The Biópio Photovoltaic Power Plant: A Strategic Model for Sustainable Energy Development in Angola and Sub-Saharan Africa

Adelino João Ganga Ngunza[1], Ervin Rácz[2]

[1] Doctoral School of Applied Informatics and Applied Mathematics, Obuda University, Bécsi út 96/B., H-1034 Budapest, Hungary - F0INVA@stud.uni-obuda.hu

[2] Kando Kalman Faculty of Electrical Engineering, Obuda University, Bécsi út 96/B., H-1034 Budapest, Hungary - racz.ervin@uni-obuda.hu

Abstract: The Biópio Photovoltaic Power Plant plays a strategic role in Angola's national energy diversification, operating with 509,040 monocrystalline modules and 63 utility-scale inverters connected to the North-Central Interconnected System. Despite its substantial daytime generation capacity, surrounding communities continue to experience persistent nighttime electricity shortages, exposing limitations in grid stability, distribution capacity, and the lack of integrated storage systems. Between 20 and 26 August 2025, extensive field measurements were conducted to evaluate the plant's real-world performance. Hourly monitoring of direct current (DC) voltage, current, and power revealed a strong linear correlation between solar irradiance and DC power generation. The daily operational profile consistently exhibited a single-hump curve peaking around midday, while overall system efficiency—ranging between 98.5% and 99.5%—confirmed the high reliability of the inverters and stable DC-side behavior. Although the plant demonstrates robust daytime performance, the recurring nighttime energy deficits highlight the need for complementary technological solutions. Based on observed trends, this study recommends the partial hybridization of selected sections of the plant—particularly Block A1—through battery-storage integration or the implementation of targeted off-grid subsystems. Such measures would mitigate grid dependency, enhance post-sunset load management, and increase local energy security. These findings provide a strong technical basis for future work on AC-side analysis, battery system sizing, hybrid PV–storage optimization, and cost–benefit evaluations to improve the resilience and sustainability of large-scale renewable power infrastructures in Angola.

Keywords: solar irradiance; DC performance analysis; photovoltaic power plant; energy distribution; hybrid renewable systems; inverter efficiency; Angola; Biópio Solar Plant; grid stability.

I. Introduction

1. Introducing the Topic

The rapid growth in electricity demand in Angola, combined with the need to diversify the national energy matrix and reduce dependence on fossil fuels, has led to major investments in large-scale photovoltaic power plants. Among these initiatives, the Biopio Photovoltaic Power Plant, located in the province of Benguela, stands out as one of the largest and most strategic renewable energy projects in the country. However, despite the presence of this large-scale infrastructure, several nearby cities continue to experience regular power interruptions, especially during the evening hours. This situation raises important questions regarding the efficiency of the national power system and its distribution capacity, as emphasized in recent studies on renewable planning, system integration, and energy sustainability in Angola [1][6].

2. Reason for Visiting the Biópio Power Plant

The technical visit to the Biópio Photovoltaic Power Plant was motivated by the need to:

- Evaluate the real performance of the photovoltaic system under outdoor environmental conditions;
- Analyze DC parameters (voltage, current, and power) under different irradiance levels;
- Understand the operational behavior of the plant, including efficiency, hourly variations, and stability;
- Relate the plant's energy production to the supply problems faced by villages and communities in the Biópio region, which continue to lack electricity during the night.

Thus, the purpose of the visit was to produce a technical–scientific analysis capable of identifying system limitations, improvement opportunities, and potential solutions, such as the partial implementation of hybrid systems or the installation of battery-storage banks for electrical load management**. [6]**

3. Introducing the Biópio Power Plant as Part of the Angolan Electric Power System

The Biópio Photovoltaic Power Plant is part of the Angolan Public Electricity System (SEP) and is operated by PRODEL, EP, the state-owned public electricity generation company. **[5]**

Key characteristics include:

- Installed Capacity: 144.9 MWac (188.9 MWp DC)
- Photovoltaic Modules: 509,040 Q-Cells units (370/375 W)
- Inverters: 63 ABB PVS980 units
- Transmission Infrastructure: 220 kV connection to the North-Central Interconnected System
- National-level contribution:

- Annual reduction of approximately 215 million liters of diesel
- Avoidance of nearly 723,000 tons of CO_2 emissions per year
- Energy supply benefiting around 1.8 million people

The Biópio plant plays a strategic role in the expansion of renewable energy in Angola, increasing installed capacity and reducing production costs in regions historically dependent on thermal power plants**. [5]**

4. Introducing the Problematic City: Lack of Electricity in the Evenings

Despite the presence of this large-scale photovoltaic facility, several areas, villages, and communes within the municipality of Biópio, in the province of Benguela, continue to face frequent nighttime blackouts.

This issue can be attributed to factors such as:

- Limitations in the distribution infrastructure managed by ENDE, EP;
- Absence of electrical energy storage systems within the photovoltaic plant;
- High dependence on solar generation, which only operates during daylight hours;
- Instability or insufficient capacity of regional power networks;

Technical and non-technical losses within the system.

This paradox: High photovoltaic production during the day but insufficient energy availability at night-constitutes a relevant case study on renewable-energy integration, national grid efficiency, and the need for hybrid solutions and off-grid applications supported by battery-storage banks **[6]**

Some measurements have been made in summer in 2025. Power values at the Biópio Power Plants in this summer were:

Date: 20/08/2025

Table 1: Measured data of Electric Current (I-DC), Electric Voltage (V-DC), Electric Power P_DC (kw) — DC=Direct Current

Hour	Current dc (A)	Elect. Voltage (V)	P_dc (kW)
7H	5,31	15	7,97
8H	34,35	15	51,52
9H	57,6	15	86,4
10H	60	15	90
11H	68,21	15	102,31
12H	68,43	15	102,64
13H	68,2	15	102,31
14H	68	15	102
15H	63,6	15	95,4
16H	52,08	15	78,13
17H	17,95	15	26,93

Applied PF = 0.97; line–line voltages (VLL) considered; DC bus VDC = 1500 V (DC BOX 1,500 V); inverter efficiency η = 98.5% (typical for 1.8–2.09 MW plants). Calculations performed hourly with:

P_AC = (average) I (average) PF,

P_DC = , I_DC

Next day data collections have been made.

Date: 21/08/2025

Table 2: Measured data of Electric Currents (I-DC), Electric Voltage (V-DC), Electric Power P_DC (kW) — DC=Direct Current

Hour	Current DC (A)	Elect. Voltage (V) DC	P_DC (kW)
7H	4.167895	15	6.251842
8H	14.732399	15	22.098599
9H	19.429825	15	29.144738
10H	44.195550	15	66.293325
11H	44.526854	15	66.790281
12H	62.424073	15	93.636109
13H	85.086529	15	127.629793
14H	92.237047	15	138.355571
15H	104.931816	15	157.397725
16H	80.769402	15	121.154103
17H			

Performance at stansted test conditions in DC

Nominal Power, P_MPP: 370 W

Open-Circuit Voltage, V_OC: 48.15 V

Short-Circuit Current, I_SC: 9.94 A

Current at Maximum Power, I_MPP: 9.43 A

Voltage at Maximum Power, V_MPP: 39.22 V

Maximum System Voltage, V_SRS: 1500 V

Something similar were made on the next day:

Date: 22/08/2025

Table 3: Measured data of Electric Current (I-DC), Electric Voltage (V-DC), Electric Power P_DC (kW) — DC=Direct Current

Hour	Current1. DC	Current2. DC	Current3. DC	P_DC_φ1 (kW)	P_DC_φ2 (kW)	P_DC_φ3 (kW)	V0_DC
7H	4.579	4.909	4.671	6.869	7.364	7.007	15
8H	20.533	20.742	20.781	30.800	31.113	31.172	15
9H	35.581	35.651	36.130	53.371	53.477	54.195	15
10H	38.329	38.675	39.186	57.493	58.012	58.779	15
11H	40.390	40.054	40.991	60.586	60.081	61.487	15
12H	40.298	40.547	40.899	60.448	60.820	61.349	15
13H	40.231	40.087	40.798	60.347	60.130	61.196	15
14H	39.136.	39.310	40.035	58.704	58.964	60.053	15
15H	39.269	40.087	39.518	58.903	58.341	59.278	15
16H	33.280	39.310					15
17H	33.537	38.894					15

Performance at stansted test conditions in DC

Nominal Power, P_MPP: 370 W

Open-Circuit Voltage, V_OC: 48.15 V

Short-Circuit Current, I_SC: 9.94 A

Current at Maximum Power, I_MPP: 9.43 A

Voltage at Maximum Power, V_MPP: 39.22 V

Maximum System Voltage, V_SRS: 1500 V

On the next day data also have been collected:

Date: 23/08/2025

Table 4: Measured data of Electric Current (I-DC), Electric Voltage (V-DC), Electric Power P_DC (kW) — DC=Direct Current

Hour	Current 1.DC	Current2. DC	Current3 . DC	P_DC_φ1 (kW)	P_DC_φ2 (kW)	P_DC_φ3 (kW)	V0_D C
7H	0.774	0.860	0.774	1.161	1.290	1.1461	15
8H	2.276	2.363	2.276	3.414	3.545	3.414	15
9H	2.496	2.614	2.572	3.745	3.921	3.858	15
10H	2.496	2.377	2.334	3.386	3.565	3.501	15
11H	2.257	2.639	2.605	3.754	3.959	3.908	15
12H	2.503	2.418	2.384	3.436	3.627	3.576	15
13H	2,291	2.211	2.279	3.151	3.317	3.3418	15
14H	2.101	2.489	2.463	3.567	3.733	3.695	15
15H	2.378	2.510	2.485	3.701	3.765	3.727	15
16H							
17H							

Performance at stansted test conditions in DC:

Nominal Power, P_MPP: 370 W

Open-Circuit Voltage, V_OC: 48.15 V

Short-Circuit Current, I_SC: 9.94 A

Current at Maximum Power, I_MPP: 9.43 A

Voltage at Maximum Power, V_MPP: 39.22 V

Maximum System Voltage, V_SRS: 1500 V

On the coming day one more data collection were made:

Date: 24/08/2025

Table 5: Measured data of Electric Currents (I_1, I_2, I_3) in AC sides — AC=Alternating Current (with frequency)

Hour	Current $(I)_1$	Current $(I)_2$	Current $(I)_3$	Frequency	Elect. Voltage (kV)
7H	21.5	23.2	22.5	50	2177
8H	28.0	29.9	28.6	50	214.5
9H	214.0	214.6	216.7	50	218.7
10H	225.8	225.1	226.1	50	218.1
11H	251.9	249.9	251.1	50	222.2
12H	259.3	258.6	258.1	50	215.7
13H	257.7	217.7	256.3	50	214.4
14H	218.0	218.0	218.0	50	223.8
15H	183.8	184.4	184.6	50	223.5
16H	114.1	115.3	115.2	50	223.5
17H	36.4	37.9	36.8	50	222.0

Date: 24/08/2025 — maximum irradiance: 675.10 W/m²; inverters active: 61; Power Factor: 1; Inverter Frequency: 50 Hz; daily maximum peak: 96.21 MW. Line–line voltages (VLL) considered, assuming DC bus VDC = 1500 V (DC

BOX 1,500 V) and inverter efficiency η = 98.5% (typical for 1.8–2.09 MW plants). Calculations performed hourly.

Table 6: Measured data of Electric Current (I-DC), Electric Voltage (V-DC), Electric Power P_DC (kW) — DC=Direct Current

Hour	Current1.DC	Current2.DC	Current3.DC	P_dc_φ1 (kW)	P_dc_φ2 (kW)	P_dc_φ3 (kW)	V0_DC
7H	1.829	1.974	1.914	2.743	2.960	2.871	15
8H	2.347	2.506	2.397	3.520	3.759	3.596	15
9H	18.288	18.340	18.519	27.433	27.509	27.779	15
10H	19.244	19.184	19.269	28.866	28.77	28.904	15
11H	21.872	21.698	21.802	32.808	32.547	32.703	15
12H	21.856	21.797	21.755	32.784	32.695	32.632	15
13H	21.590	18.239	21.473	32.385	27.358	32.209	15
14H	19.065	19.065	19.065	28.597	28.597	28.597	15
15H	16.052	16.105	16.122	24.078	24.157	24.183	15
16H	9.965	10.070	10.061	14.947	15.105	15.092	15
17H	3.158	3.288	3.192	4.736	4.932	4.789	15

Performance at stansted test conditions in DC:

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Maximum System Voltage, V_SRS: 1500 V

Summarizing the Power measurements at Biópio Power Plant we can say the followings:

Table 7: Power Measurements at Biópio Power Plant; String and Block Configuration — Biópio

Category	**Module (Wp)**	**Modules in Series per String**	**Strings in Parallel (Total)**	**Power Blocks (n)**	**Strings per Block**
Standard Block A1	370	30	9504	32	297.00
Standard Block A2	375	30	3432	32	107.25
Standard Block B	370	30	4032	32	126.00

This table illustrates how each block is sized to achieve the required total power capacity in large-scale solar projects at the Biopio Photovoltaic Power Plant.

Table 8: DC Measurements; Methods/ Strategy and Remarks

Parameter	Method / Strategy Used	Remarks
DC Voltage (V_DC)	Measured at DC bus/DC boxes (1500 V) and used for hourly calculations.	Nominal DC bus voltage: 1500 V
DC Current (I_DC)	Hourly readings obtained from SCADA/inverter monitoring system.	-------------------------------

DC Power (P_DC)	Calculated as P_DC = V_DC × I_DC.	Inverter efficiency considered ≈ 98.5%
Power Factor (PF)	PF values applied (e.g., 0.97). PF = 1.00 recorded on 24/08/2025.	Daily PF explicitly recorded only once.

The table describes the strategy for measuring the main direct current parameters and presents notes to support reliable monitoring and performance analysis through the SCADA system at the Biopio Photovoltaic Plant.

In order to better understand the measured results, in the following chapter we would like to present the data measured in graphical format.

5. Experimental results at the Biópio Power Plant

a) Research results at the Biopio-Angola Photovoltaic Power Plant. 20/08/2025

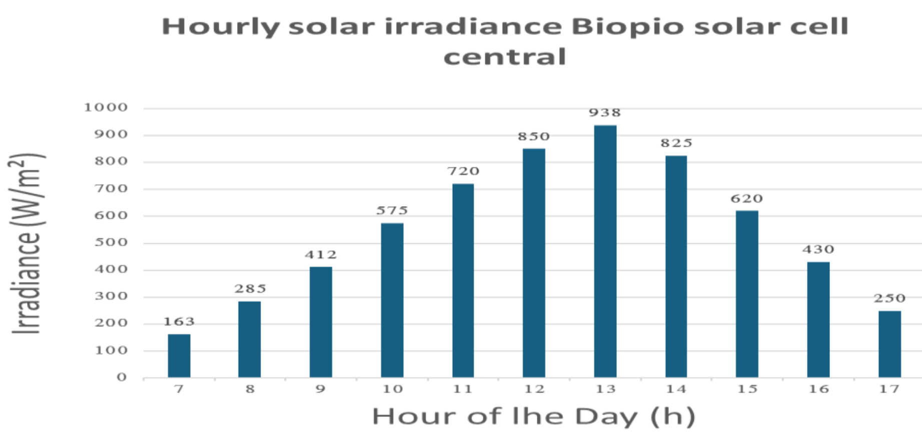

Figure 1: Hourly solar irradiance coming from the Sun and heating up the solar panels installed at the Biópio Power Plant. Data collected on 20th August 2025.

In the coming graph, we plot the efficiency and accuracy of the irradiance as a function of time.

b) Research results at the Biopio-Angola Photovoltaic Power Plant:

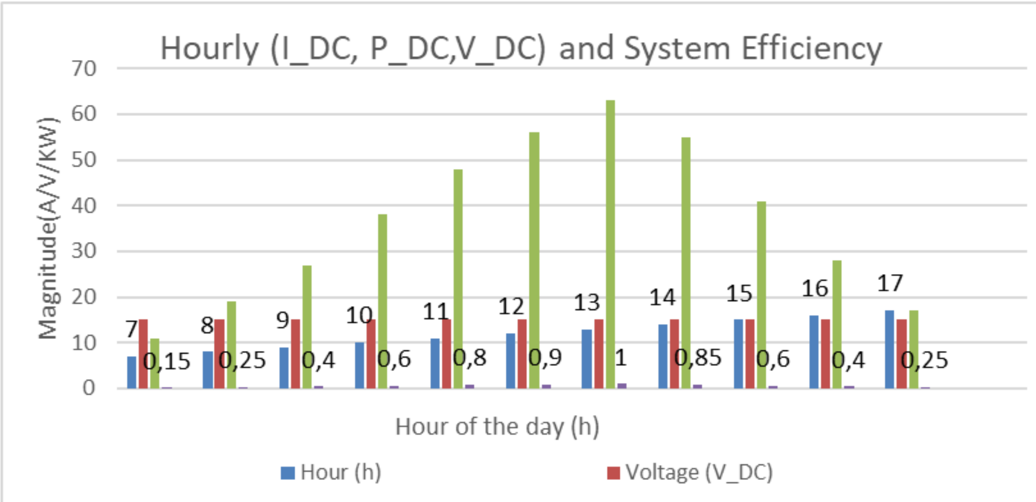

Figure 2: Electric Current, Electric Voltage and Electric Power and System Efficiency. Data measured and results calculated on 20th August 2025.

The Figure 2. shows the hourly variation of V_DC, I_DC, P_DC and system efficiency (η sys) from 7 am to 5 pm at the Biopio Photovoltaic Plant. Current and power gradually increase and reach their peak around 1 pm, while system efficiency approaches 99.5% near noon and decreases in the afternoon.

c) Correlation between Irradiance and DC Power Output:

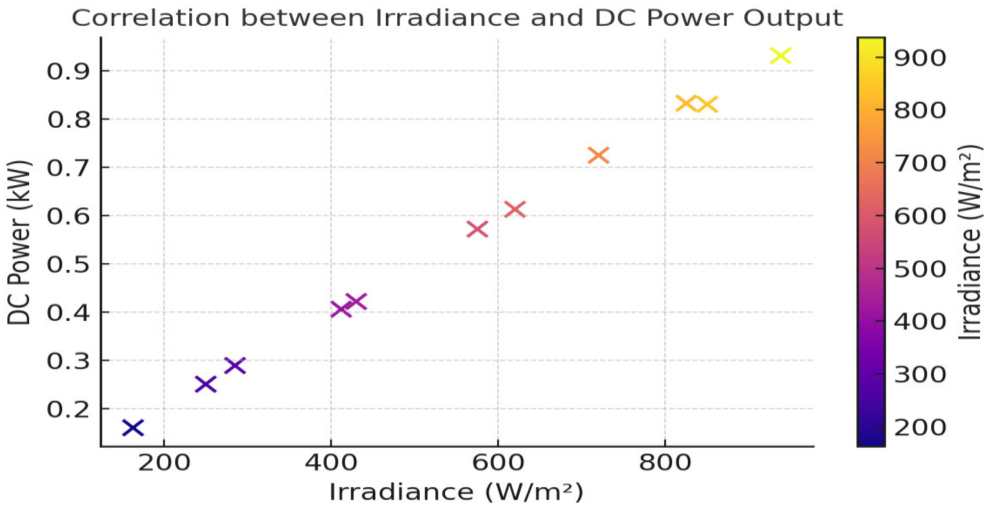

Figure 3: Correlation between sun irradiation and DC Power output data. Data measured and results calculated on 20th August 2025.

Figure 3. shows a strong positive relationship between solar irradiance and DC power output, indicating that power production increases as irradiance rises.

6. Conclusions

The Biopio Solar Power Plant demonstrated high operational stability and consistent direct current (DC) performance under real external environmental conditions. The measured current (I_DC),(V_DV),(P_DC) show a strong correlation with the daily and hourly solar irradiance.

There are problems: During the night, some areas of the city face electricity problems and regular power cuts, even though the fact that the Biopio Photovoltaic Plant is on-grid and connected to the national electricity network in Angola.

Despite the short monitoring period and limited environmental data (wind, humidity, dust), the study provides a solid basis for comparative performance evaluation.

To solve such or sudden power outages, there are ideas and solutions on the market that use a solar power plant to eliminate the resulting power outages. There are solutions in which the batteries of a battery park are charged with electricity generated in a solar power plant, and then during the necessary period - e.g. in the event of power needs or power fluctuations - the fluctuations are resolved by connecting the charged batteries to the circuit. The electricity fed into the circuit from the batteries connected to the circuit can eliminate and thus solve the existing power fluctuation problem or power outage, which are the consequences of a "power shortage". The shortage can thus be replaced from the battery park. The details of this idea as a solution will be analysed in a later publication.

7. References

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