World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

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Feasibility Study and Sizing of a Photovoltaic Power Plant for Integration into the Kasongo Distribution Grid

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World Journal of Advanced Research and Reviews, 2026, 29(02), 1002-1011

Publication history: Received on 09 January 2026; revised on 16 February 2026; accepted on 18 February 2026

Article DOI: https://doi.org/10.30574/wjarr.2026.29.2.0404

Abstract

This study sizes and analyzes the feasibility of a 6.8 MWp autonomous solar power plant to electrify the Kasongo territory (DRC). For a population of 936,018 inhabitants, the system includes 15,113 PV modules, 153 Li-ion batteries, and 136 inverters. The $11.97M investment achieves a return on investment from the 8th year. RETScreen/PVsyst simulations confirm a daily production of 22,308 kWh and a performance ratio of 49%.

Keywords: Photovoltaic Solar Energy; Sizing; Kasongo; DRC; Autonomous Power Plant; Economic Feasibility.

1. Introduction

The majority of rural areas in the Democratic Republic of the Congo, including the Kasongo territory, remain without access to electricity despite significant national energy potential [5]. This study aims to provide this region with an energy source suited to its local resources, leveraging its favorable geographical position near the equator for the development of photovoltaic solar energy [1].

An in-depth analysis of photovoltaic technology is conducted, covering cell modeling, the influence of irradiance and temperature, and the impact of configurations on performance [4]. The crucial role of the DC-DC converter in optimizing efficiency is also examined.

1.1. Solar Array and Module

A solar array consists of interconnected photovoltaic modules. Each module, or panel, assembles elementary cells to produce a usable voltage and power, as a single cell generates a limited voltage (0.5 to 1.5 V) [2].

1.2. Producible Energy

Producible energy refers to the energy that can actually be generated by the photovoltaic solar array; it depends on the conversion efficiency of the PV modules [4].

$$E_p = \frac{E_{jd}}{\eta} \quad (1)$$

Where:

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- E_p: producible energy from the photovoltaic array [kWh]
- E_{jd}: increased daily energy [kWh]
- η: conversion efficiency (generally 0.65 – 0.75)

1.3. Photovoltaic Solar Array Power

$$P_p = \frac{E_p \times k}{I_r} \quad (2)$$

Where:

- P_p: peak power [kWp]
- k: solar constant [dimensionless]
- I_r: solar irradiation [kWh/m^2/day]

1.4. Number of Modules

The total peak power was determined; subsequently, photovoltaic cells with a maximum power $P_{max} = 450$ Wp were selected [2]. The number of modules is given by:

$$N_{mod} = \frac{P_p}{P_{max}} \quad (3)$$

Where:

- N_{mod}: number of modules
- P_p: peak power [kWp]
- P_{max}: maximum power per module [kWp]

1.5. Number of Series-Connected Modules

N_{mods} represents the number of series-connected modules.

$$N_{mods} = \frac{U_n}{U_m} \quad (4)$$

Where:

- U_n: nominal system voltage [V]
- U_m: module voltage [V]

1.6. Number of Parallel-Connected Modules

N_{mp} represents the number of parallel-connected modules.

$$N_{mp} = \frac{N_{mod}}{N_{ms}} \quad (5)$$

In practice, the product of the number of series-connected modules and the number of parallel-connected modules may exceed the calculated number of modules required for the total power generated by the solar array [2]. The actual number of modules to be installed is:

$$N_{mt} = N_{ms} \times N_{mp} \quad (6)$$

1.7. Determination of Solar Array Area

$$S = N_{mt} \times S_u \quad (7)$$

Where:

- S: solar array area [m^2]
- S_u: area per unit module, often 2.2 m^2

1.8. Charge Controller

The charge controller is the central element of an autonomous photovoltaic system, ensuring the control of energy flows [3]. It protects batteries against overcharging and deep discharge, guarantees the safety of the installation, and can integrate Maximum Power Point Tracking (MPPT) [4]. In advanced systems, it also manages hybrid energy sources and provides information on the system status [1].

1.9. Selection and Number of PV Inverters

PV inverters act as regulators; they convert DC/AC power from the array for proper control [3]. They depend on the installed power, and their power rating should be between (1.3 to 2) times the peak power. In this study, a factor of 1.5 P_p is considered for the PV inverter [2].

The number of inverters is determined by the following formula:

$$N_{Inv} = \frac{P_{inv}}{P_u} \quad (8)$$

Where:

- N_{Inv}: number of inverters
- P_{inv}: inverter power [kW]
- P_u: unit power of the inverter [kW]

1.10. Battery

The role of the battery in autonomous photovoltaic systems is to store electrical energy for use during the night or during consecutive cloudy periods without radiation [1].

Battery capacity is defined by the producible energy and the autonomy of the installation [2]:

$$C_{tot} = \frac{E_p \times N}{U_{bat} \times DOD} \quad (9)$$

Where:

- C_{tot}: total accumulation capacity [Ah]
- E_p: producible energy [kWh]
- N: autonomy [days] (1 day)
- U_{bat}: battery connection voltage [V]
- DOD: depth of discharge of batteries (90% for optimal battery lifespan) [2]

Calculation of storage capacity or Storage Energy in Wh:

$$C_s = C_{tot} \times U \quad (10)$$

Where:

- C_{tot}: total accumulation capacity [Ah]
- C_s: storage energy or storage capacity [kWh]
- U: battery connection voltage (battery bank voltage) [V]

The number of battery packages:

$$N_{bp} = \frac{C_s}{C_{up}} \quad (11)$$

Where:

- N_{bp}: number of battery packages
- C_s: storage energy or storage capacity [kWh]
- C_{up}: unit energy of the package or unit capacity of the package [kWh]

1.11. Converter

Converters are devices used to transform the direct current provided by batteries to adapt it for receivers operating either at a different direct current voltage or at an alternating current voltage [3].

Today, the vast majority of converters are electronic, but generators driven by DC motors providing 230VAC can still be found [1].

1.12. Wiring and Protection

$$S = \frac{I}{J} \quad (12)$$

Where:

- S: conductor cross-section [mm²]
- I: electric current intensity [A]
- J: electric current density [A/mm²] [3]

$$S_{app} = U \times I \quad (13)$$

Where:

- S_{app}: apparent power of the branch [VA]
- U: connection voltage of the branch [V]
- I: current intensity flowing through the branch [A]

From equation (13):

$$I = \frac{S_{app}}{U} \quad (14)$$

Adopting fuse protection, the fuse current rating will be [3]:

$$I_f = 1.2 \times I \quad (15)$$

Where:

- I_f: fuse current intensity [A]
- I: branch current intensity [A]

2. Methodology

The Kasongo territory constitutes the setting for this research. Located at coordinates 4°27′ South, 26°39′ East, the Kasongo territory in Maniema province is bordered to the North by the Pangi territory, to the South by the provinces of Kasai Oriental and Katanga, to the East by the Kabambare territory and South Kivu province, and to the West by the Kibombo territory [5].

2.1. Approach

The analytical method, supported by documentary techniques, interviews, and field visits with a data collection tool, was applied for this research.

The methodological approach consisted of:

- Analyzing the existing situation [5];
- Translating demographics into households;
- Determining sectoral power demands [2];
- Determining the total power demanded by the Kasongo territory;
- Estimating the energy needs of Kasongo town;
- Sizing the photovoltaic solar power plant [4];
- Performing simulations in an appropriate environment to assess project viability [4].

3. Results and discussion

The population and the number of households are [5]:

$$P = \mathbf{936,018\ inhabitants}$$

For Class C, consisting of families with a low social level and representing 80% of the total population, the number of households is [2]:

$$N_{hC} = \frac{936{,}018 \times 80}{8 \times 100} = \mathbf{93,602\ households}$$

For Class B, consisting of families with an average social level and representing 15% of the total population, the number of households is:

$$N_{hB} = \frac{936{,}018 \times 15}{8 \times 100} = \mathbf{17,550\ households}$$

For Class A, consisting of families with an upper-middle social level and representing 5% of the total population, the number of households is:

$$N_{hA} = \frac{936{,}018 \times 5}{8 \times 100} = \mathbf{5,850\ households}$$

The power demand for all sectors of the Kasongo territory is :

$$\mathbf{P_d = 16,730}\ kW$$

By hypothesis, one-third of this power will be supplied by the photovoltaic system, with the remainder provided by other primary energy sources.

To meet the energy needs of the Kasongo territory, a photovoltaic system is sized with the following characteristics. The technical characteristics of the designed system are:

- Photovoltaic Power: 5,577 kW
- Daily energy produced: 22,308 kWh
- Number of modules: 15,113 modules of 450 W
- Area occupied: 33,249 m^2
- Storage capacity: 368,849 Ah
- Number of batteries: 153 Li-ion packs of 232 kWh
- Number of PV inverters: 84 inverters of 100 kW
- Number of charger inverters: 68 units of 100 kVA

Table 1 Total project cost: 6.8 MWp solar power plant

No.	Equipment Description	Model	Quantity	Unit Cost ($)	Total Cost ($)
01	Solar Panels	Go Solar, 450W	15,113	240	3,627,120
02	Charger Inverter	SMA 100 kW	136	7,356.86	1,000,532.96
03	PV Inverter	Fronius Tauro 100 kW	552	6,377.18	3,520,203.36
04	Battery	Battery Power Pack 232 kWh Lithium Ion	153	9,500	1,453,500
05	**Sub-total (1)**				**9,601,356.32**
06	Cables and other accessories (3% of sub-total 1)				288,040.69

07	**Sub-total (2)**				**9,889,397.01**
08	Transport (10% of sub-total 2)				988,939.70
09	**Sub-total (3)**				**10,878,336.71**
10	Operation and Maintenance (4% of investment)				435,133.47
11	Technical Studies (2% of sub-total 3)				217,566.73
12	Contingencies (5% of sub-total 3)				543,916.84
	Total Investment Cost				**11,966,170.38**

Following investment, the cumulative cash flow diagram is presented as follows:

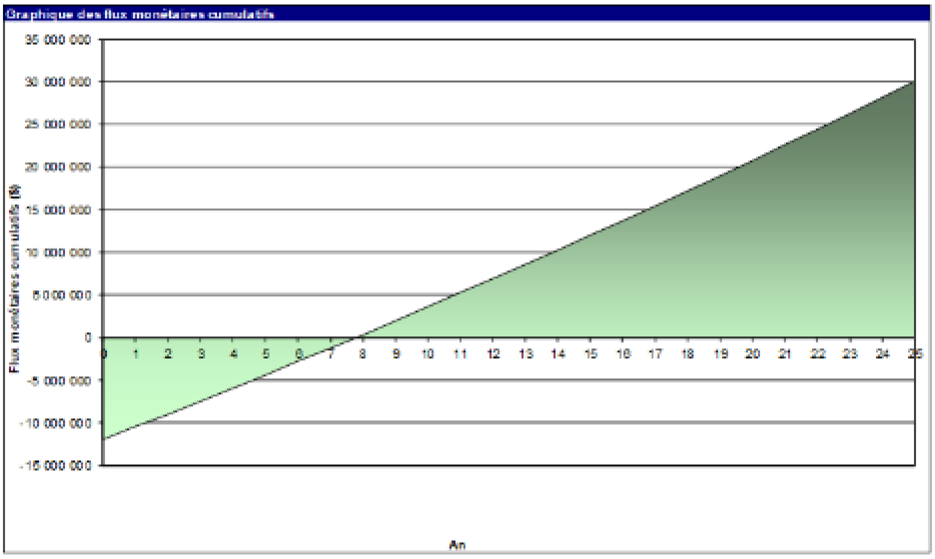

Figure 1 Cumulative cash flow diagram

The flow diagram from RETScreen software shows that the project is economically viable, as from the **eighth** year over the project's lifespan (25 years), the return on equity is achieved – an important economic indicator as shown by the cumulative cash flow graph of the financial analysis – and after this date, the same graph indicates the project's success.

Beyond these key results, other findings can be presented, notably the daily input/output graph, the evolution of irradiation, or the energy received by the modules.

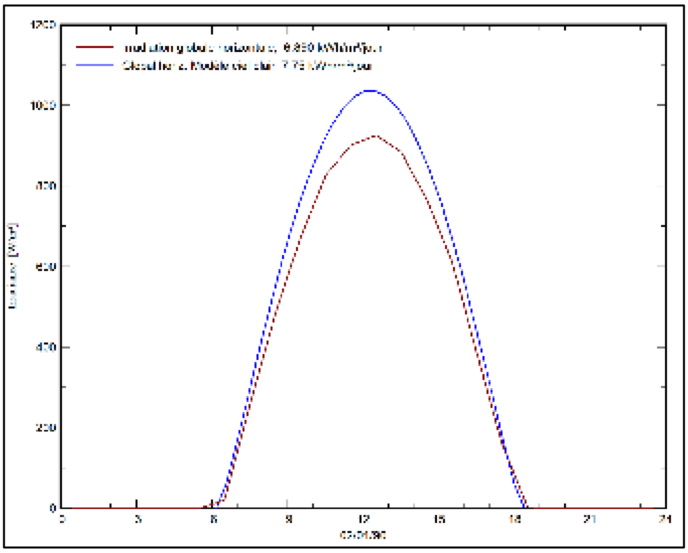

Figure 2 Daily irradiation evolution

It should be noted that irradiation begins around 6 a.m. during sunrise and reaches its peak around 12 p.m. before declining towards 6 p.m..

The position of the sun plays an important role in insolation; thus, Figure 3 below shows the evolution of insolation relative to the sun's position.

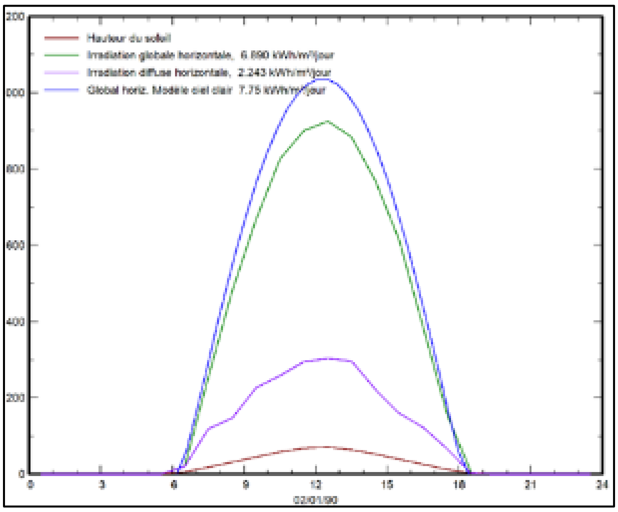

Figure 3 Variation of irradiation relative to sun position

It is clear that the position of the sun (shown in red in the base) influences the variation of irradiation. Figure 3 above shows that the height of the sun relative to the plane of the photovoltaic modules is an important factor for optimizing the desired irradiation quantity.

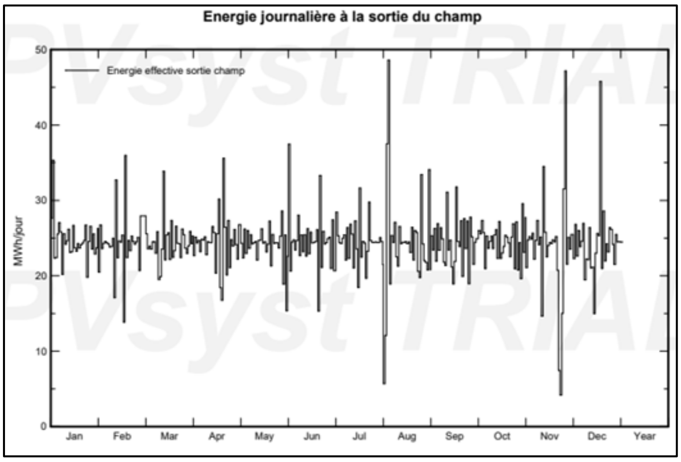

Figure 4 Daily energy output from the solar array

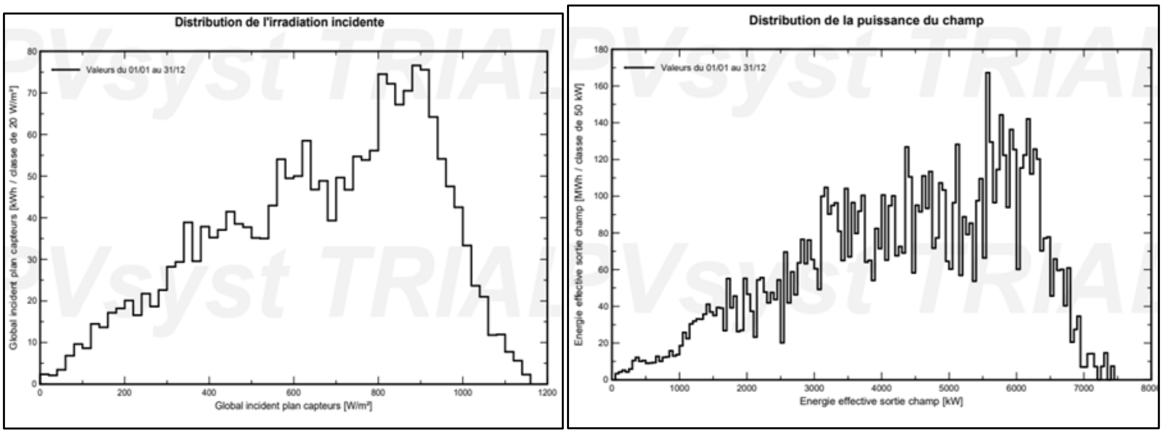

Figure 5a Power distribution | Figure 5b: Energy distribution

Despite the oscillations, the daily energy output from the PV solar array ranges between 20 MWh/day and 30 MWh/day. Peaks are observed in July and November, likely due to the climatic conditions during these months.

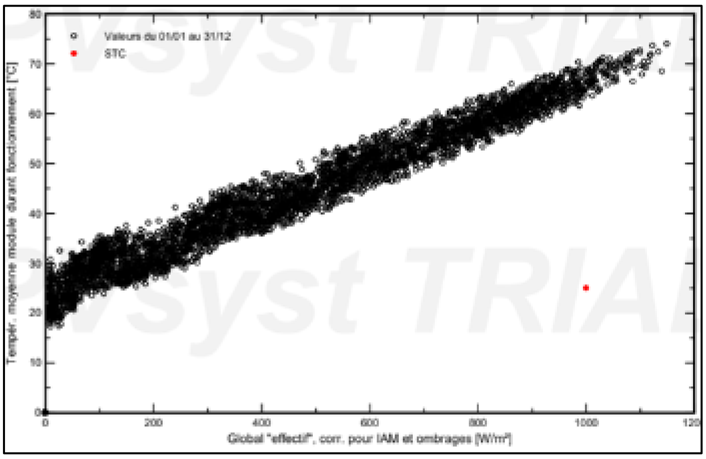

Figure 6 Evolution of irradiation relative to temperature

Irradiation is a function of temperature; it describes a linear function of the temperature variable.

Figures 7, 8, and 9 below revisit performance and producible energy, taking into account losses.

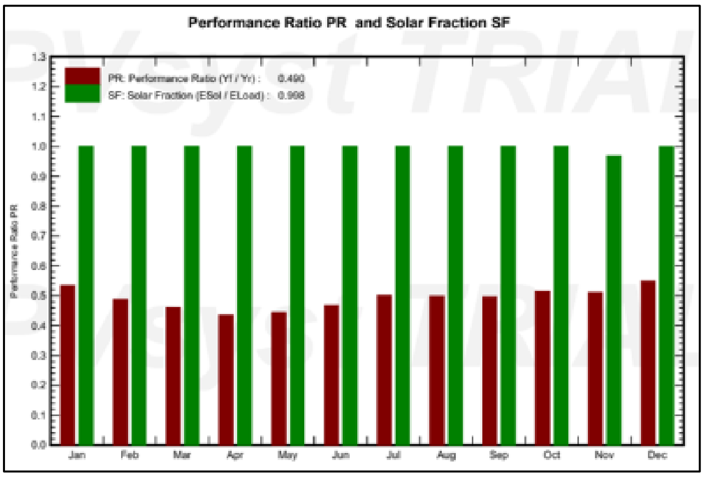

Figure 7 Performance ratio and solar fraction

For a solar system whose efficiency is often equal to 35%, a performance ratio of 49% is largely conclusive. Figure 8 below shows the distribution of power at the output of the PV solar array.

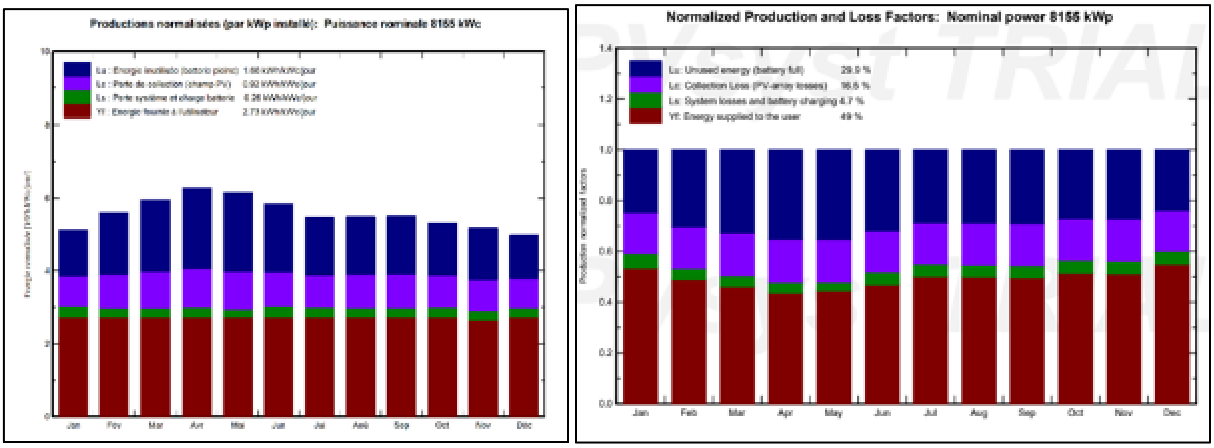

Figure 8 Distribution of produced power

As mentioned for the performance ratio, 49% of the production reaches the end-use, while 29.9% of the solar array's production is used by the batteries, with 16.5% and 4.7% constituting overall losses.

To conclude this presentation, the monthly irradiation is recalled with reference to the average daily irradiation in Figure 9 below.

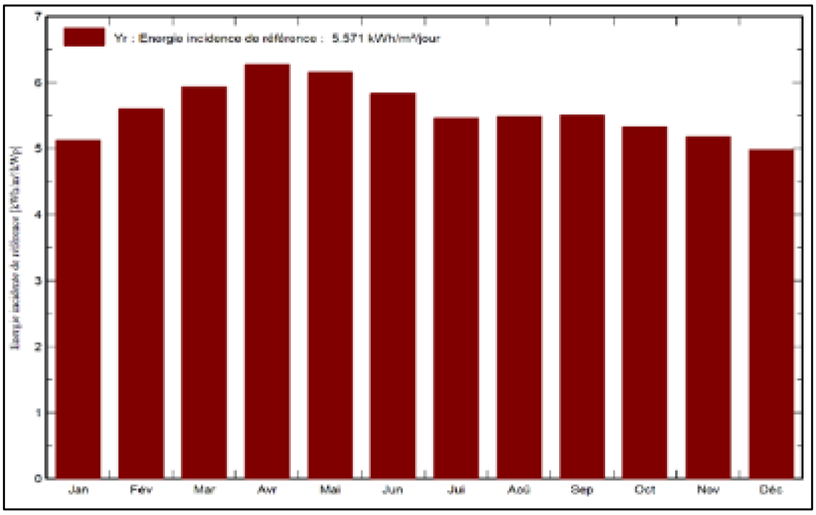

Figure 9 Reference incident energy in the collector plane

From January to December, the monthly irradiation is greater than or equal to the expected average daily irradiation of 5.571 kWh/m^2/day.

This chapter on sizing, viability, and simulation has demonstrated how this study is not only feasible but also, and most importantly, economically viable. The number of modules, the number of batteries, and the simulations performed using software have confirmed this feasibility.

4. Conclusion

This study demonstrates the technical and economic feasibility of a 6.8 MWp autonomous photovoltaic solar power plant for the Kasongo territory in the DRC. The sizing results in an installation of 15,113 modules, with a 35.5 MWh storage system ensuring energy autonomy.

The simulations confirm robust performance (daily production of 22,308 kWh, performance ratio of 49%) and proven economic viability (return on investment in 8 years for a total cost of $11.97 million over 25 years).

This project constitutes a sustainable solution to break the energy isolation of the region, foster its socio-economic development, and offer a replicable model for rural electrification in the DRC using renewable energies.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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