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Techno-economic Analysis of a 10 MW Photovoltaic Solar Power Plant Connected to the BADIADINGI Substation (Kinshasa, DRC)

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ABSTRACT

The BADIADINGI HV/MV substation (Selembao, Kinshasa) is overloaded: two of its 15 MVA transformers are operating at 105.2% and 121.9% of their nominal capacity, necessitating load shedding on the 30 kV MV network. This study evaluates a 10 MW (20 MWp) photovoltaic solar power plant connected to the substation's 30 kV busbar.

The power plant is designed as ten 1 MW / 2 MWp units, each equipped with 2,857 700 W TOPCon modules and a 3 MWh lithium-ion storage system integrating a regulator and inverter. Grid stability was simulated using MATLAB/Simulink, and energy production and profitability were calculated using PVsyst.

The grid connection remains stable, with transient fluctuations quickly damped. The performance index is between 70 and 80% year-round, and each unit produces approximately 1.7 GWh /year. At approximately USD 2.87 million per unit, the payback period is 9.6 years and the return on investment is 384.7% over 25 years. Each unit avoids approximately 11,400 net tonnes of CO_2.

KEYWORDS: *solar photovoltaic energy, grid connection, distribution substation, energy storage, techno-economic analysis, PVsyst, MATLAB/Simulink, Kinshasa.*

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1. INTRODUCTION

Despite an estimated hydroelectric potential of over 100,000 MW, the DRC provides access to electricity to only about 21.5% of its population, according to the Energy Compact developed with the World Bank. The government aims for 62% by 2030.

In Kinshasa, the electrification rate reaches approximately 60%. However, population growth and urbanization are increasing demand faster than supply, resulting in load shedding, voltage drops, and overloading of distribution substations.

The Badiadingi substation, a strategic link in the SNEL network, illustrates this situation, even though the city benefits from ample sunshine. The question then arises: to what extent can a grid-connected photovoltaic power plant improve the technical and economic performance of this substation?

The main hypothesis is that a 10 MW power plant would reduce the substation's overload while being profitable and beneficial for the environment, despite a significant initial investment.

2. Materials and Methods

2.1. Study site and job data

The substation's current deficit is 5.09 MVA and is projected to reach 13.56 MVA (approximately 10.85 MW) in 25 years, thus justifying a 10 MW power plant. The substation is located at approximately 4.4° S and 15.3° E, at an altitude of 300 m. Its main 60 MVA (132/30 kV) transformer feeds three 15 MVA transformers.

Transformer	Power	Load rate
Main (132/30 kV)	60 MVA	approximately 85%
No. 1	15 MVA	105.2%
#2	15 MVA	less than 80%
No. 3	15 MVA	121.9%

The overload at transformers #1 and #3 represents 4.07 MVA. By limiting the load to 80% of the nominal power, as recommended by standards, this deficit decreases to 5.09 MVA, equivalent to approximately eight 630 kVA substations being unloaded. The 25-year projection assumes an annual demand growth of 4% (SNEL and JICA data).

2.2. Solar Resource

The site receives 4.5 to 5.2 kWh/m² per day, or 1,650 to 1,900 kWh/m²/year (NASA POWER, PVGIS, Meteonorm, Global Solar Atlas). The specific energy production is 1,400 to 1,650 kWh/ kWp /year, for an average temperature of 25 to 27 °C. The optimal tilt angle for the modules is 10 to 15°.

2.3. Methodological approach

The study combines four components:

- **Analysis:** sizing of the power plant and selection of equipment.
- **Technique:** transient stability during connection, simulated under MATLAB/Simulink in reduced quantities (base 2.5 MVA and 30 kV).
- **Economic:** CAPEX, OPEX, NPV, IRR and payback time, calculated under PVsyst.
- **Environmentally friendly:** carbon footprint over 25 years.

The design is based on the standards IEC 62548-1, IEC 61727, IEC 62116, IEC 62109 and IEC 62271.

3. Power plant sizing

3.1. Modular principle

The power plant is divided into ten identical 1 MW nominal units, which ensures reliable calculations and allows for phased implementation. Each unit supports the grid during peak hours from 5 PM to 11 PM, representing a daily requirement of 6 MWh. With a reference irradiance of 4.8 kWh/m²/day and an overall efficiency of 65%, the calculated peak power is 1.92 MWp, rounded up to 2 MWp per unit (20 MWp total).

3.2. Photovoltaic field

The chosen module is a 700 W Trina Solar Vertex (N-type i- TOPCon, efficiency up to 22.5%). The DC voltage is limited to 1000 V, hence the need for strings of 24 modules in series (972 V). The maximum current of 2058 A requires 119 strings in parallel, or 2857 modules per unit.

The area occupied is approximately 2.25 hectares per unit, including spacing, totaling 22.5 hectares for the power plant. The neighboring valley of the BADIADINGI firing range offers over 500 hectares of available land.

3.3. Storage and conversion

Megapack containerized lithium-ion storage system : 3 MWh, 1.5 MW nominal (2 MW peak), 93-94% efficiency. It includes a regulator, a 30-35 kV three-phase inverter, a BMS, and SCADA compatibility. Since the inverter outputs directly at medium voltage, no step-up transformer is required.

3.4. Protections and connection to the station

Element	Characteristic retained
DC surge protector	1500 V
DC Fuse	2300 A, 1000 V
circuit breaker per unit	400 A, 30 to 35 kV
DC Cable	3 × 500 mm² copper
cable per unit	3 × 70 mm², 30 kV
Main busbar set	600 mm² copper per phase, 30 kV
Main circuit breaker	SF_6, 100 kA
Link to the station	Line underground 30 kV

3.5. Project Cost

The equipment cost estimate is approximately USD 16.06 million. Additional costs add 78%: services (25%), VAT (16%), transportation (10%), site cleanup (7%), and civil engineering (20%). The total cost is therefore approximately USD 28.59 million for 10 MW.

4. Results and discussion

4.1. Connection stability (MATLAB/Simulink)

Simulations show a stable connection: all quantities oscillate at the connection point, then quickly dampen. The simulation is performed on a single unit, using reduced dimensions, with an irradiation ramp from 1000 to 250 W/m² and then back, and a temperature step at the end of the cycle.

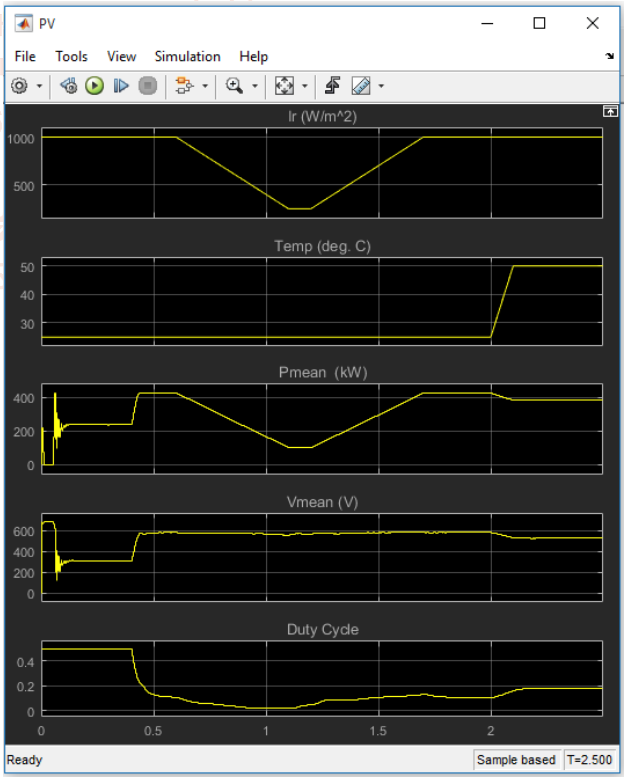


Figure 1 — Characteristic of the PV field: irradiation, temperature, average power and voltage, duty cycle (MATLAB/Simulink).

The active power fully undergoes the transient connection phase, then the oscillations subside and it follows the irradiation ramp. The average field voltage settles around 600 V and remains stable, with the duty cycle of the MPPT chopper adjusting automatically.

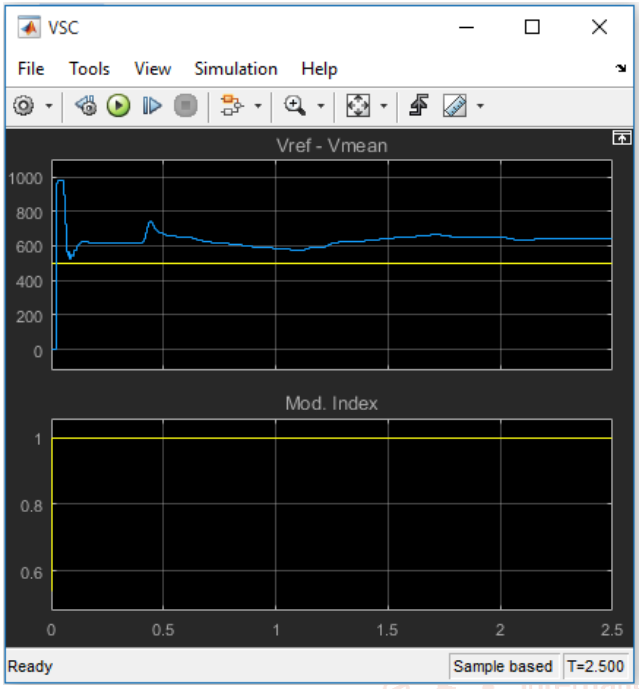


Figure 2 — VSC inverter: difference between setpoint and average DC bus voltage (Vref – Vmean) and modulation index.

On the inverter side, the initial peak exceeds 1000 V before dropping and settling around 600 V within the first few hundred milliseconds. The residual difference becomes negligible once synchronous operation is reached, confirming that the regulation quickly regains control after the circuit breaker closes.

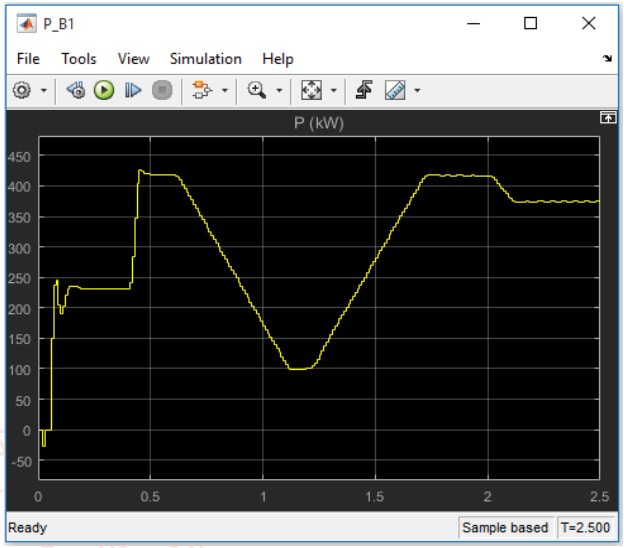


Figure 3 — Power at the 30 kV busbar during unit commissioning.

The power transmission experiences the same transient constraints, then stabilizes in the synchronous regime: the unit injects its nominal power without causing instability.

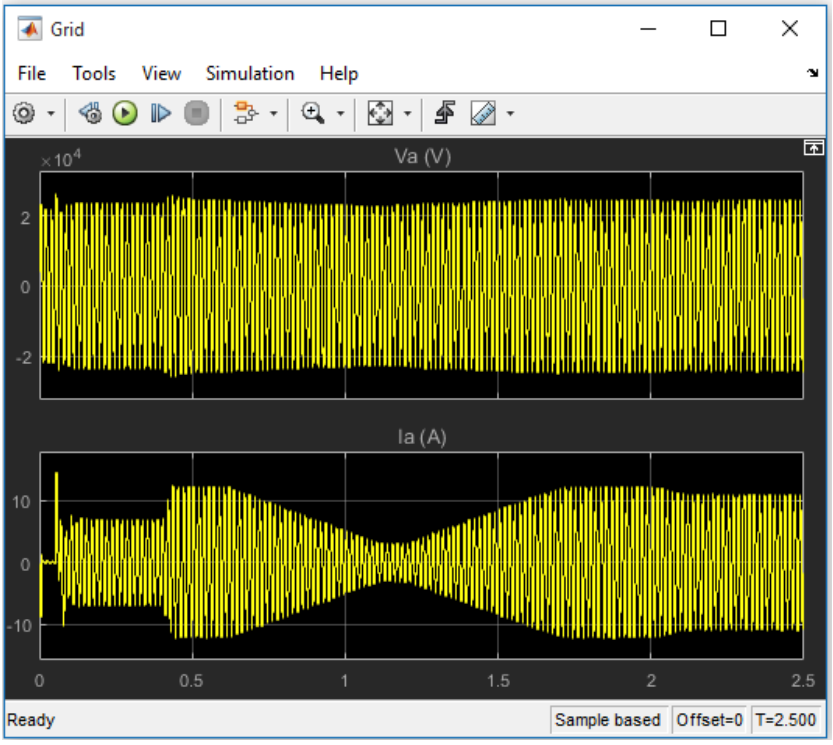


Figure 4 — Voltage (Va) and current (Ia) at the busbar during and after connection.

The voltage in the busbars remains practically unchanged, as the grid is significantly more powerful than the power plant; only a slight transient overvoltage appears. The current, slowed by the circuit's inductances, experiences a brief spike before following the production envelope.

4.2. Energy Performance (PVsyst)

Each unit injects approximately 3.7 GWh /year. Normalized monthly energy values show that the useful energy output from the inverter far outweighs the losses, regardless of the month.

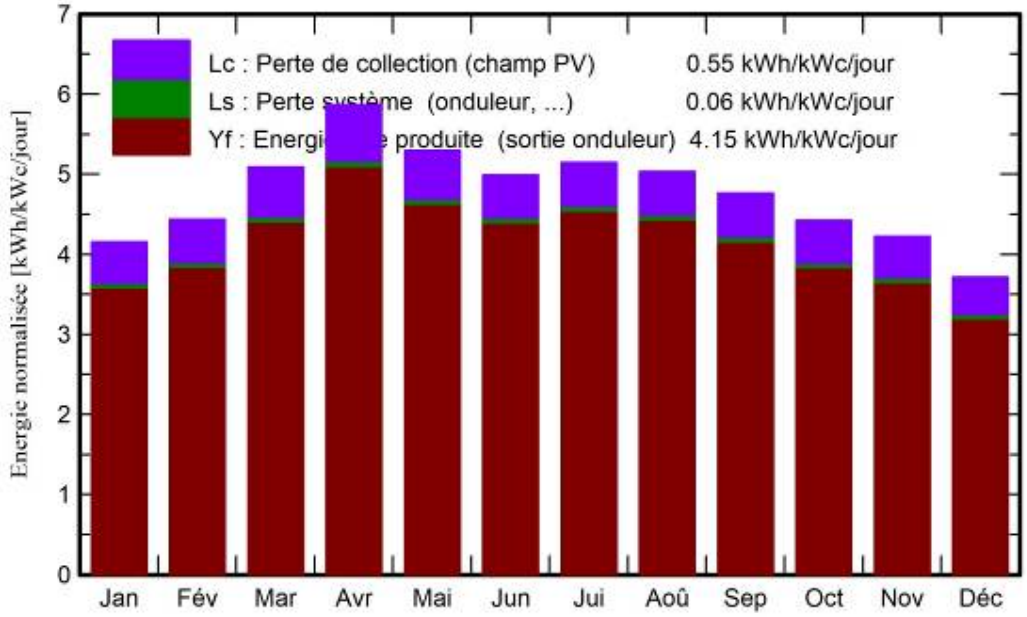


Figure 5 — Normalized energies per month: useful energy produced (Yf), collection losses (Lc) and system losses (Ls), in kWh/ kWp /day.

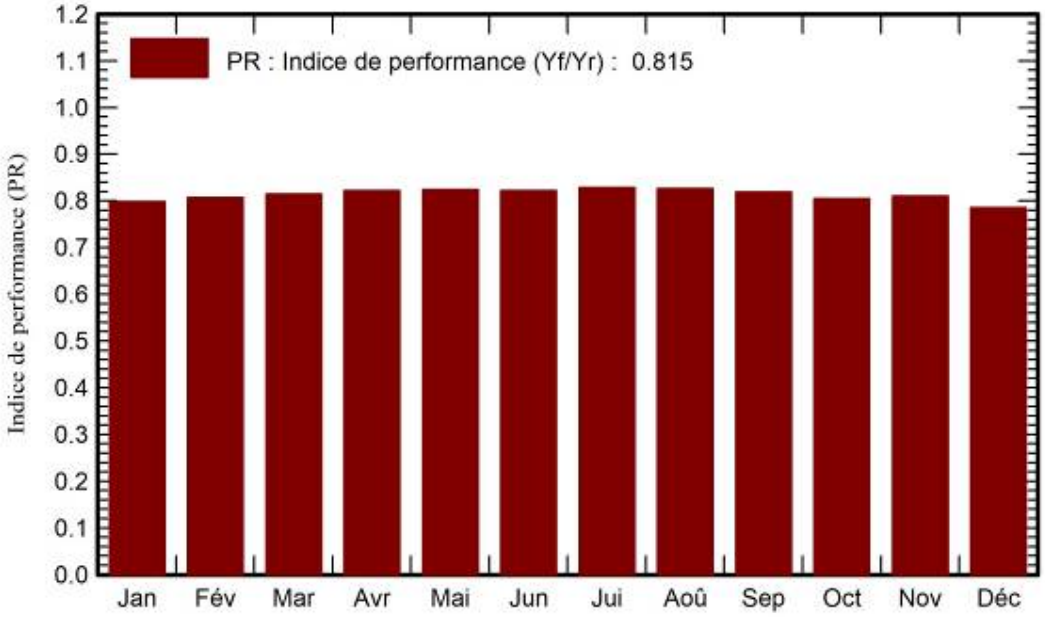


Figure 6 — Monthly performance index (PR); annual average of 0.815.

The performance index remains high and consistent throughout the year, including during the dry season. The loss diagram confirms this result: 27.4% cumulative losses, meaning approximately 72.6% of the available energy is actually utilized.

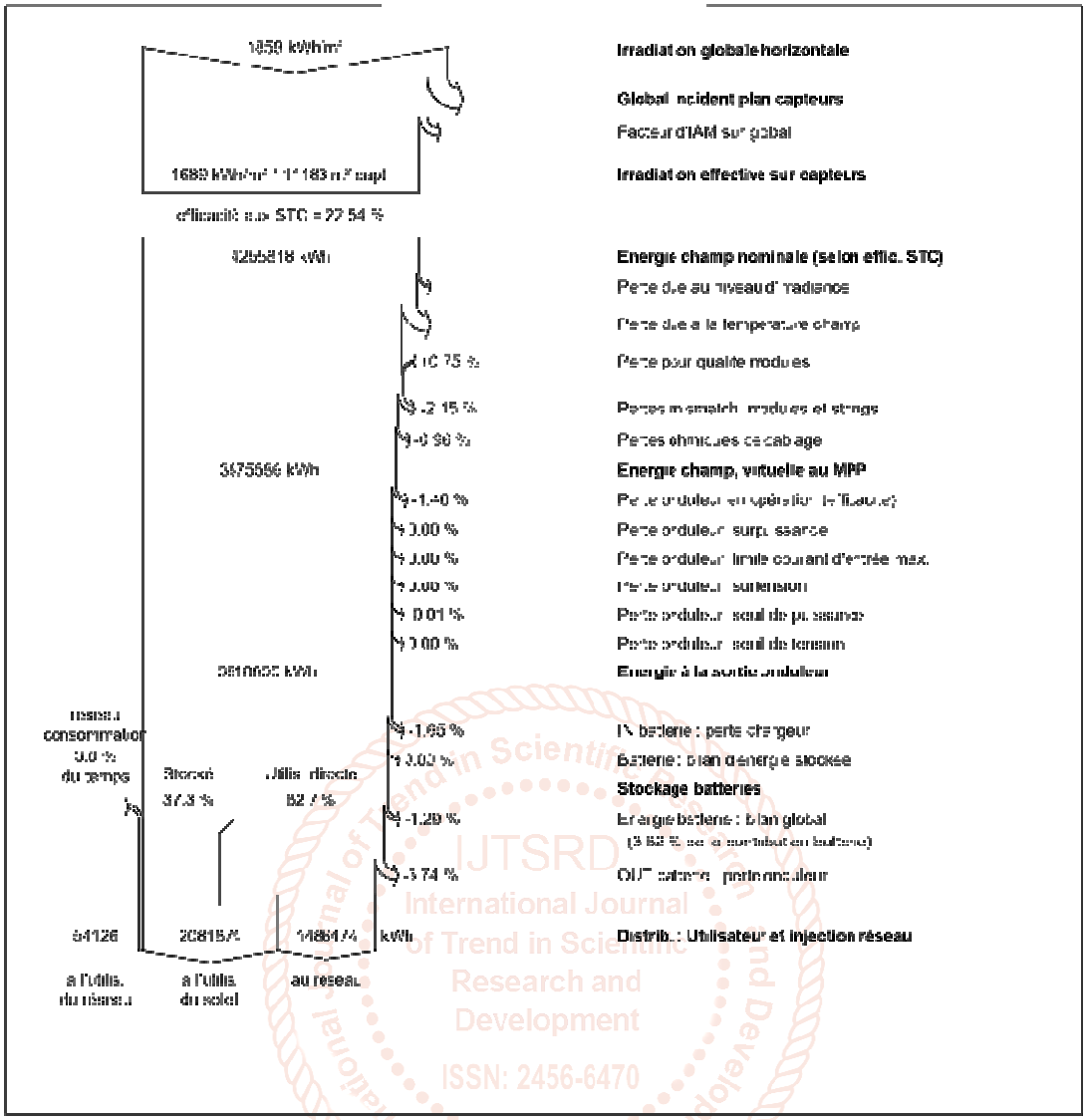


Figure 7 — Diagram of PVsyst losses, from global horizontal irradiation to injection into the network.

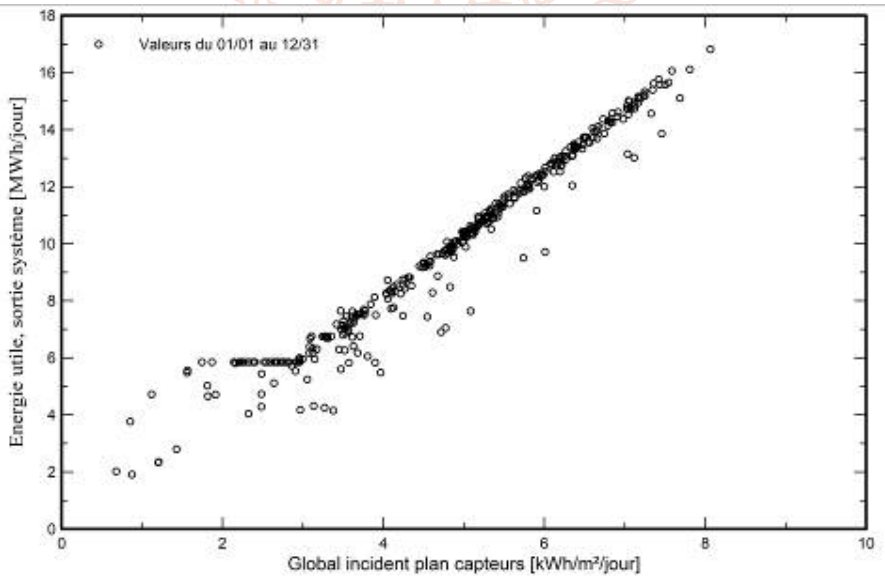


Figure 8 — Daily input/output diagram: useful energy at system output as a function of incident irradiation, from January 1 to December 31.

The scatter plot remains very tightly clustered around a straight line, indicating regular and predictable behavior of the installation. The plateau visible around 6 MWh /day corresponds to the power limit imposed by the conversion and storage system.

4.3. Economic profitability

The analysis covers 25 years from 2027, with a buyback rate of 0.20 USD/kWh guaranteed for 15 years and an inflation rate of 5%/year.

Indicator (per 1 MW unit)	Value
Cost installation	USD 2,872,800
Operating expenses	USD 240,544/year
Return time	9.6 years
VAN	approximately USD 11.05 million
Return on investment	384.7%

The remaining 15.4 years after the return generate only profits. Extrapolated to the ten units, the cumulative profit would reach approximately USD 110.5 million.

4.4. Environmental assessment

The carbon footprint is negative for the first seven years, the time needed to offset the manufacturing of the equipment, then becomes positive and grows linearly.

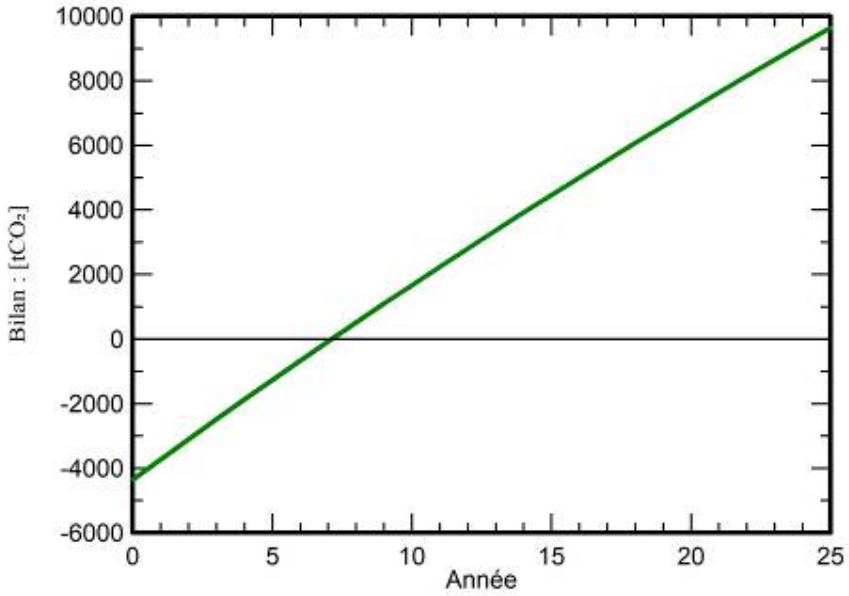


Figure 9 — CO_2 emissions balance over 25 years: equilibrium reached around the 7th year.

The manufacture of the equipment emits approximately 4,356 t of CO_2, while the operation avoids approximately 15,752 t over 25 years, resulting in a net gain of approximately 11,396 t, or 261.6% of manufacturing emissions.

5. Conclusion

A 10 MW photovoltaic power plant with storage, connected to the 30 kV busbars of the BADIADINGI substation, addresses the substation's power deficit. It is technically viable, financially profitable, and beneficial to the environment.

Its design, based on 1 MW units, allows for a phased deployment, adapted to the financing capacities of SNEL and its partners (the Congolese government, JICA, and multilateral donors). Further studies are still needed regarding actual load data, tariff assumptions, and the simultaneous integration of multiple units.