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Energy Efficiency Assessment of a Residential Building Integrating a Photovoltaic System: A Case Study of Yaoundé, Cameroon

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Abstract

The residential sector represents one of the main sources of energy consumption in the emerging economies of sub-Saharan Africa. Against a backdrop of rapidly growing electricity demand and increased vulnerability to load shedding, integrating photovoltaic (PV) systems into residential buildings offers a promising pathway to improve energy efficiency and strengthen household energy autonomy. This study analyzes the techno-economic and environmental performance of nine PV installation scenarios across three representative residential building typologies in Yaoundé (Cameroon), using the RETScreen Expert software. The simulations reveal a specific yield of 1425 kWh/kWp/year with seasonal variation limited to ±18%, confirming the region's excellent solar resource. The economic analysis demonstrates internal rates of return (IRR) ranging from 7.5% to 13.2% and payback periods of 10 to 12 years for installations between 2 and 12 kWp. The optimal installations avoid between 2.6 and 7.8 tonnes of CO_2 per year. These results confirm the viability of residential photovoltaics in a tropical context and provide operational recommendations for policymakers and industry stakeholders.

Keywords

Energy Efficiency, Residential Photovoltaics, RETScreen, Techno-Economic Analysis, Yaoundé, Cameroon

1. Introduction

Buildings account for approximately 40% of global final energy consumption and

more than 36% of energy-related CO_2 emissions [1]. In sub-Saharan Africa, and particularly in Cameroon, the residential sector faces a twofold pressure: rapid urbanization that is driving up demand [2] and an aging electrical grid whose distribution losses reach 29% [3]. SONEL, privatized in 2001 and subsequently replaced by ENEO and then SOCADEL in 2026, faces demand growth of around 8% per year, which installed generation capacity struggles to absorb.

In this context, integrating photovoltaic systems into residential buildings constitutes a genuine solution: it improves household energy efficiency while reducing grid dependence. Cameroon benefits from an average solar irradiation of 1650 kWh/m^2/year in Yaoundé (Centre-South region), a potential that remains largely untapped [4]. Yet few quantitative studies specifically address the economic viability of residential photovoltaics in the Cameroonian context.

This study systematically evaluates the technical, economic, and environmental performance of a grid-connected photovoltaic installation for three residential building typologies in Yaoundé. It addresses the following three research questions:

- To what extent does integrating a PV system improve the energy efficiency of residential buildings?
- How do building characteristics influence the techno-economic performance of the PV system?
- What optimal PV system site maximizes profitability according to building type?

2. Energy Context and Solar Resource in Cameroon

2.1. Status of the Electricity Sector

Cameroon generates its electricity primarily from hydropower (75%) and thermal sources (25%). The average grid emission factor is 0.3 kg CO_2/kWh, but the marginal factor associated with thermal generation is 0.8 kg CO_2/kWh, which significantly increases the positive carbon impact of photovoltaics. The residential electricity tariff billed by SOCADEL (Cameroon Electricity Corporation), formerly ENEO, does not include surplus electricity buy-back mechanism and is structured as follows:

- 0 to 110 kWh: 50 FCFA/kWh (excluding tax);
- 111 to 220 kWh: 79 FCFA/kWh (excluding tax);
- 221 to 400 kWh: 94 FCFA/kWh (tax inclusive);
- Above 400 kWh: 99 FCFA/kWh (tax inclusive).

2.2. Solar Resource in Yaoundé

Yaoundé (3.87˚N, 11.52˚E) benefits from an annual global horizontal irradiation of 1650 kWh/m^2/year. Seasonal variation remains moderate (±18% between the optimal January-March period and the low-yield July-August period), giving the resource a notable regularity compared to temperate regions, where winter output can drop by more than 70%. The average ambient temperature of 25˚C causes a

module efficiency loss of approximately 8% relative to Standard Test Conditions (STC), partially offset by the high irradiation.

3. Materials and Methods

3.1. Simulation Tool

The simulations were performed using RETScreen Expert (version 9), an internationally recognized software package for the evaluation of clean energy projects [5]. The "PV Solar Energy" module incorporates NASA meteorological data (POWER database) [6], a multi-parameter PV yield model, and financial analysis algorithms based on discounted cash flow methods (NPV, IRR, payback period).

3.2. Building Typologies

Three representative typologies of Yaoundé's urban residential fabric were defined based on a literature review and consumption surveys as seen illustrated in **Table 1** below.

Table 1. Characteristics of the building typologies studied.

Parameter	Type A—Economy	Type B—Mid-range	Type C—Modern villa
Floor area (m^2)	80 m^2	120 m^2	200 m^2
Number of rooms	3	4	6
Consumption (kWh/month)	~489 kWh	~885 kWh	~1451 kWh
Installed capacity	2 to 4 kWp	3 to 7 kWp	5 to 12 kWp

The monthly consumption of each building type was calculated through an energy balance of electrical equipment (lighting, appliances, air conditioning), while incorporating daytime and nighttime usage profiles specific to the tropical context. For each building type, the following energy characteristics were defined:

Lighting:

- Type A: 15 LED light points at 10 W;
- Type B: 20 LED light points at 12 W;
- Type C: 30 LED light points at 15 W.

Appliances:

- Type A: 150 W refrigerator, 60 W fan, 100 W TV;
- Type B: 200 W refrigerator, 2 × 75 W fans, 150 W TV, 500 W washing machine;
- Type C: 250 W refrigerator, 3 × 75 W fans, 200 W TV, 600 W washing machine, 2 × 1500 W air conditioners.

Consumption profiles: Hourly consumption profiles were established based on field surveys and literature data. They incorporate local living habits, with evening consumption peaks (6 p.m. - 10 p.m.) and continuous baseline consumption (refrigeration). As shown in **Figure 1** below.

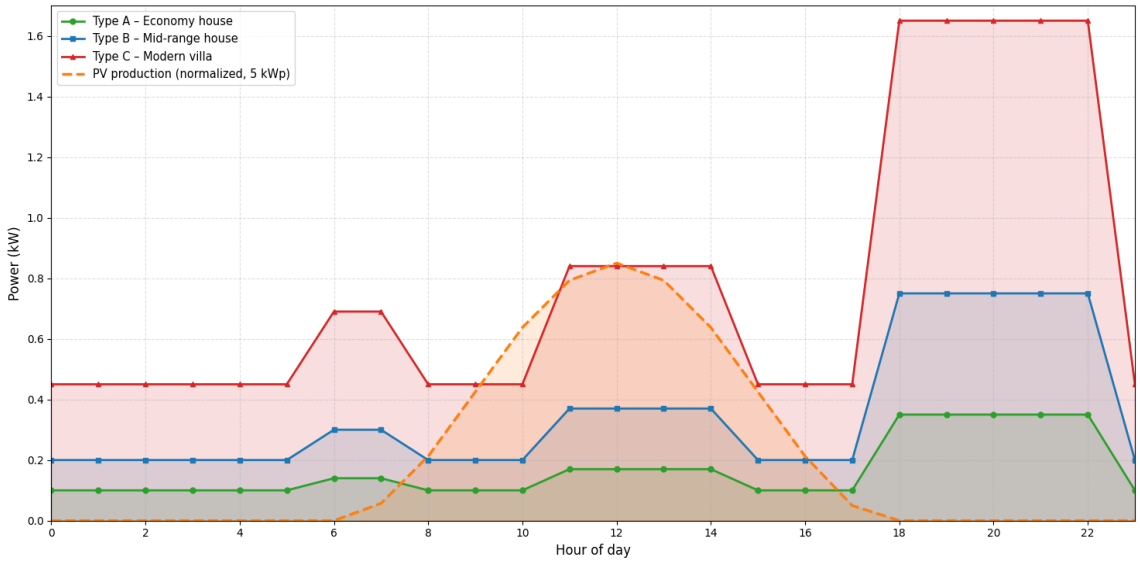


Figure 1. Hourly consumption profiles by building type and normalized PV output (5 kWp installation).

3.3. Photovoltaic Installation Scenarios

For each typology, three sizing scenarios were defined, corresponding to progressive levels of energy demand coverage (partial, intermediate, total). Nine scenarios are thus studied (A1 - A3, B1 - B3, C1 - C3). The common technical assumptions are as follows:

- Monocrystalline modules (efficiency 19.1%, performance ratio 87%, degradation 0.45%/year);
- String inverter with a guaranteed service life of 25 years;
- Orientation: 180˚ (true south), tilt angle of 5˚ (tropical optimum), as shown in Figure 2 below.

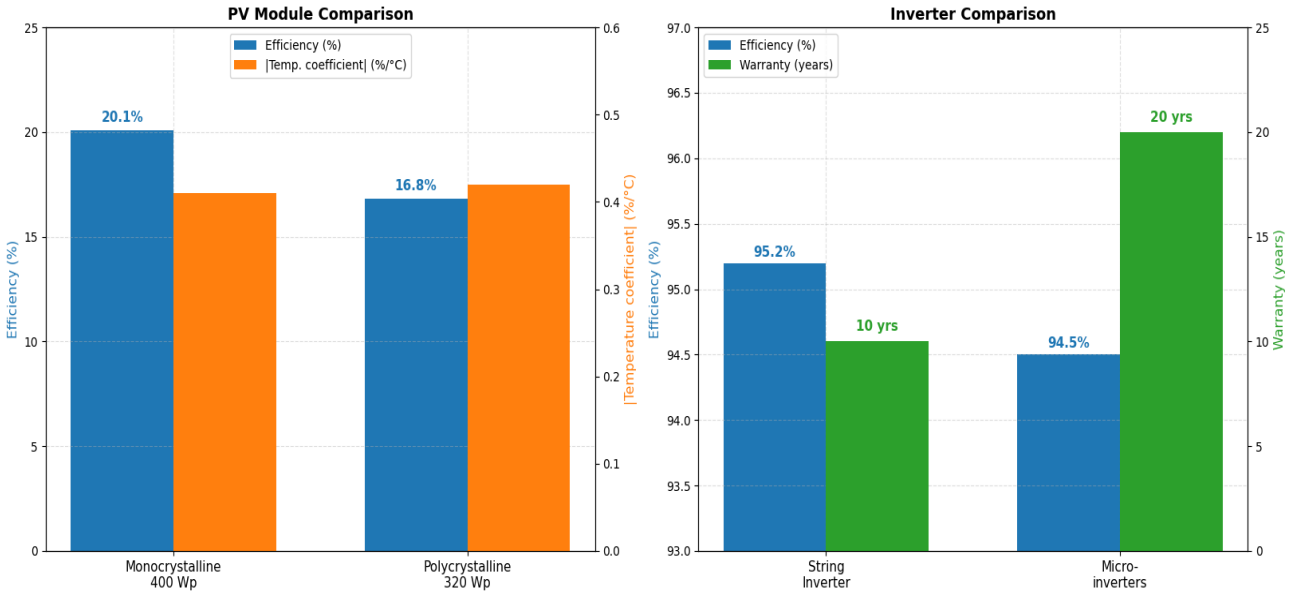


Figure 2. Technical characteristics of the selected photovoltaic components (modules and inverters).

3.4. Economic Parameters

The financial parameters adopted are as follows: an investment cost of 1,350,000 FCFA/kWp (supply and installation), an annual operating cost of 1% of the investment, a discount rate of 8%, an electricity tariff of 94 FCFA/kWh (held constant in the base scenario), and a 25-year analysis horizon. A sensitivity analysis covers variations in the tariff (±30%), investment cost (±20%), and production (±10%).

4. Results

4.1. Photovoltaic Production Performance

The simulated annual specific yield is 1425 kWh/kWp for all scenarios, with a monthly variation of ±18% (peaking at 150 kWh/kWp/month in January-March and dipping to 102 kWh/kWp/month in July-August). This production level exceeds that observed in most European regions (1000 - 1200 kWh/kWp) and is comparable to reference tropical zones (Brazil: 1200 - 1500 kWh/kWp; India: 1300 - 1600 kWh/kWp). As shown in Figure 3 below.

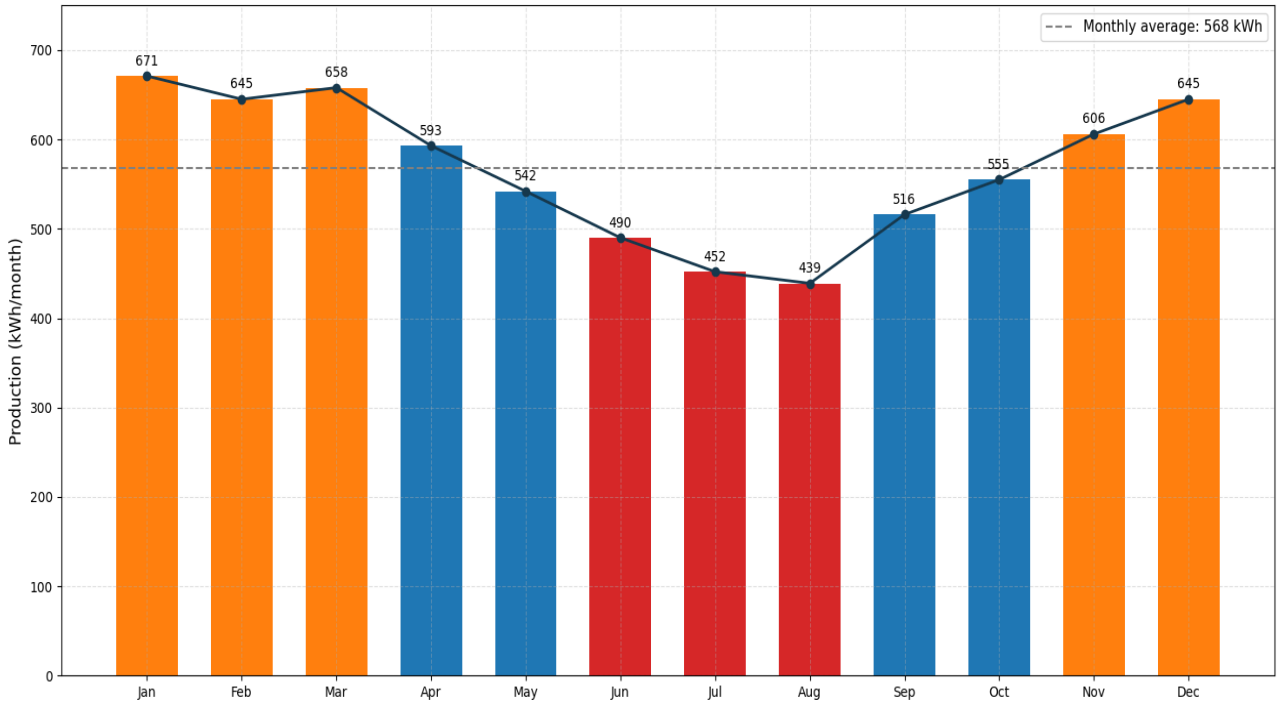


Figure 3. Simulated monthly photovoltaic production for a 5 kWp installation in Yaoundé.

Table 2 presents the annual production and self-consumption rates by scenario.

The profile analysis reveals a natural alignment between the solar production curve (midday peak) and the tropical residential consumption profile (daytime cooling demand), favoring direct self-consumption without the need for energy storage. Scenarios sized for full demand coverage (A3, B3, C3) inject 45%, 44%,

and 42% of their production into the grid, respectively, with no tariff compensation under the current regulatory framework. As shown in Figure 4.

Table 2. Photovoltaic production summary by scenario.

Scenario	Capacity (kWp)	Production (kWh/year)	Self-consumption (%)	Demand coverage (%)
A1	2	2850	95	55
A2	3	4275	75	83
A3	4	5700	55	100
B1	3	4275	98	47
B2	5	7125	78	79
B3	7	9975	56	100
C1	5	7125	99	47
C2	8	11,400	85	75
C3	12	17,100	58	100

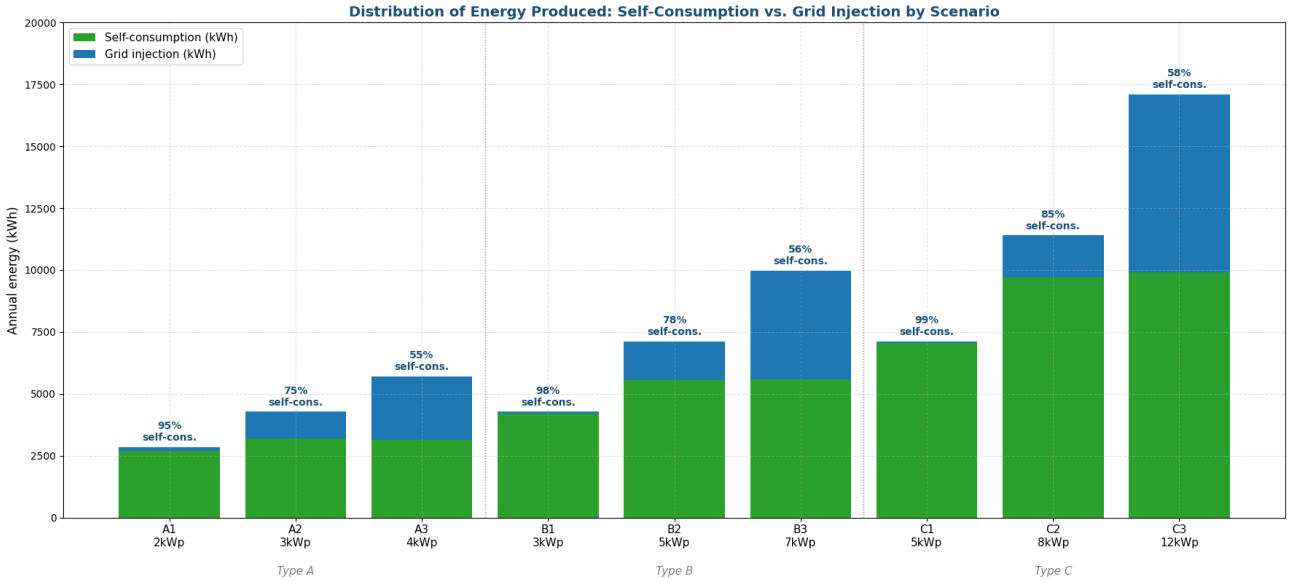


Figure 4. Self-consumption/grid injection breakdown by scenario (A1 - C3).

4.2. Economic Analysis

The profitability indicators calculated by RETScreen Expert are reported in Table 3.

Table 3. Economic profitability indicators by scenario.

Scenario	Investment (FCFA)	Savings/year (FCFA)	IRR (%)	Payback period (years)	NPV at 25 years (FCFA)
A1 (2 kWp)	2,700,000	257,260	11.2%	10.5	+496,000
A2 (3 kWp)	4,050,000	368,370	9.8%	11.0	+289,000

Continued

A3 (4 kWp)	5,400,000	451,800	7.5%	11.9	+82,000
B1 (3 kWp)	4,050,000	403,155	12.1%	10.0	+658,000
B2 (5 kWp)	6,750,000	622,030	11.5%	10.9	+882,000
B3 (7 kWp)	9,450,000	794,490	9.9%	11.9	+539,000
C1 (5 kWp)	6,750,000	674,425	13.2%	10.0	+1,440,000
C2 (8 kWp)	10,800,000	1,023,150	11.7%	10.6	+1,150,000
C3 (12 kWp)	16,200,000	1,372,980	9.5%	11.8	+470,000

The analysis reveals an economic optimum for installations of 2 to 5 kWp depending on building type, favoring self-consumption over grid injection. Scenario C1 shows the highest IRR (13.2%), while the oversized scenarios (A3, B3, C3) exhibit a decline in NPV due to the lower self-consumption rate. All scenarios display a positive NPV, confirming the economic viability of residential photovoltaic in Yaoundé. As shown in Figure 5.

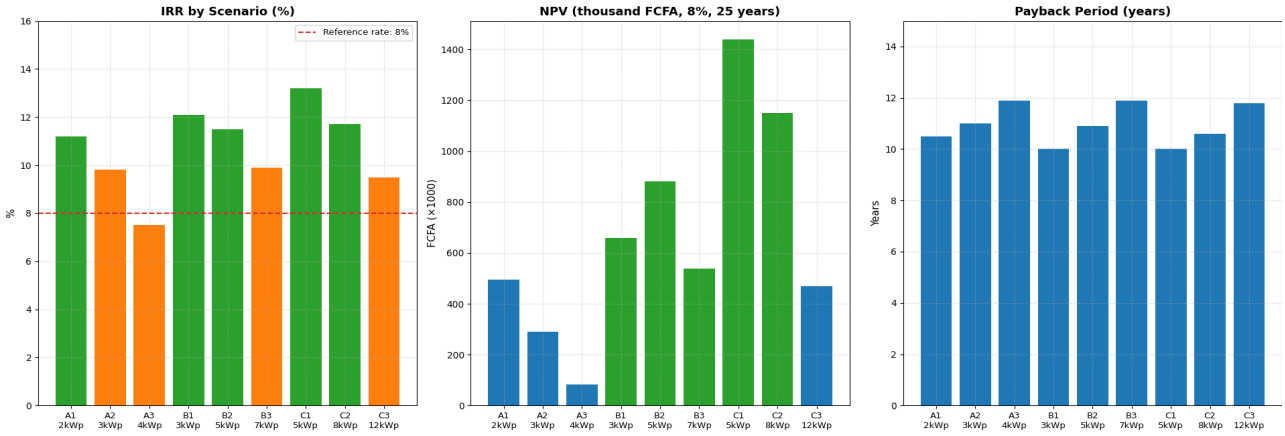


Figure 5. Economic profitability indicators (IRR, NPV, payback period) by scenario.

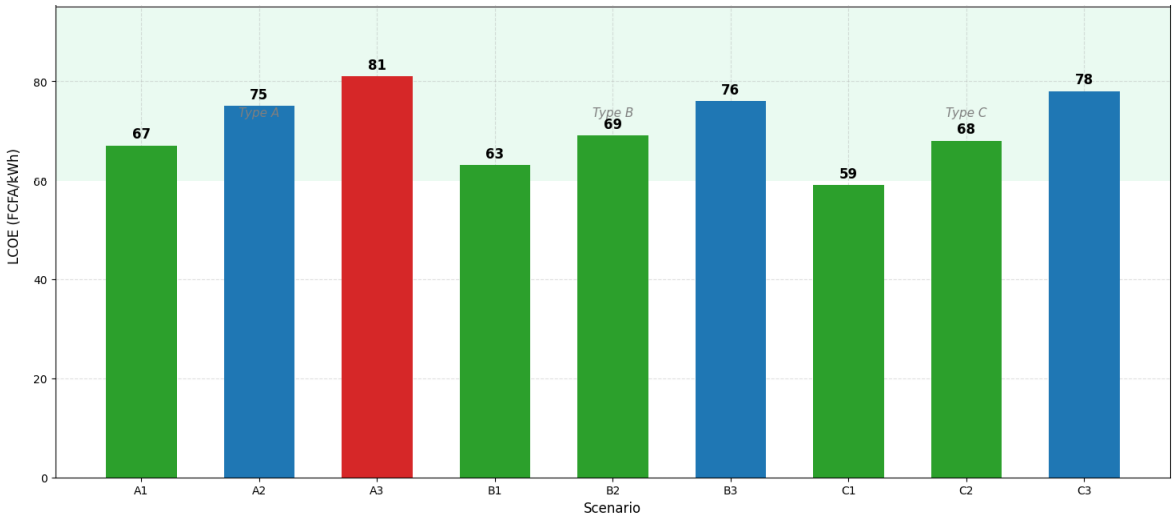


Figure 6. Levelized cost of electricity (LCOE) by scenario, compared with grid and buy-back tariffs.

The levelized cost of electricity (LCOE) ranges from 59 to 81 FCFA/kWh depending on the scenario, and remains below the grid tariff of 94 FCFA/kWh, providing a structural competitive advantage. As shown in Figure 6.

4.3. Sensitivity Analysis

The figure ranks the influence of each parameter on the NPV of the reference scenario B2:

- Electricity tariff: ±45% impact on NPV (most sensitive parameter);
- Investment cost: ±35% impact;
- PV production: ±25% impact;
- Discount rate: ±20% impact;
- Buy-back tariff: ±15% impact;
- Operating costs: ±8% impact.

As illustrated in Figure 7 below.

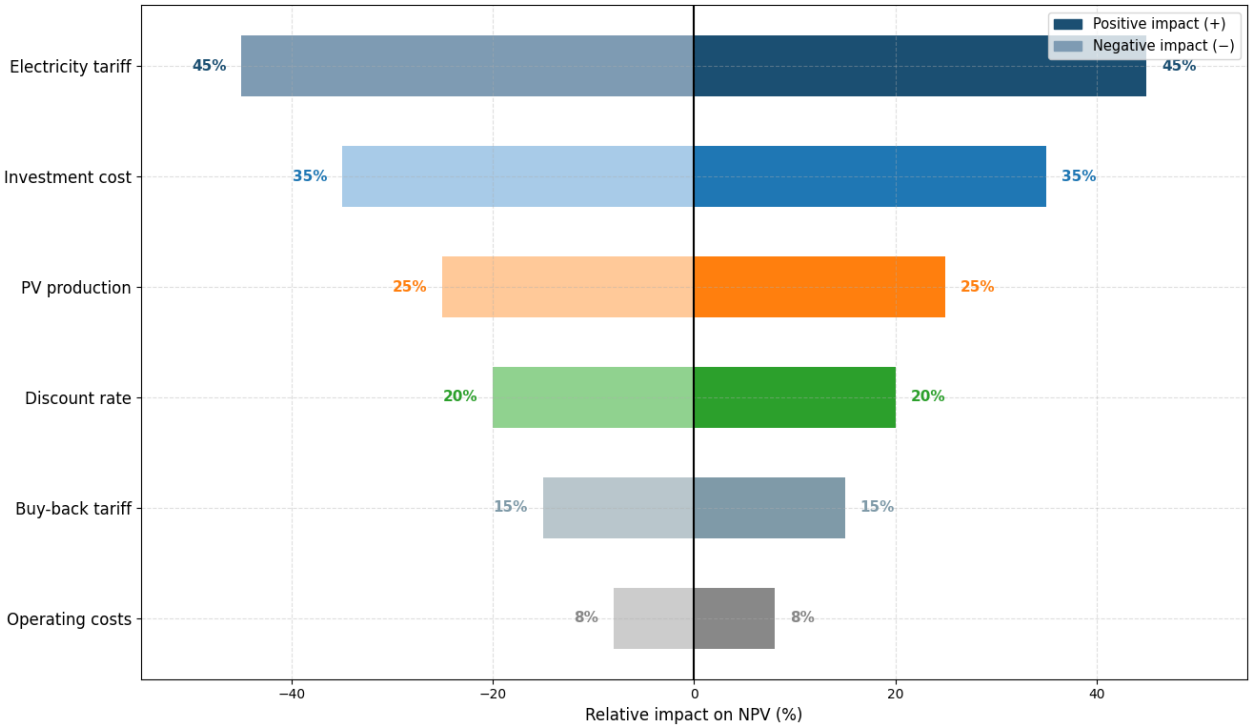


Figure 7. Tornado diagram of the NPV sensitivity analysis for the reference scenario B2.

A 30% increase in the electricity tariff would improve the NPV by 60% to 80% and shorten the payback period by 2 to 3 years. Conversely, a 20% reduction in investment costs (through economies of scale and local supply chain development) would improve the NPV by 25% to 40%.

4.4. Environmental Analysis

Table 4 presents the avoided CO_2 emissions for the reference scenarios of each building type.

Table 4. Environmental assessment of the reference scenarios.

Indicator	Type A—Scenario A2 (3 kWp)	Type B—Scenario B2 (5 kWp)	Type C—Scenario C2 (8 kWp)
Self-consumption/year (kWh)	3206	5558	9690
CO_2 avoided/year (tonnes)	2.6 t	4.4 t	7.8 t
CO_2 avoided over 25 years (tonnes)	65 t	110 t	195 t
Energy payback time	10 months	10 months	10 months
Energy return ratio over 25 years	24:1	24:1	24:1

Life-cycle analysis of the modules (crystalline silicon) reveals a carbon footprint of 55 to 75 g CO_2/kWh produced. The energy payback time is only 10 months, yielding an energy return ratio of 24:1 over 25 years. The carbon ratio (avoided emissions/manufacturing emissions) reaches 12:1, attesting to the excellent environmental performance of PV installations in this context. As illustrated in Figure 8 below.

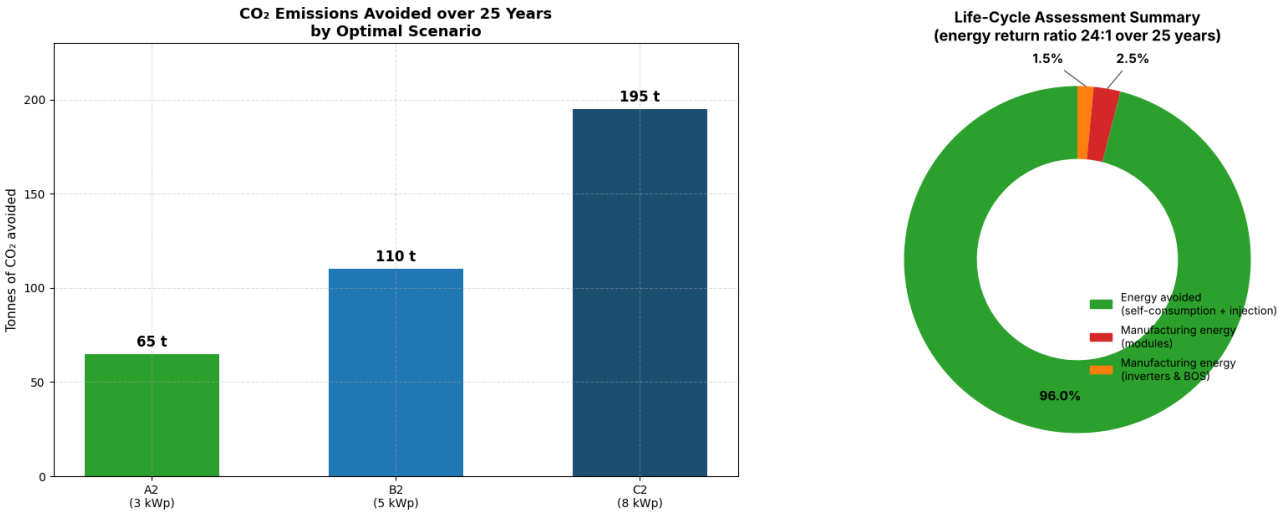


Figure 8. Environmental analysis of residential PV installations: CO_2 emissions avoided over 25 years and life-cycle assessment (energy return ratio 24:1).

5. Discussion

5.1. Performance in Tropical Climate Compared with Temperate Climate

The specific yield of 1425 kWh/kWp obtained in Yaoundé exceeds typical Northern European values by 20% to 40%. This superiority stems from the combination of high irradiation and low seasonal variability. The thermal loss of −8% remains limited because the stability of temperatures (22˚C - 28˚C) avoids the thermal peaks that stress modules in desert regions.

These performances are consistent with data from other tropical countries: Brazil (1200 - 1500 kWh/kWp), India (1300 - 1600 kWh/kWp), Thailand (1100 - 1400

kWh/kWp) [7], validating the robustness of the RETScreen simulations for this type of context.

5.2. Sizing Optimum and Self-Consumption

Unlike industrial installations that benefit from economies of scale, larger residential installations do not exhibit better profitability. Oversizing degrades the self-consumption rate and generates an unvalued surplus in the absence of a buy-back tariff. The economic optimum lies between 2 and 5 kWp, depending on building type, with a target self-consumption rate above 80%. As illustrated in **Figure 9** below.

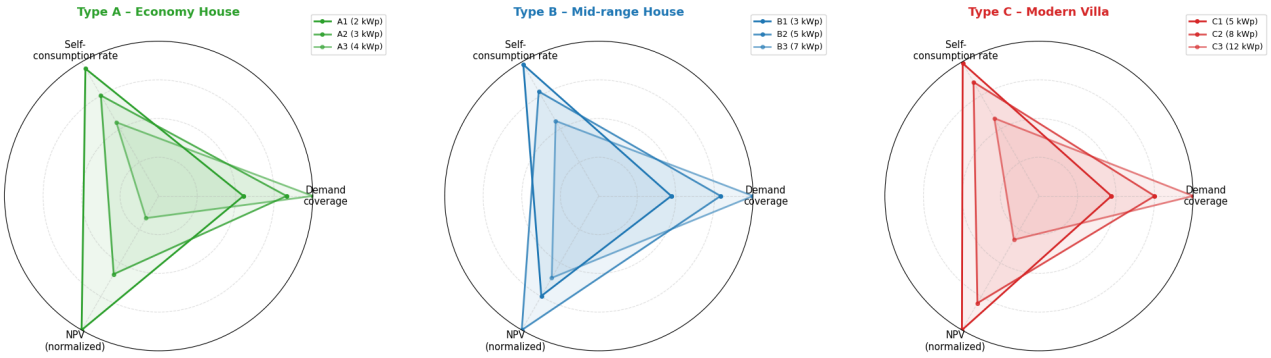


Figure 9. Comparative analysis of scenarios by building type (demand coverage, self-consumption rate, normalized NPV).

This result is consistent with observations from other developing countries without net metering, but contrasts with countries that have progressive tariff structures or surplus buy-back mechanisms, where larger installations are economically favored.

5.3. Specific Features and Limitations of the Cameroonian Context

Two specific features distinguish the Cameroonian context from international studies. First, the absence of time-of-use pricing and the flat tariff of 94 FCFA/kWh reduce the appeal of battery storage, whose LCOE largely exceeds the grid tariff. Second, the absence of a surplus buy-back mechanism (net metering) strongly penalizes oversized installations.

The study has several limitations: the consumption profiles are average values that do not reflect individual diversity; the average meteorological data does not capture extreme years and the analysis is limited to Yaoundé, without extension to Cameroon's other climatic regions (Sahel, coastal, highlands).

6. Conclusions

This study demonstrates that integrating photovoltaic into residential buildings in Yaoundé constitutes a technically efficient, economically viable, and environmentally beneficial solution. With a specific yield of 1425 kWh/kWp/year, IRRs of 9% to 13.2%, and payback periods of 10 to 12 years, residential photovoltaics offer com-

petitive performance in the Cameroonian tropical context.

The key to success lies in optimizing the system size to maximize self-consumption (2 - 5 kWp depending on building type) rather than pursuing full demand coverage. The sensitivity analysis clearly identifies three levers for improvement: the reform of the tariff framework (net metering) [8] [9], reduction of investment costs through local supply chain development, and the quality of installation and maintenance.

At a time when Cameroon has committed to implementation under the Paris Agreement [10], residential photovoltaics represent a concrete and effective lever, accessible to households, for simultaneously contributing to national energy resilience goals and reducing greenhouse gas emissions.

Future research could extend the study to other climatic regions of Cameroon, examine storage alternatives offered by newer, lower-cost battery generations, and explore alternative financing models.

Conflicts of Interest

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

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