2.72 GWh/year
Annual fuel savings	800,000 USD/year
Annuual CO_2 reduction	1642 kg CO_2/year = 1.64 t CO_2/year
VAN	615,000 USD
Recovery time	2 years

$$G_{ann} = 2100\ \mathrm{kWh/m^2/year}$$

For the Sahelian region of N'Djamena.

The diesel fuel price was fixed at:

$$C_{diesel} = 1.45\ \mathrm{USD/L}$$

based on local energy market data and international fuel price statistics published by Global Petrol Prices [12].

The investment and maintenance costs of photovoltaic systems were extracted from recent technical reports published by the International Energy Agency and the International Renewable Energy Agency, particularly:

- IEA—Projected Costs of Generating Electricity [13];
- IRENA Renewable Power Generation Costs [14].

The discount rate was set to:

$$r = 10\%$$

in accordance with commonly adopted practices in techno-economic studies of energy projects in developing countries, as recommended in studies and reports published by the World Bank, International Renewable Energy Agency, and several techno-economic assessment studies conducted in Sub-Saharan Africa.

3.1.1. Photovoltaic Production Model

The annual photovoltaic energy production is calculated considering the optimized installed PV capacity, the annual solar irradiation, the performance ratio of the PV system, and the annual degradation of the PV modules. The annual PV energy production at year t is expressed as:

$$E_{PV}(t) = P_{PV} \times G \times PR \times (1-d)^t \tag{1}$$

where $E_{PV}(t)$ is the annual PV energy production (KWh/year), P_{PV} is the optimized installed PV capacity (kW), G is the annual solar irradiation (kWh/kW/year), PR is the performance ratio of the PV system, d is the annual PV degradation rate, and t is the operating year. A similar formulation models generator production with a failure rate factor included.

For the present study, the optimized PV capacity is **2024 kW**, the annual solar resource is **2100 kWh/kW/year**, the performance ratio is **0.80**, and the annual degradation rate is **0.8%**. Accordingly, the initial annual PV production is approximately **3.40 GWh/year**.

The energy effectively injected into the distribution network is determined using the injection ratio:

$$E_{inj}(t) = \eta_{inj} E_{PV}(t) \tag{2}$$

where η_{inj} represents the fraction of PV production effectively injected into the network. In this study, $\eta_{inj} = 0.80$.

3.1.2. Generator Production Model

The annual energy supplied by the diesel generator units is modeled according to their available generation capacity, annual operating hours, and failure rate. The annual diesel generation is expressed as:

$$E_{GE}(t) = P_{GE} \times H(1-f) \tag{3}$$

where E_{GE}, t is the annual diesel energy production (kWh/year), P_{GE} is the available diesel generation capacity (kW), H is the annual operating time (h/year), and f is the generator failure or unavailability rate.

For the reference system, the available diesel generation capacity is 77 MW, the annual operating time is 3000 h/year, and the assumed failure rate is 10%. Following PV integration, the residual diesel generation is reduced according to the amount of PV energy injected into the network.

3.1.3. Economic Model

The economic performance of the proposed PV integration is assessed using the net present value (NPV), internal rate of return (IRR), and payback period. The NPV is calculated as:

$$NPV = -CAPEX + \sum_{i=1}^{N} \frac{CF_t}{(1+r)^t} \tag{4}$$

where $CAPEX$ is the initial investment cost (USD), CF_t is the net cash flow in year t, r is the discount rate, and N is the project lifetime.

The annual net cash flow is calculated from the electricity sales revenue and the annual operating and maintenance expenditure:

$$CF_t = R_t - OPEX_t \tag{5}$$

where the annual electricity revenue is given by:

$$R_t = E_{inj}(t) \times T \tag{6}$$

where $E_{inj}(t)$ is the annual PV energy injected into the distribution network and T is the electricity sale tariff.

The internal rate of return is determined as the discount rate for which the NPV becomes zero:

$$NPV(IRR) = 0 \tag{7}$$

The payback period is determined as the first year in which the cumulative undiscounted cash flow becomes positive.

3.1.4. Environmental Model

The environmental assessment focuses on the operational CO_2 emissions avoided through PV integration, without considering embodied or life-cycle emissions associated with PV manufacturing, transportation, installation, or disposal.

The annual avoided CO_2 emissions are calculated as:

$$CO_{2,avoided}(t) = E_{inj}(t) \times EF \tag{8}$$

where CO_2, avoided, (t) represents the annual avoided CO_2 emissions, $E_{inj}(t)$ is the annual PV energy injected into the network, and EF is the diesel generation emission factor. An emission factor of **0.483 kgCO$_2$/kWh (483 kgCO$_2$/MWh)** is adopted.

4. Uncertainty Modeling

The following parameters in Table 3 are treated as random variables:

Table 3. Random variables.

Parameter	Distribution	Range
PV degradation	Uniform	0.5% - 1%
Solar irradiation	Normal	$\mu = 2100$, $\sigma = \ldots$
Generator failure rate	Uniform	5% - 15%
Injection tariff	Uniform	0.08 - 0.12 $/kWh
Fuel cost variation	±20%	
Subsidy	Uniform	0% - 3%

4.1. Monte Carlo Simulation

Uncertain parameters such as PV degradation rate, generator failure rate, tariff levels, and fuel price are modeled as uniform random variables. A Monte Carlo simulation with 1000 iterations generates probabilistic distributions of NPV and other metrics (Figure 1).

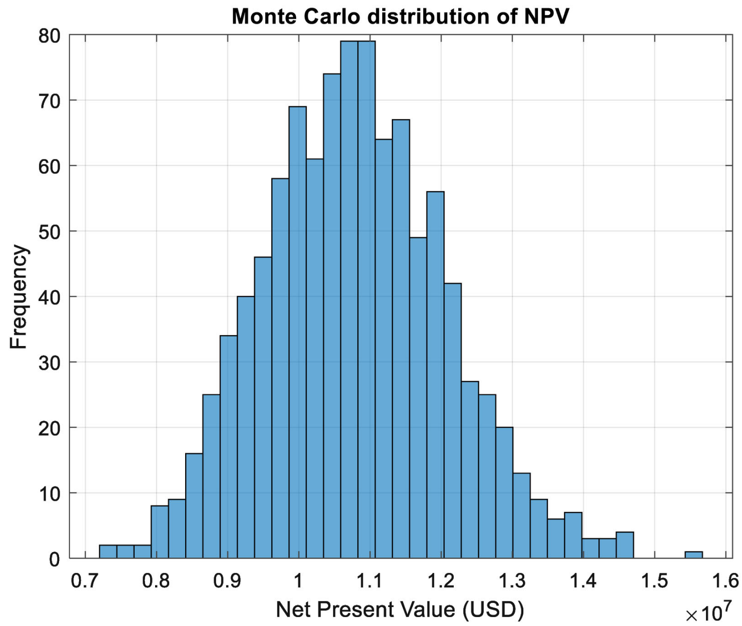

Figure 1. Histogram of net present value NPV.

The Monte Carlo analysis provides a risk-based economic evaluation of the photovoltaic project. The relatively narrow spread of the NPV distribution indicates low financial risk. The absence of negative NPV values means that the probability of economic loss is extremely low. Therefore, the project can be considered financially secure and robust against uncertainties such as PV degradation, fuel price fluctuations, and demand variability.

The following Table 4 presents results of Monte Carlo simulation on Net Present Value (NPV).

Table 4. Results of Monte Carlo simulation of NPV.

Indicator	Valeur
Average NPV	10,790,393 USD
Standard deviation	1,279,606 USD
Percentile 5%	8,796,502 USD
Median	10,730,546 USD
Percentile 95%	12,959,769 USD
Average LCOE	0,0313 USD/kWh
Average IRR	50%

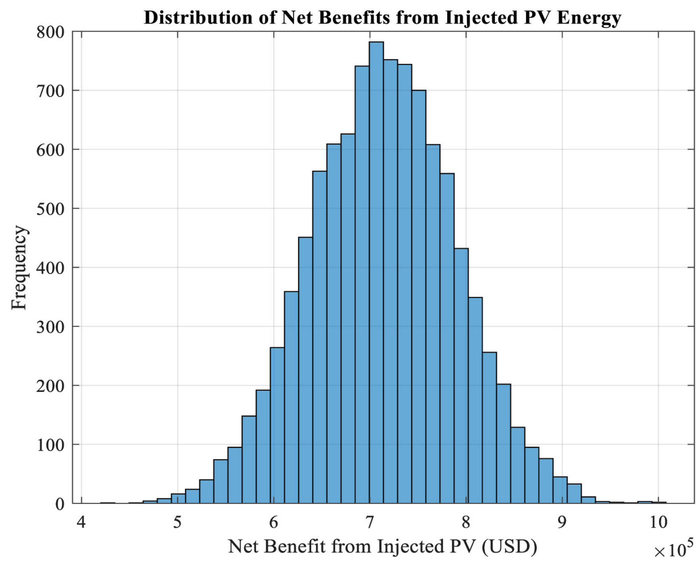

Figure 2. Histogram of net profit injected by PV.

This histogram represents the distribution of net profits generated by injecting photovoltaic electricity into the grid, simulated using a Monte Carlo analysis (thousands of scenarios with uncertainties regarding prices, production, etc.). We observe that:

- The distribution is right-skewed (slightly skewed towards higher profits).
- This shows that in most scenarios, the injected PV yields a reasonable economic gain.

We observe moderate but not excessive uncertainty, meaning that the investment is relatively robust.

Figure 2 is the equivalent of the previous one, but for the total cost of conventional diesel production, again using a Monte Carlo analysis (Figure 3). We observe that:

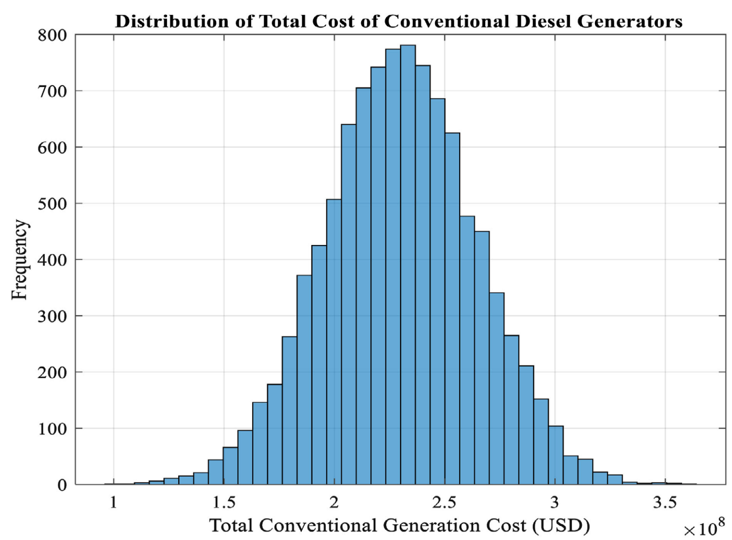

Figure 3. Histogram of the total cost of conventional (diesel) production.

- Diesel is not only expensive on average, but also highly unpredictable due to fluctuations in fuel prices, maintenance, etc.
- The curve is wider than that of PV, which means there is greater economic uncertainty with the thermal (diesel) production system.
- Compared to the previous figure, private PV is more economically stable.

Monte Carlo simulations were performed using normal probability distributions to model uncertainties in fuel costs, photovoltaic production, and economic parameters. The resulting histograms show bell-shaped distributions, indicating that most economic outcomes are concentrated around the expected values.

The net benefits from photovoltaic energy injection show a relatively narrow distribution, demonstrating economic stability and low investment risk. In contrast, the diesel generation cost distribution is wider, indicating higher economic uncertainty due to fuel price volatility.

Comparison with probabilistic studies in the literature shows the effectiveness of this approach in addressing PV penetration uncertainty [5] [6].

The following **Table 5** presents the probabilistic results of the MonteCarlo simulation numerically.

Table 5. Presentation of the probabilistic results of the MonteCarlo simulation.

Indicator	Average	Standard deviation	P5	Median	P95
NPV (USD)	**615,000**	**42,500**	**542,000**	**616,000**	**684,000**
Fuel savings (USD/year)	**800,000**	**38,000**	**735,000**	**801,000**	**862,000**
CO_2 reduction (t/year)	**1314**	**64**	**1205**	**1312**	**1422**

To verify the robustness of the uncertainty analysis, a convergence test was performed on the Monte Carlo simulation. The cumulative mean values of the Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Energy (LCOE) stabilized before reaching 1000 iterations, demonstrating that the selected number of simulations is sufficient to obtain statistically stable estimates. Therefore, 1000 Monte Carlo iterations were considered adequate for the probabilistic assessment. The following **Figure 4** present the convergence curve of NPV.

The convergence curves above show that the cumulative averages become practically stable after approximately **700 - 800 simulations**, while changes beyond **1000 simulations remain below 1%**, confirming that **1000 Monte Carlo iterations are sufficient** to obtain statistically stable estimates.

4.2. Levelized Cost of Energy (LCOE)

LCOE is a key comparative metric:

$$\text{LCOE} = \frac{\sum C_t}{\sum E_t} \tag{9}$$

This metric contrasts cost effectiveness across PV, generator, and hybrid storage scenarios, similar to approaches applied in grid analysis [7] [8].

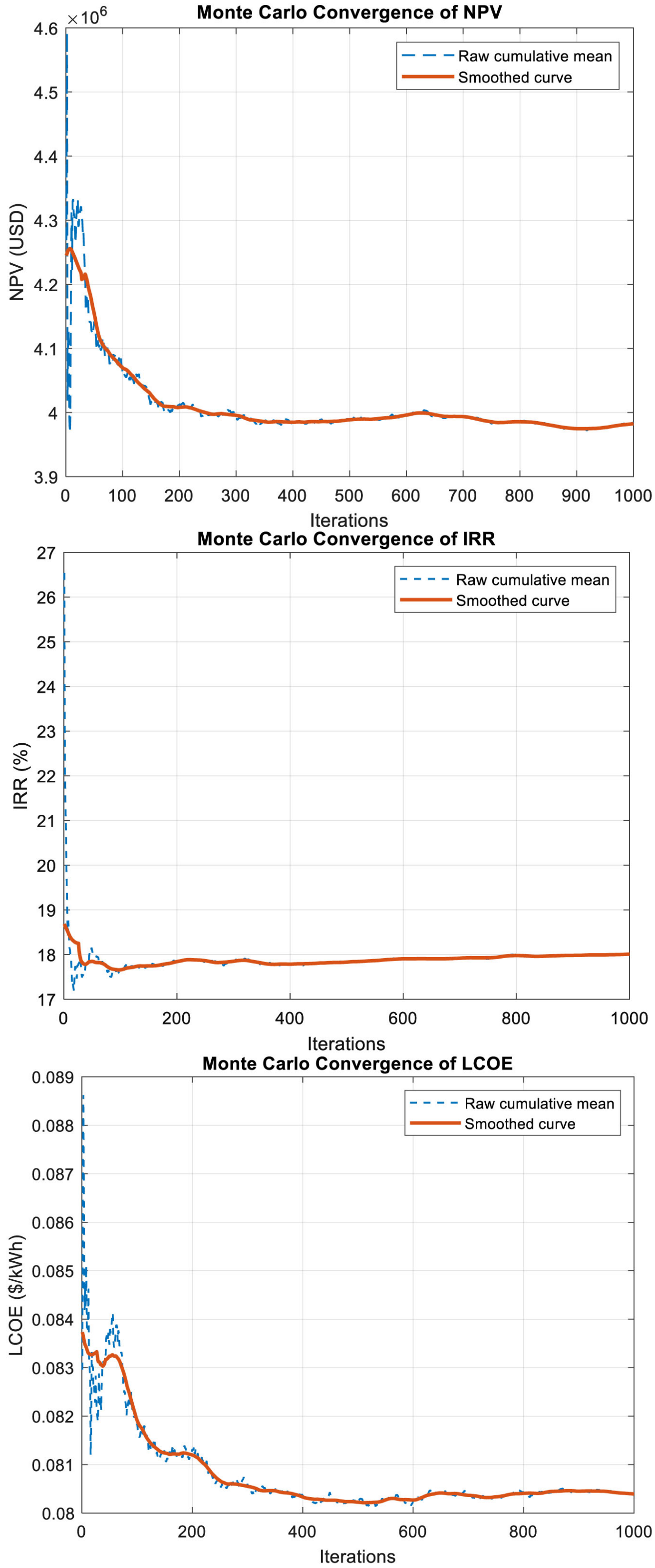

Figure 4. Monte Carlo convergence of NPV, IRR and LCOE.

5. Results and Discussion

The results obtained from the techno-economic and environmental analysis of decentralized photovoltaic injection are presented in this section. The analysis was carried out over a 25-year planning horizon considering photovoltaic degradation, fuel price variability, and system uncertainties.

5.1. Photovoltaic Energy Production

The optimal photovoltaic (PV) capacity of:

$$P_{PV,opt} = 2024\ \text{kW}$$

was determined using an Improved Particle Swarm Optimization (IPSO) algorithm. The proposed optimization approach aims to identify the optimal allocation and sizing of distributed photovoltaic generation within the distribution network while satisfying the operational constraints of the system.

The mains parameters of the IPSO are those presented in the following Table 6.

Table 6. Mains parameters of the IPSO.

Parameter	Value
Population size	50
Maximum iterations	200
Inertia weight	0.9 → 0.4
Cognitive coefficient	2
Social coefficient	2
Number of particles	50
Stop criterion	Relative improvement $<10^{-6}$

The primary objective of the optimization process is to minimize a multi-objective function combining:

- the total production cost;
- carbon dioxide (CO_2) emissions;
- and network reliability indices.

The objective function is expressed as follows:

$$F = \omega_1 C_{tot} + \omega_2 CO_2 + \omega_3 \text{EENS} \tag{10}$$

where:

- C_{tot} represents the total system operating cost;
- CO_2 denotes the total carbon emissions;
- EENS is the Expected Energy Not Supplied;
- ω_1; ω_2 and ω_3 are weighting coefficients satisfying:

$$\omega_1 + \omega_2 + \omega_3 = 1 \tag{11}$$

with $\omega_1 = 0.5$; $\omega_2 = 0.3$ and $\omega_3 = 0.2$.

Power flow calculations were performed using the Newton-Raphson solver implemented in MATLAB.

The optimization variables include:

- the PV power injected at each candidate site;
- and the geographical coordinates of the installation locations.

The optimization problem is subject to several technical and operational constraints to ensure the secure and reliable operation of the distribution network.

Voltage Constraints

The network voltage at each bus must remain within the admissible operating limits:

$$V_{min} \le V_k \le V_{max} \tag{12}$$

PV Power Constraints

The injected photovoltaic power at each site is limited by the maximum admissible installation capacity:

$$0 \le P_i \le P_{imax} \tag{13}$$

Transformer Capacity Constraints

The apparent power flowing through each transformer must not exceed its nominal capacity:

$$S_{tr} \le S_{trnom} \tag{14}$$

Geographical Constraints

The installation sites must belong to the predefined authorized areas for PV integration within the conventional distribution network:

$$(x_i, y_i) \in \text{Authorized Zone}$$

PV Grid Injection Interface Architecture

To ensure the efficient integration of photovoltaic power into the conventional distribution network, after optimizing both the generated PV power and the energy demand at each production site, an intelligent grid-interfacing system is implemented to guarantee stable, secure, and reliable power injection.

The proposed interfacing system consists of the following main components:

- a pure sine-wave inverter designed to ensure synchronization with the distribution network and to maintain power quality during grid disturbances;
- an intelligent voltage and frequency stabilization unit capable of maintaining the operating parameters of both the PV generation site and the distribution network within acceptable technical limits;
- a smart meter enabling real-time monitoring of the generated energy, local energy consumption, and the energy injected into the utility grid;
- an intelligent residual-current circuit breaker ensuring continuous protection and supervision of the bidirectional power exchange between the PV injection system and the conventional distribution network.

The overall architecture of the proposed photovoltaic grid injection system is illustrated in **Figure 5**.

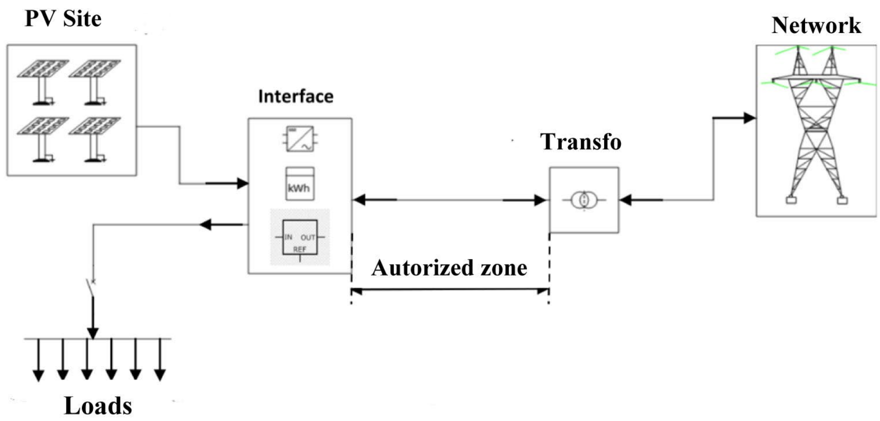

Figure 5. Architecture of photovoltaic grid injection system.

In this study, the optimization process considers:

- network voltage limitations;
- transformer loading limits;
- maximum allowable PV penetration levels;
- and a total number of 25 candidate PV installation sites.

To improve the realism of the techno-economic assessment, several uncertainties affecting the system were incorporated into the model:

- solar irradiation variability modeled using a normal probability distribution;
- PV degradation modeled using a uniform distribution;
- subsidy reduction modeled through a linearly decreasing function;
- diesel fuel price fluctuations modeled using a normal distribution characterized by mean μ and standard deviation σ.

These uncertainties enable a more realistic evaluation of the long-term technical and economic performance of the proposed PV integration strategy under variable operating conditions.

The 25 photovoltaic production sites produce approximately 3.40 GWh per year. However, due to PV module degradation, the energy production slightly decreases over time. This degradation results in a gradual reduction in annual energy production and cumulative energy over the project lifetime. Nevertheless, the total energy produced remains significant and contributes substantially to the reduction of diesel generator operation.

Figure 6 presents the evolution of photovoltaic energy production for the 25 PV sites over the 25-year project lifetime. Two scenarios were considered: without uncertainty and with annual uncertainty of parameters of PV modules. The results show that photovoltaic energy production gradually decreases due to module aging and the fluctuation of its parameters and variation of irradiance and so on.

The cumulative energy production over the project lifetime remains significant, demonstrating the long-term contribution of photovoltaic systems to the distribution network. The gradual decrease in production slightly affects economic performance but does not compromise the overall economic viability of the project.

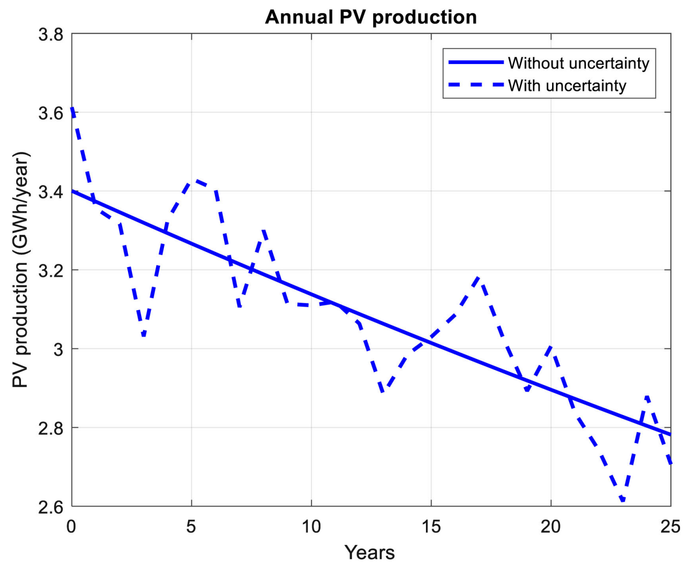

Figure 6. Annual PV production of the optimized 25 PV sites.

This result confirms that photovoltaic uncertainty production must be considered in long-term techno-economic studies to obtain realistic energy and economic projections.

5.2. Injected Energy into the Grid

The energy injected into the distribution network by the photovoltaic system represents an important contribution to the total energy demand. The results show that PV injection reduces the dependency on thermal generation and improves the overall efficiency of the power system. The injected energy remains relatively stable over the years, with a slight decrease due to PV degradation and uncertainty production.

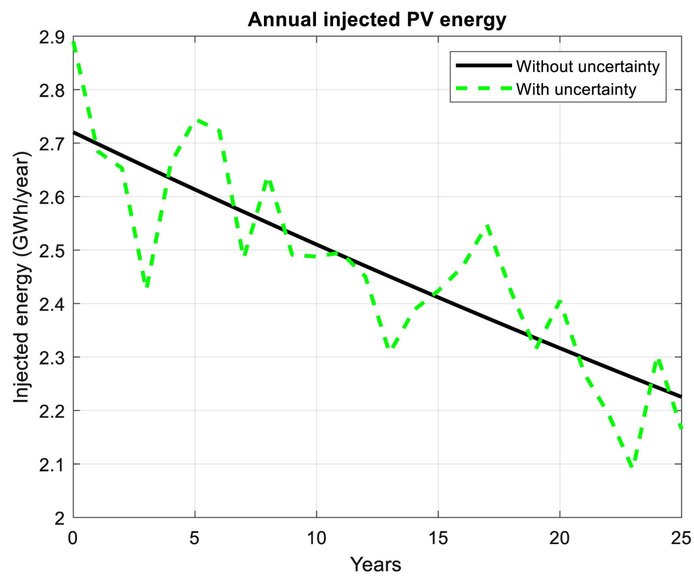

Figure 7. Annual PV energy injected into the distribution network.

Figure 7 shows the evolution of photovoltaic energy injected into the distribution network over a 25-year period, distinguishing between the case without uncertainty (solid black line) and the case with uncertainty (dashed green line).

In the scenario without uncertainty, the injected energy gradually decreases from approximately 2.72 GWh/year at the start of the project to 2.23 GWh/year in the 25th year. This decrease is primarily attributed to the annual degradation of the photovoltaic modules, set at 0.8%/year in the model. This evolution is consistent with the expected behavior of photovoltaic systems, whose production declines slowly over their lifespan.

In contrast, the scenario with uncertainty exhibits fluctuations around this average trend. These variations stem from the Monte Carlo simulation, which takes into account the uncertainty associated with the main input parameters, including:

- annual solar irradiance;
- the degradation rate of the photovoltaic modules;
- the system's operating conditions.

Despite these year-to-year fluctuations, the overall trend remains downward and close to the deterministic curve. This indicates that the uncertainties considered primarily modify the annual variability of production without compromising the overall performance of the photovoltaic system.

The relatively small difference between the two curves also shows that the optimal sizing obtained by the IPSO algorithm is robust to the uncertainties studied. In other words, even when the parameters vary randomly, the system maintains a stable injection capacity, which strengthens the reliability of the proposed solution.

Finally, the gradual decrease in injected energy directly explains the slight decline observed in fuel savings, CO_2 emission reductions, and electricity sales revenue over the project's lifetime.

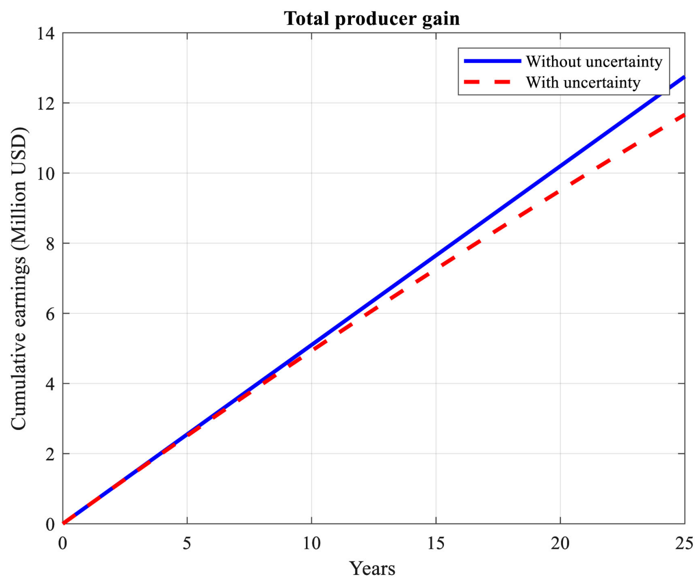

Figure 8. Curves of gains of producers private from energy injected by PV with and without uncertainties of indicators.

As shown in **Figure 8** above, the cumulative gain for private producers exhibits near-linear growth, demonstrating the progressive profitability of the system. The widening gap reflects the cumulative effect of the injected revenues. It should also be noted that uncertainties do not significantly impact these producers' gains, as the gap between the two curves in the figure above is not substantial over the project's lifespan.

Furthermore, given that the annual gain is defined as:

$$G(t) = E_{PV}(t) \times Tarif \tag{15}$$

Therefore:

- If the injected energy is constant, the profit will also be constant.
- If the energy decreases (due to the degradation of PV production), the profit decreases proportionally.

The profit curve thus has the same shape as the injected energy curve, simply multiplied by the tariff.

Analysis of the case without uncertainty

In this scenario:

- Annual production is constant;
- The tariff is fixed ($0.12/kWh);
- And no aging is taken into account.

Shape of the curve:

- Horizontal line;
- Stable revenue over 25 years;
- Constant annual cash flow.

Analysis of the case with uncertainty (degradation)

In this case:

$$E_{PV}(t) = E_0(1-d)^t \tag{16}$$

Therefore:

$$G_{PV}(t) = E_0(1-d)^t \times Tarif \tag{17}$$

According to the previous equation, the curve shows a gradual decrease with a slightly negative slope. Visually, it appears almost linear (due to the small d value).

Scientific Quantification

The calculations performed previously yielded:

- Cumulative energy loss: 7.81 GWh;
- Gross revenue loss: USD 937,200;
- Present Value (PV) loss ≈ USD 615,000.

Therefore, the curve, with uncertainty, shows:

✓ An increasing annual loss over time;
✓ A significant cumulative impact;
✓ But not a financial collapse.

Even with the decline in photovoltaic production:

- Revenue remains significantly higher than production costs;

- The PV remains positive;
- The IRR remains relatively short.

This demonstrates:

- ✓ The financial stability of the self-consumption + grid injection model;
- ✓ Low sensitivity to moderate uncertainties;
- ✓ The technological maturity of PV.

5.3. Economic Analysis

The economic analysis was performed using Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Energy (LCOE) (**Figure 9**). The results show that the NPV remains positive over the project lifetime, indicating that the photovoltaic investment is economically viable. The internal rate of return indicates that the investment payback period is approximately two years, which demonstrates strong economic profitability.

The Levelized Cost of Energy of photovoltaic generation is lower than that of diesel generation over the long term, confirming the economic competitiveness of photovoltaic systems in distribution networks with high fuel costs.

Our findings show strongly positive NPV in most scenarios, consistent with recent work indicating grid-connected PV can be economically viable with favorable feed-in tariffs and incentives [6]. LCOE results confirm that PV systems often outcompete conventional generation when accounting for long-term costs [7], [8]. Hybrid PV-storage systems show improved stability but reduced economic returns, resonating with other techno-economic storage studies [9].

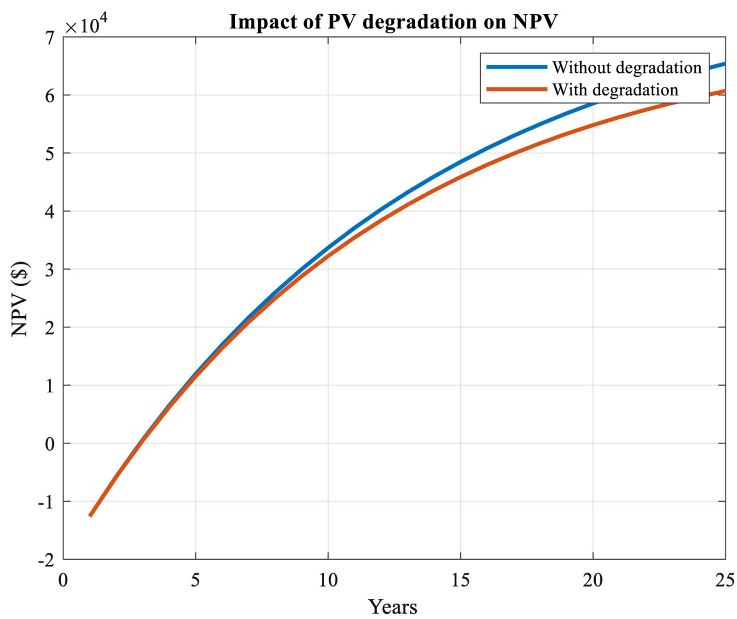

Figure 9. NPV evaluation over the project's lifecycle.

PV degradation slightly reduces the Net Present Value over the project lifetime but does not compromise the overall economic viability of the investment.

5.4. Fuel Savings

The integration of photovoltaic generation significantly reduces diesel fuel consumption. The annual fuel savings are estimated at approximately $800,000 per year. Over the project lifetime, this represents substantial economic savings and contributes to improving the financial performance of the project.

5.5. Environmental Impact

The environmental analysis shows that photovoltaic integration reduces carbon dioxide emissions by approximately 1313 tons of CO_2 per year. This reduction is mainly due to the decrease in diesel generator operation. Increasing PV penetration leads to significant environmental benefits and contributes to sustainable energy development.

Environmental Impact and CO_2 Reduction

Figure 10 shows the reduction of CO_2 emissions as a function of photovoltaic penetration level in the distribution network. The results indicate that increasing PV penetration significantly reduces carbon emissions due to the reduction of diesel generator operation.

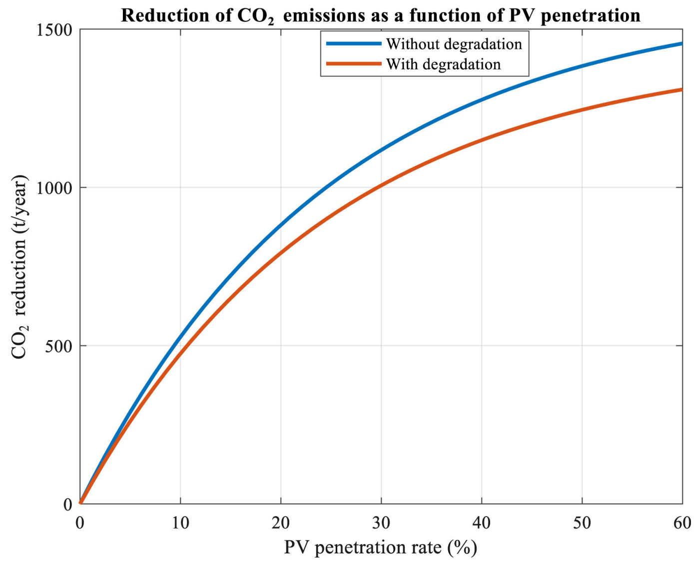

Figure 10. CO_2 emission reduction based on PV penetration.

At low penetration levels, the reduction in CO_2 emissions is relatively small. However, as PV penetration increases, diesel generator usage decreases significantly, leading to substantial emission reductions. The curve tends to stabilize at high penetration levels because diesel generators are already operating at minimum levels.

The results show that the maximum CO_2 reduction reaches approximately 1313 tons of CO_2 per year, demonstrating the significant environmental benefits of photovoltaic integration in diesel-based power systems.

The results indicate that the environmental performance of photovoltaic integration remains significant even under uncertainty and degradation conditions.

Although degradation slightly reduces the environmental benefits, the overall CO_2 reduction remains substantial. This demonstrates the long-term environmental sustainability of decentralized photovoltaic systems.

It confirms that photovoltaic integration not only improves the economic performance of the power system but also significantly reduces environmental impact. Therefore, increasing photovoltaic penetration in distribution networks represents an effective strategy for reducing greenhouse gas emissions and improving energy sustainability.

CO_2 emission reductions are significant, aligning with findings in environmental assessments of PV systems across climate zones [15]. Carbon reduction is an important consideration in policy frameworks promoting renewable generation.

5.6. Sensitivity Analysis

Sensitivity analysis shows that the most influential parameters affecting the economic viability of the project are fuel price, feed-in tariff, and discount rate. An increase in fuel price improves the profitability of photovoltaic systems, while an increase in discount rate reduces the Net Present Value. The system remains economically viable for a wide range of economic conditions.

Sensitivity analysis highlights that feed-in tariff and fuel price volatility are primary drivers of economic outcomes. Similar observations are reported in grid integration and tariff studies [6] [16] [17].

5.7. Multi-Objective Optimization

Multi-objective optimization was performed to minimize both electricity production cost and CO_2 emissions. The Pareto front obtained shows a trade-off between economic and environmental objectives. The optimal operating region corresponds to an intermediate photovoltaic penetration level where both cost and emissions are reasonably minimized in **Figure 11** below.

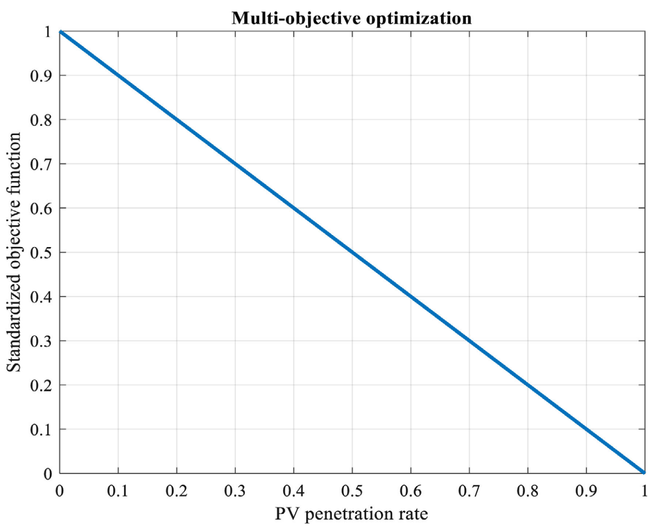

Figure 11. Evolution of the objective function as a function of PV penetration rate.

5.8. Overall Discussion

Overall, the results demonstrate that decentralized photovoltaic injection in distribution networks is technically feasible, economically viable, and environmentally beneficial. The integration of photovoltaic generation reduces fuel consumption, electricity production cost, and greenhouse gas emissions while improving the sustainability of the power system.

6. Conclusions

This research demonstrates that decentralized PV injection in conventional distribution networks is technically viable, economically robust, and environmentally beneficial under uncertainty. Monte Carlo analysis reveals a high probability of positive financial return, while LCOE analytics supports cost competitiveness. Storage systems enhance reliability but with cost implications. Policymakers and planners should consider integrating PV with supportive tariff structures and stability frameworks to maximize benefits.

Over a 25-year horizon, PV degradation results in a cumulative energy loss of approximately 7.81 GWh, corresponding to a 7.4% reduction in total production. When discounted at 8%, the associated reduction in Net Present Value reaches approximately 615,000 USD. Despite this impact, the project maintains strong economic viability, demonstrating resilience to long-term performance degradation.

The integration of photovoltaic generation in diesel-based distribution networks significantly reduces fuel consumption and carbon emissions while improving the economic profitability of the power system. The results demonstrate that increasing photovoltaic penetration leads to substantial environmental benefits and contributes to sustainable energy development in developing countries.

The environmental analysis under uncertainty and degradation conditions confirms that photovoltaic integration significantly reduces carbon emissions even in pessimistic scenarios. Therefore, decentralized photovoltaic systems represent a sustainable and robust solution for reducing greenhouse gas emissions in diesel-based distribution networks.

Author Contributions

Moussa Ahmat: Conceptualization, methodology, data collection, software, simulation, formal analysis, visualization, and writing original draft preparation.

Jean Benjamin Bidias: Translation, writing—review and editing, and practical guidance.

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All authors have read and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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