PERFORMANCE INVESTIGATION OF A 5 MW PHOTOVOLTAIC SYSTEM: ALFASHIR SUDAN

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Abstract

This study comprehensively analyzes the operational performance and economic feasibility of a 5MW grid-connected photovoltaic in Sudan over a two-year monitoring period. Leveraging the capabilities of PVSyst software, the actual plant performance was rigorously compared to simulation predictions. Results revealed a significant disparity between observed and simulated energy generation, prompting the exploration of potential areas for enhancement. Seasonal fluctuations in the performance ratio were evident, with peak values during some seasons, albeit not consistently aligning with simulation projections. Despite these challenges, the Plant made a notable impact by reducing CO2 emissions, highlighting the environmental benefits of solar energy. Financial analysis unveiled discrepancies between actual and simulated savings, underscoring the need for optimization and efficiency improvements. The equity payback period, influenced by electricity pricing policies, was estimated at 15 years, emphasizing its role in assessing project economics. The region's high radiation intensity and humidity levels emerged as significant factors affecting plant performance. Addressing these challenges is crucial for maximizing the PV plant's operational efficiency and viability. Our Recommendations include thoroughly examining control system functions during commissioning and improving operational accuracy.

5 MW FOTOVOLTAİK SİSTEMİN PERFORMANS İNCELEMESİ: ALFASHIR SUDAN

Anahtar Kelimeler

Şebeke Bağlantılı
Maksimum Performans Oranı (MPR)
Fotovoltaik
PVSist

Öz

Bu Makale, Sudan'daki 5MW'lık şebekeye bağlı fotovoltaik santralin çalışma performansını ve ekonomik fizibilitesini iki yıllık bir izleme süresi boyunca kapsamlı bir şekilde analiz etmektedir. PVSyst yazılımından yararlanılarak gerçek santral performansı, simülasyon tahminleriyle karşılaştırılmıştır. Sonuçlar, gözlemlenen ve simüle edilen enerji üretimi arasında önemli bir eşitsizliği göstermektedir. Performans oranındaki mevsimsel dalgalanmalar açıkça görülmektedir, her ne kadar simülasyon projeksiyonlarıyla tutarlı bir şekilde uyumlu olmasa da, bazı mevsimlerde en yüksek değerlere ulaşmaktadır. Bu zorluklara rağmen tesis, CO2 emisyonlarını azaltarak kayda değer bir etki yaratmıştır. Finansal analiz, gerçek ve simüle edilmiş tasarruflar arasındaki farklılıkları ortaya çıkararak optimizasyon ve verimlilik iyileştirmelerine olan ihtiyacın önemini göstermektedir. Elektrik fiyatlandırma politikalarından etkilenen öz sermaye geri ödeme süresi, proje ekonomisinin değerlendirilmesindeki rolü vurgulanarak 15 yıl olarak tahmin edilmiştir. Bölgenin yüksek radyasyon yoğunluğu ve nem düzeyleri, tesis performansını etkileyen önemli faktörler olarak ortaya çıkmıştır. Bu zorlukların üstesinden gelmek, PV tesisinin verimliliğini ve yaşaya bilirliğini en üst düzeye çıkarmak için çok önemlidir. Önerilerimiz, devreye alma sırasında kontrol sistemi fonksiyonlarının kapsamlı bir şekilde incelenmesini ve operasyonel doğruluğun iyileştirilmesini içermektedir.

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1. Introduction

In light of the undeniable sustainability challenges and the well-documented contributions of hydrocarbon sources, such as coal and oil, to global warming, it is imperative to take decisive actions to expedite the adoption and deployment of renewable energy technologies. This imperative stems from the pressing need to address air pollution issues and meet the energy demands of a rapidly growing global population, all within the context of our fast-paced and energy-driven civilization (Roshana, Indamine, Sujeev Rithan, Krishnakumar and Vishal, 2021). Indeed, the transition to sustainable electricity from renewable sources has become an imperative in virtually every facet of modern life.

The notion that renewable sources have the potential to satisfy global energy needs entirely is not mere conjecture but rather a conclusion drawn from decades of relentless research and innovation. This transformative journey commenced with the development of pioneering systems like solar water heating and has now culminated in the remarkable emergence of hydrogen-powered vehicles on our roads. Among the diverse array of renewable energy technologies, solar photovoltaic (PV) technology stands out as a beacon of hope and practicality, characterized by rapid development and a robust response to global energy concerns (Saheb-Koussa, Koussa and Said, 2013). The PV system cost reduction trajectory has propelled global photovoltaic capacity beyond the remarkable milestone of 635 GW in 2021 (Fadlallah and Benhadji Serradj, 2020). However, despite these monumental achievements, a significant chasm persists between the burgeoning demand for clean energy and the capacity to supply it, necessitating an accelerated and expanded deployment of this technology in the coming decades. Insights from the 2019 World Energy Outlook underscore that achieving zero CO2 emissions hinges upon a resolute decarbonization of our energy supply, compelling us to expand installed solar capacity to a staggering 7208 TWh by 2040 (Fadlallah and Benhadji Serradj, 2020). It is crucial to recognize that the performance of PV systems is intricately intertwined with many factors, ranging from geographical nuances to solar irradiance and the complex interplay of meteorological variables encompassing wind and temperature (Roshana et al ,2021; Mohammadi and Cenk, 2022). These multifaceted dynamics must be meticulously considered in designing and assessing photovoltaic systems.

Against these global imperatives, the African continent grapples with escalating energy demand, which poses a formidable challenge to attaining Sustainable Development Goals (SDGs). The primary obstacle lies in the pervasive lack of access to electricity, which impacts the lives of approximately 700 million people who still rely on traditional biomass for their daily energy needs (Adenle,2020). Despite the significant renewable energy potential that most African nations possess, investments in renewable projects remain meager, hampered by the tardy execution of comprehensive renewable energy plans by governments and the lamentable absence of transparent and credible frameworks.

Like many developing nations, Sudan confronts a chronic electricity scarcity characterized by unreliable supply, frequent outages, and even complete system blackouts. Only 76% of the available power is usable, with 24% lost to inefficiencies (Rabah, Rabah, Nimer, Doud and Ahmed, 2016). Moreover, a mere 35% of the population has access to electricity. This dire situation is exacerbated by a paucity of funds for both conventional and renewable energy projects, as well as Sudan's reliance on expensive fossil fuel imports following the loss of significant oil reserves and gas due to the secession of South Sudan. Although studies have indicated that hydropower and biofuel hold promise as primary electricity sources, the variability of hydropower and the volatility in oil product pricing and availability cast doubt on these findings.

Recent scholarly endeavors have employed simulation tools to assess the feasibility, efficiency, and Output of solar power installations in Sudan. For instance, one study simulated (Abdeen, Mourad and Salim, 2019) a photovoltaic (PV) installation connected to a grid across ten Sudanese cities, utilizing the PVSyst software to categorize these cities based on their potential energy production levels. A 5MW PV system was also constructed, and its yearly energy output was calculated using modeling software, revealing a substantial energy production potential for Sudan cities. Other studies (Sudhakar and Samykano, 2018) have explored the capacities and outputs of 8MW mono-silicon and poly-silicon solar PV systems in cities like Kuala Lumpur and Lucknow, shedding light on the impact of ambient temperature variations on energy production. Furthermore, comprehensive solar resource and production assessments have been conducted (Jamil, Zhao, Zhang, Rafique and Jamil, 2019) for a 3*50 MW PV plant, providing valuable insights into energy production unpredictability's and the deterioration of power over time. Another study (Faiz, Shakoor, Raheem, Umer, Rasheed and Farhan, 2021) delved into the performance of a 3 MW PV system in Pakistan, demonstrating significant coal savings and ecological benefits.

Similarly, investigations have been conducted on various grid-connected PV systems worldwide (Goel and Sharma, 2021; Mondol, Yohanis, Smyth and Norton, 2006; Kymakis, Kalykakis and Papazoglou, 2009; Shiva Kumar and Sudhakar, 2015), providing valuable data on performance ratios and annual energy production. These collective findings reinforce the credibility and utility of simulation tools in assessing PV system performance across diverse geographic and climatic conditions, strengthening the foundation of our research. However, despite these efforts, the performance of Sudan's first giant grid-connected PV plant in Al-Fashir, operational for over three years, has not met expectations. This presents an opportunity for a comprehensive performance review using the PVSyst software package, which offers valuable insights for policymakers and researchers in the Sudan energy sector. Notably, this study will mark the first economic assessment conducted on the Plant, providing crucial operation data for the Sudanese energy sector.

In conclusion, this comprehensive research initiative aims to address the pressing challenges associated with sustainable energy development in Sudan, mainly through the critical evaluation of the performance of the Al-Fashir PV plant. Using advanced simulation tools, such as PVSyst, offers an invaluable means of assessing plant efficiency and economic viability. Furthermore, this study's outcomes have the potential to shape policymaking and strategic decisions within the Sudanese energy sector, providing a path forward toward a more sustainable and reliable energy future in the region. The originality of this work lies in its focus on evaluating the economic aspects and real-world performance of a substantial grid-connected PV plant in Sudan, contributing to the body of knowledge on renewable energy deployment in developing nations.

This paper is structured into nine sections. Section 1 introduces the study, providing context and objectives. Section 2 delves into the PVsyst software, explaining its role in our analysis. Section 3 briefly summarizes Sudan, setting the geographical and environmental context. Section 4 explores the layout of the Al Fashir photovoltaic station, detailing its design and components. Section 5 focuses on the photovoltaic modules and inverters used in the system. Section 6 describes the simulation process, outlining how data was generated and analyzed. Section 7 presents the simulation results, showcasing key findings and performance metrics. Section 8 conducts a comprehensive feasibility analysis of the Plant's operation, considering economic factors. Finally, Section 9 concludes the paper by summarizing key insights and implications. The paper concludes with a list of references for further reading and verification of sources.

2. Pvsyst Software

The utilization of PVSyst, a sophisticated energy modeling software, plays a pivotal role in our research. PVSyst is a versatile computer program specifically designed for simulating the energy production of solar plants both before and after deployment (Ashok Kumar, Indragandhi and Uma Maheswari, 2020). It offers a comprehensive suite of meteorological data and tools tailored for in-depth photovoltaic (PV) systems analysis. A remarkable feature of PVSyst is its extensive database housing solar-related information, facilitating the seamless design of solar power plants at specific geographic locations. This includes critical data such as solar path analysis, indispensable for accurate system design. Furthermore, PVSyst empowers users to make informed decisions regarding selecting PV panels and inverters based on project requirements, ensuring optimal system configuration.

Our investigation centers on various crucial variables critical to the success of solar power systems. These variables encompass the intricacies of framework construction, meticulous assessment of power yield with charts and graphs, in-depth analysis of PV module performance, and the intricate task of delineating power distribution curves. Our focus concerns grid-connected solar networks, a prevalent and environmentally responsible choice. Within our research, we employ PVSyst software to emulate the behavior of photovoltaic modules and converters, employing a circuit configuration analogous to the one illustrated in Figure 1. The structural composition of our study primarily comprises three fundamental elements: PV modules, the system architecture, and the load profiles, collectively forming the basis for our rigorous analysis and insights in this work.

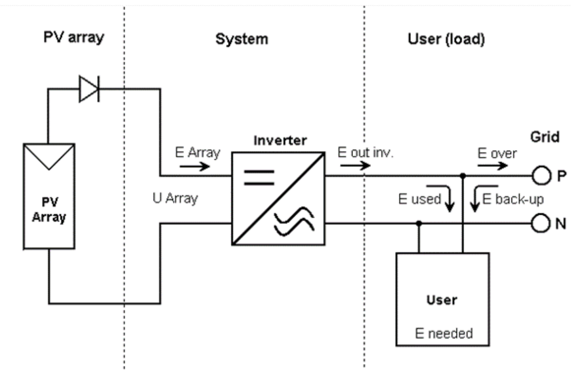


Figure 1. System Structure

3. Sudan in Brief

Sudan, an agrarian nation endowed with fertile soil, abundant water resources, and a thriving ecosystem, harbors a population of approximately 42 million. Alarmingly, only 30% of this populace resides in urban centers with access to electricity (Abdalla and Özcan,2021). In stark contrast, a staggering 70% inhabits smaller towns and rural regions without such access. This disparity is exacerbated because solar energy remains conspicuously underutilized despite Sudan's significant solar potential characterized by high solar radiation levels and extended daylight hours averaging between 7.3 to 10.5 hours daily (Adenle,2020). Sudan distinguishes itself with an annual average solar irradiation of 436 to 639 W/m^2, surpassing the global norm of 100 to 250 W/m^2 observed in most nations. This noteworthy irradiation potential is visually depicted in Figure 2, corroborating the immense untapped solar energy resources awaiting exploration and development.

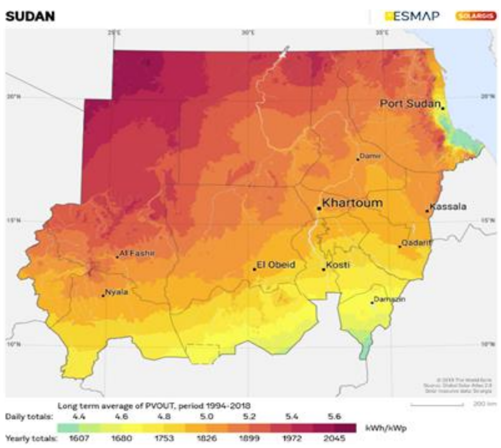


Figure 2. Sudan Irradiation Potential

4. Al Fashir Photovoltaic Station Layout

Alfashir, a prominent town situated in eastern Sudan boasting a population of 264,734 (2006) (Eltayeb and Hamza, 2018), occupies a geographical position at latitude 25°46'30" north and longitude 13°67'104" east. This region experiences a temperature range from 10.5 degrees Celsius to 30 degrees Celsius during summer and can drop as low as 10 degrees Celsius in winter. NASA's data reveals that Alfashir enjoys an abundant global irradiation average of 6.27 kWh/m^2/day, signifying its immense solar potential and making it a prime candidate for PV power plant construction. Table 1 provides a comprehensive overview of NASA's global and horizontal temperature data for the city.

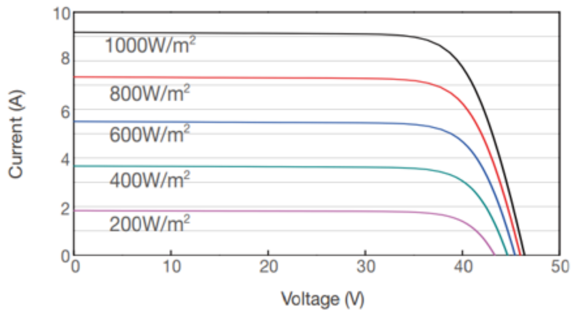


Figure 3. Show All the Specifications for PV Module I-V Characteristics

Despite the backdrop of civil unrest and displacement of residents to refugee camps, where security concerns dictate their movements, the PV plant serves as a beacon of progress for the town. It contributes to urban development and addresses the burgeoning residential energy demand. The Plant has been meticulously designed with a capacity of 5 MW, integrated with the thermal station. It comprises 16,220 modules sourced from Ja Solar, each boasting 325 W output (illustrated in Figure 3 and Table 2, offering a concise summary of the equipment and coupling process). To facilitate energy transfer from the arrays to the utility grid, 84 inverters, each with a 60-kW capacity from SMA, are employed. Additionally, the system incorporates four transformers with capacities of (21500 and 21000) and spans a 13 km overhead transmission line, ensuring efficient energy transmission.

5. Photovoltaıc Modules and Inverters

The PV station employs polycrystalline modules manufactured by Ja Solar, each with a power rating of 325W and an impressive module efficiency of 16.73%. Detailed specifications for PV module I-V characteristics are comprehensively presented in Table 3, while Figure 3 visually encapsulates this crucial information. It is worth noting that these assessments are conducted under Standard Test Conditions, with irradiance set at 1000W/m2 and a temperature of 25°C.

Furthermore, the chosen inverter is sourced from SMA and belongs explicitly to the SUNNY TRI-POWER 60 series, a pivotal component within a cutting-edge global system solution tailored for commercial and industrial photovoltaic (PV) installations. This inverter boasts a substantial rated capacity power of 60KW, complemented by an impressive efficiency of approximately 98%. Notably, every group inverter efficiently communicates energy output and various vital parameters to inverter managers via a dedicated communication data bus, as elegantly visualized in Figure 4, which illustrates the inverter's efficiency curve.

Table1. Climatic Conditions ALFASHIR City

Months	Global Horizontal irradiation kW/m²/day	Horizontal diffuse irradiation kW/m²/day	Temperature °C
January	4.12	1.03	10.5
February	5.38	1.04	12.8
March	6.33	1.32	18.1
April	7.11	1.60	24.0
May	7.51	1.79	28.6
June	8.19	1.61	31.5
July	8.16	1.54	31.2
August	7.67	1.44	30.9
September	6.71	1.34	29.4
October	5.67	1.12	23.9
November	4.54	0.99	17.6
December	3.82	0.98	12.1
Year	6.27	1.32	22.6

Table 3. Show all the specifications for PV module I-V characteristics

Rated Maximum Power (Pmax) [W]	325W
Open Circuit Voltage (Voc) [V]	46.38V
Maximum Power Voltage (Vmp) [V]	37.39V
Short Circuit Current (Isc) [A]	9.17A
Maximum Power Current (Imp) [A]	8.69A
Module efficiency %	16.73%
Power Tolerance	-0~+5W

Table 2. Electrical Devices and Coupling Process

Pos	Amount Modules	Amount Strings	Station Type	Amount Inverter	Amount Strings	Amount Per Strings	Amount Module s	Power AC	Power DC	No Strings
3MW	9960	483	1500	17	10	20	3400	1020	1105	242
				8	9	20	1440	480	468	
			1500	16	10	20	3200	960	1040	241
				9	9	20	1620	540	526.5	
2MW	6560	328	1000	13	10	20	2600	780	845	166
				4	9	20	720	240	234	
			1000	9	10	20	1800	540	585	162
				8	9	20	1440	480	468	
5 MW	16220	811	5MW	84			16220	5040	5271.5	811

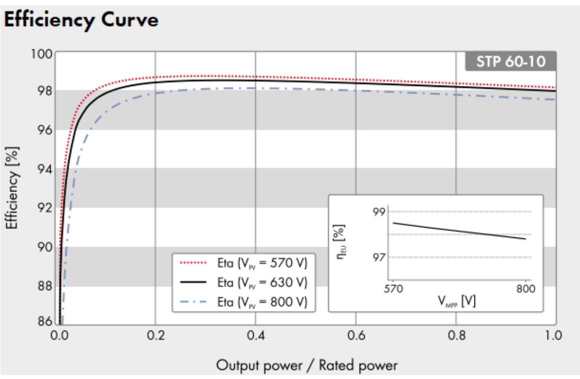


Figure 4. Efficiency Curve for Inverter

5.1. The Operation Performance of the PV Plant

The PV plant, commissioned in 2019, underwent a detailed performance assessment for 2020 and 2021. Notably, in 2020, the Plant demonstrated an impressive power output of 5150.28 MWh, which increased to 6839.36 MWh in 2021, reflecting a consistent growth trajectory. The average annual power generation for the Plant stands at 5862.71 MWh/year, highlighting its remarkable contribution to the region's energy needs. Figures 5 and 6 visually depict the monthly average values of energy and power generated for 2020 and 2021, showcasing the Plant's reliability and consistent performance throughout both years.

For a deeper understanding of the Plant's operational performance, it is essential to scrutinize monthly power generation trends. In 2021, the Plant exhibited a monthly power generation range from 274,144 kWh (January) to an impressive 797,417 kWh (April), as presented in Figure 7-a and Figure 7-b. Similarly, the performance spanned from 0 to 619 MWh (April and May 2020), culminating in a total annual output of 5150 MWh. Notably, the Plant displayed its optimal performance during the summer months (February, March, April, May, and June), contributing 9.24%, 11.37%, 12.07%, 10.92%, and 9.44% of the total annual power generation, respectively.

However, as autumn set in (July, August, September, and October), there was a decline in energy capture, accounting for 9.14%, 5.57%, 7.36%, and 8.86% of the annual total. Winter months (November to January) witnessed power generation averaging 404.77 MWh, 251.12 MWh, and 280.43 MWh, respectively, making up 6.91%, 4.29%, and 4.79% of the total annual Output. This evident seasonal variation underscores the Plant's adaptability and the importance of considering these fluctuations in future planning and energy management strategies.

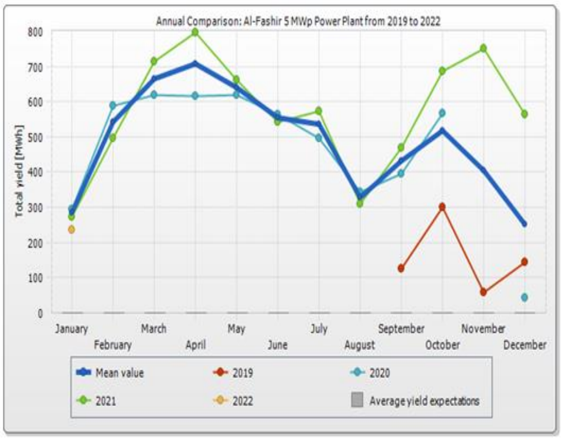


Figure 5. Annual Comparison Total Yield for The Plant

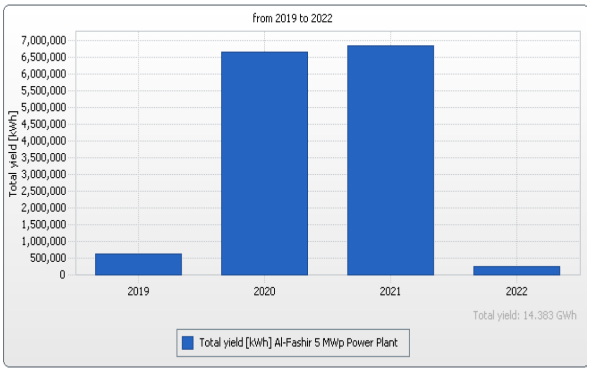
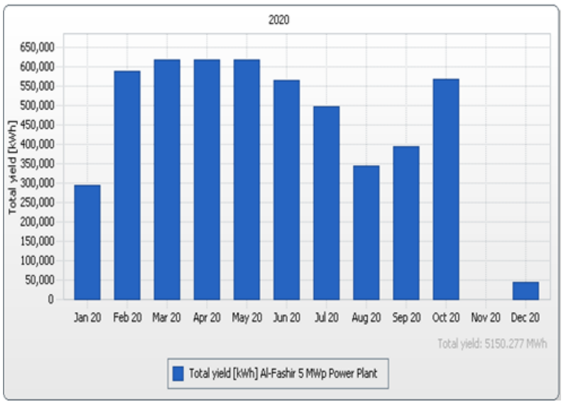
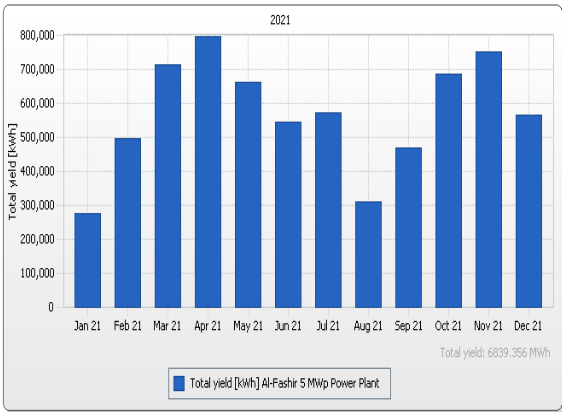


Figure 6. Total Yield by Years [Kwh]



(a)



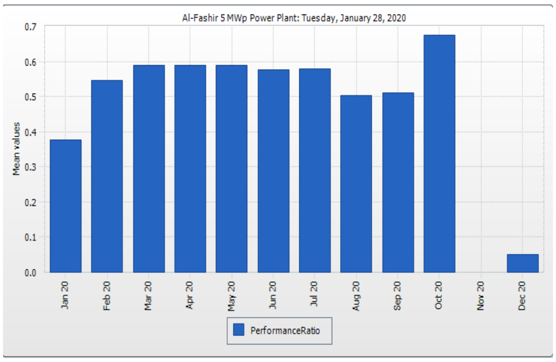
(b)

Figure 7. a) Total Yield from The Power in 2020, b) Total Yield in 2021.

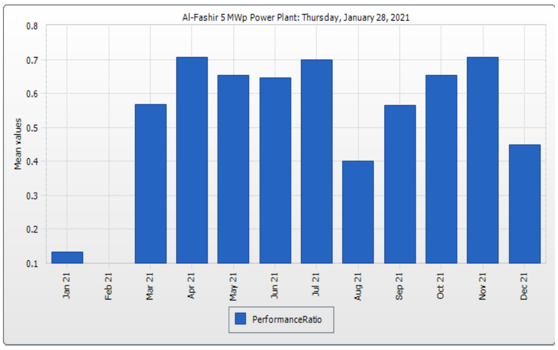
5.2. Performance Ratio for the PV Plant:

The Performance Ratio (PR) is a crucial metric in assessing the effectiveness of grid-connected photovoltaic systems (Faiz et al., 2021), considering various environmental factors that can impact system performance. In 2021, the PR was recorded at 0.515, while in 2020, it stood at 0.455, resulting in an annual average PR of 0.485, signifying an overall system efficiency of 48.5% for the year. This key performance indicator provides valuable insights into the station's ability to operate optimally under varying conditions.

Figures 8-(a&b) visually present the PR trends for 2020 and 2021. Notably, in October 2020, the PR reached an impressive 0.65, demonstrating a notable peak in performance. Similarly, in 2021, the PR surged to 0.7 in April, July, and November, underlining the system's capability to achieve higher efficiency during specific periods.



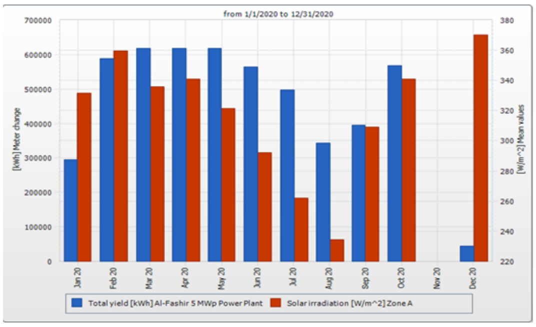
(a)



(b)

Figure 8. a) Performance Ratio for 2020 b) Performance Ratio for 2021

Examining Figures 9-(a&b), which depict irradiation and power yield for the same years, it becomes evident that the lower PR recorded during certain months, compared to the 0.7 PR achieved in others, can be attributed to specific environmental factors. Notably, during the autumn season, when the sun's position is lower in the sky, the fixed tilt of the Plant leads to shading losses. These shading losses primarily occur due to mutual shadowing between module rows, particularly in the mornings and afternoons. This seasonal variation underscores the importance of optimizing system design and tilt angles to minimize shading losses and enhance overall performance. Further investigation into the specific reasons for these fluctuations could provide valuable insights for future system improvements.



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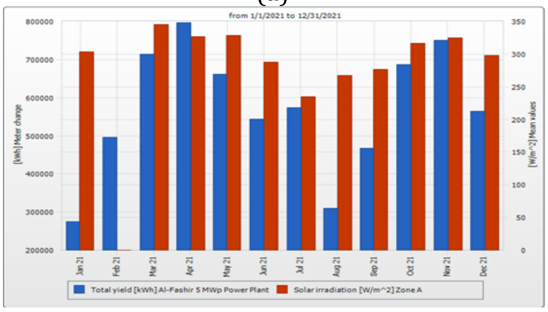


(b)

Figure 9. a) Irradiation with Total Yield in 2020 b) Irradiation with Total Yield in 2021

6. Simulation

In this section, we present the results of our comprehensive evaluation of performance metrics, including a comparative analysis with theoretical outcomes generated by PVSyst. Notably, PVSyst consistently delivers results that closely align with theoretical expectations, a testament to the program's robust features and versatile capabilities. One of the standout advantages of PVSyst lies in its ability to seamlessly integrate data from sources such as Mateo and personnel records, enhancing its utility and relevance.

Furthermore, PVSyst, leveraging site-specific climatic conditions and coordination data, provides invaluable specifications for the electrical components employed in the Alfashir PV plant's on-grid scheme. The program's ability to process hourly input parameters is instrumental in determining system output and critical metrics for our research objectives. Specifically, in our investigation of the annual power outputs of a 5MW PV solar plant at the Alfashir site, we harnessed the power of PVsyst software. To maximize solar irradiation, we employed a system orientation strategy that set the tilt angle at 27 degrees and the azimuth at 0 degrees, a configuration determined by latitude and longitude considerations. Figure 10 visualizes this orientation system modeling, highlighting the precision and detail that underlie our approach to optimizing energy capture at the Alfashir PV plant.

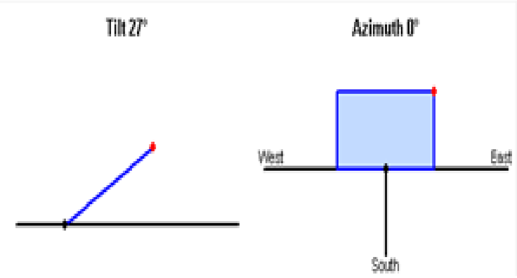


Figure 10. PV Plant Orientation and Tilt Angle

7. Simulation Results

In our analysis, we have delved into the simulation results to unveil the optimal design parameters for the PV plant, aiming to achieve an annual power injection of 10,580 MWh, as illustrated in Figure 11. When comparing this aspiration with the actual recorded data, we observed that the total annual power generation for the Plant amounted to 5,150.28 MWh in 2020, as presented in Figure 7) a. In 2021, the Plant's total power generation escalated to 6,839.36 MWh, as indicated in Figure 7) b. This implies that the PV plant maintains an average annual generation of 5,862.71 MWh.

However, we noted certain discrepancies, particularly in January 2021, where there were a few days without recorded data despite suitable irradiation levels. This raises questions about the grid's responsiveness to supply interruptions. Additionally, while the simulation predicted a maximum value of 900 MWh for April, the Plant recorded 800 MWh, resulting in a 100 MWh difference.

To contextualize our findings, we referred to studies conducted by other researchers. Author (Abdeen et al.,2019) for instance, examined ten towns in Sudan, including Nyala and Elginina, which are geographically close to Alfashir. Their work indicated annual generation figures of approximately 8,297,722 kWh for Elginina and 8,241,718 kWh for Nyala, closely aligning with our simulation predictions for Alfashir. The author (Abdalla and Özcan,2021) also presented an annual average that closely mirrors the predictions generated by PVsyst.

Table 4 provides insights into the normalized production per installed kWp, while Figure 12 visually represents the system's Output. Figure 13. a&b illustrates the energy distribution estimated by simulation for an array of plants throughout the year, offering a comprehensive view of daily energy input into the grid. These figures contribute to a holistic understanding of the PV plant's performance.

One of the most pivotal parameters for evaluating PV plant performance is the Performance Ratio (PR). Notably, various nations, including the United States, Australia, and the European Union, continually rely on PR as a critical performance metric to optimize their photovoltaic systems. The analysis of the power plant's energy output (YF) in 2020 and 2021, totaling 5,150 MW and 6,839 MW, respectively, compared to the reference value of 5,142 MW, reveals an overall assessment of losses' impact on the expected power output. The following equation was used for calculation:

$$PR = \frac{YF}{YR} = \frac{\frac{\text{Output energy}}{\text{Rated power for plant}}}{\frac{\text{In plane irradiation}}{\text{Reference irradiation}}} \tag{1}$$

Our investigation highlights the significant role of shading and high temperatures in autumn and summer, leading to considerable degradation in system performance. Various losses, including those stemming from irradiance level fluctuations, array soiling, module quality, array incompatibility, and AC and DC ohmic losses, come into play. A detailed power flow diagram (Figure 14) provides a comprehensive overview of these planned PV system losses throughout the year. Figure 15, depicting a daily input/output diagram, further elucidates the relationship between global incidence energy received by the absorber plane and the power generated by the PV system. This linear graph reaffirms the suitability of our on-grid model, showcasing that the PV plant consistently provides a minimum of 25,000 kilowatt-hours of electricity to the grid on most days throughout the year. Finally, our comprehensive analysis and simulations, as presented in Appendix (1), provide a robust foundation for understanding the performance, challenges, and potential of the Alfashir PV plant. These findings contribute valuable insights into optimizing the efficiency and reliability of PV systems, particularly in regions with abundant solar resources like Sudan.

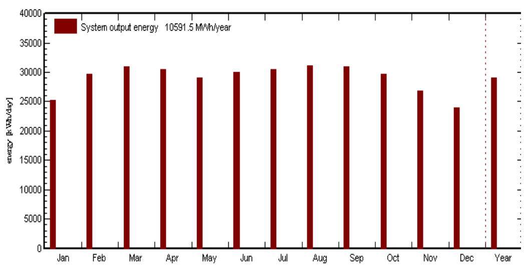


Figure 11. Simulation Output

Table 4. System Output

	Horizontal global kWh/m2/day	Coll.Plane kWh/m2/day	System output kWh /day	System output kWh
Jan.	4.12	5.93	25161	778988
Feb	5.38	6.99	29663	830662
Mar	6.33	7.27	30875	957135
Apr	7.11	7.17	30451	913540
May	7.51	6.85	29101	902134
June	8.19	7.07	30019	900580
July	8.16	7.18	30483	944966
Aug	7.67	7.34	31160	965945
Sep	6.71	7.27	30882	926445
Oct.	5.67	7.00	29724	921435
Nov	4.54	6.32	2888	805730
Dec	3.82	5.65	23971	743090
Year	6.27	6.83	29018	10591531

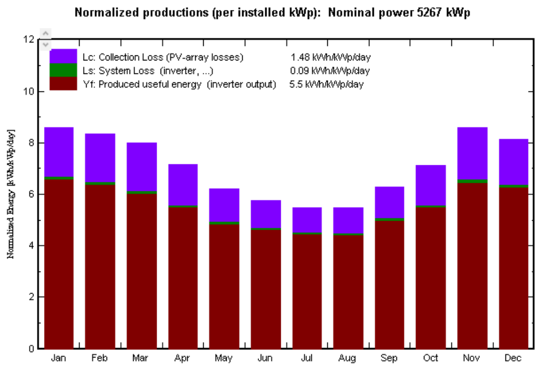
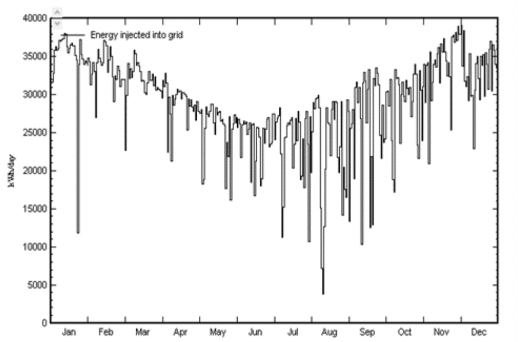
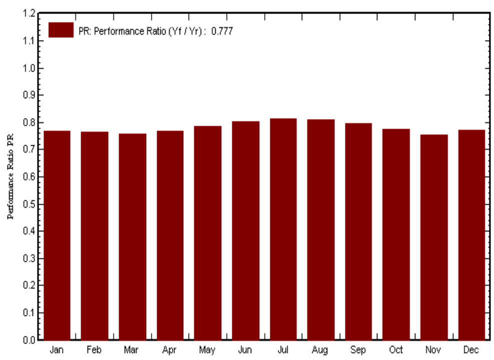


Figure 12. Nominal Power



(a)



(b)

Figure 13. a) Daily System Output Energy b) Performance Ratio [PR]

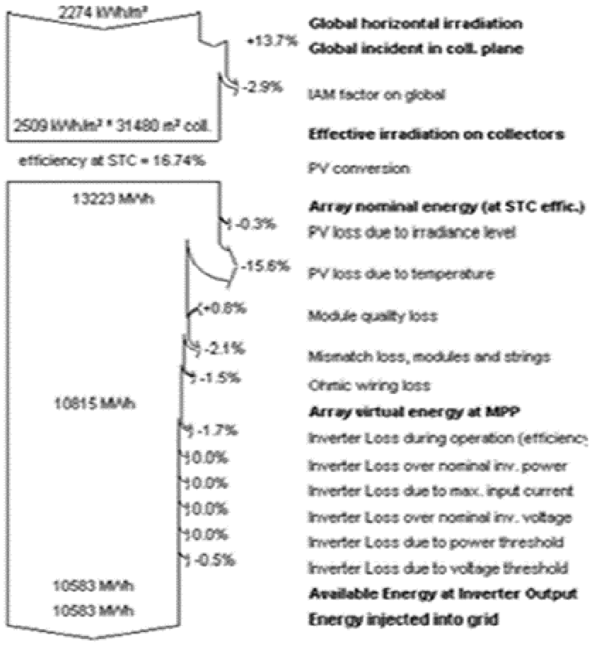


Figure 14. Losses Diagram

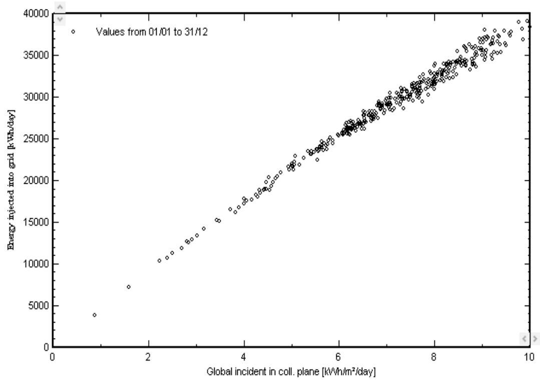


Figure15. Daily Input and Output Diagram

8. Feasibility Analysis of the Plant Operation

The Sudanese Government's decision to contract a local firm to install a 5 MW PV system without conducting a pre-design or feasibility study, as highlighted by (Ibrahim et al., 2020), resulted in a total cost of $6,862,846.25M. This cost is significantly higher than the global benchmark price of one dollar per watt, indicating that the total cost should ideally be around $5 million for a project of this scale. We employed two primary methods to evaluate the economic feasibility of such a photovoltaic plant. Firstly, the Levelized Cost of Electricity (LCOE) analysis was employed, calculating the cost of solar electrical energy and comparing it to grid energy. Secondly, a return on investment (ROI) approach was adopted, considering positive cash flow values for energy generation and savings against negative cash flow values for the initial cost and maintenance expenses. Cash flow analysis is integral to PV project investment, with energy generation, revenue, and savings contributing to positive cash flows, while operational costs are expressed as negative cash flows.

Based on the investment cost and input parameters, the PVSyst program was utilized to simulate the system's operation and derive comprehensive results. The LCOE analysis indicated a cost of $0.081 per kWh, in line with the findings of a research article (Fadlallah and Benhadji, 2020; Mohammadi and Cenk, 2023) citing a cost of $0.08746 per kWh for a 20 MW plant in Sudan. The total power generated by the Plant in 2020 and 2021 was 5,150 MW and 6,839 MW, respectively, with an average of 5,862.71 MWh/year over two years. In contrast, the simulation suggested an optimal design with an annual output of 10,580 MWh.

The financial assessment considered the anticipated 25-year lifespan of the PV panels, with computations of annuity estimates, net present value (NPV), and payback period. The payback period was found to be 15 years, influenced by the electricity price, with Sudanese electricity tariffs ranging from $0.034 to $0.085 per kWh. The study adopted the national tariff of $0.085 per kWh, exceeding the LCOE ($0.081 per kWh). Exploring different tariff scenarios, such as $0.09 per kWh, reduced the payback period to 12 years, and at $0.10 per kWh, it dropped to less than ten years. However, it is essential to note that these calculations depend on factors like tariffs, subsidies, and energy generation capacity.

The disparity between the annual energy savings projected by the software (10,580 MWh/year) multiplied by the tariff ($0.085 per kWh) and the actual annual power generation (5,862.71 MWh/year) resulted in a noticeable discrepancy. Over half of the annual savings were lost due to various factors, including limited operating hours due to fluctuating solar radiation, output reductions to avoid grid frequency interference and environmental factors such as dust deposition and humidity.

Dust deposition on PV panels, which can reduce efficiency by up to 40%, is a significant concern in dry, arid regions. Additionally, humidity can affect the efficiency of PV panels by refracting and scattering incoming light. To maximize solar energy production, photovoltaic power plants should be strategically located in areas with high solar irradiance, low dust levels, humidity, and clear atmospheric conditions (Abdalftah and Atabak, 2022). Our analysis underscores the importance of conducting feasibility studies, optimizing system design, and considering environmental factors when planning photovoltaic projects in regions like Sudan, rich in solar resources but susceptible to various operational challenges.

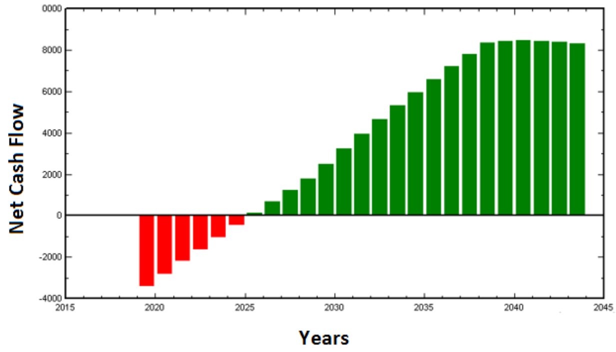


Figure 16. The Cumulative Cash Flow

9. Conclusion

This study evaluated a 5MW grid-connected PV plant's operational performance and economic feasibility in Sudan over two years, utilizing PVsyst software for analysis and simulation. Notably, we observed a significant discrepancy between the actual energy generation and the predictions from the simulation, with the annual average falling far short of expectations. The performance ratio (PR) exhibited seasonal variations, reaching its peak in the spring months, but the actual performance showed fluctuations, suggesting room for optimization.

Despite these challenges, the PV plant substantially contributed to reducing CO2 emissions, emphasizing the environmental benefits of solar energy in Sudan. Additionally, the financial analysis revealed that while annual savings were realized, they fell considerably short of the simulation's projections, indicating the need for further optimization. The equity payback period, influenced by electricity pricing policies, was estimated at 15 years, highlighting its significance in assessing financial viability. Challenges such as high radiation intensity and humidity were identified, underscoring the need for control system improvements and addressing shading issues.

This study provides a robust foundation for enhancing PV system performance and informs future research directions in renewable energy. Addressing these challenges is imperative for optimizing the PV plant's operational efficiency and viability. Looking ahead, we recommend a comprehensive assessment of the system's functions during the commissioning phase and emphasize the importance of continually improving accuracy in the PV plant's operations. Additionally, future research endeavors could explore the shadowing effects on PV system efficiency and delve into the intricacies of the grid-PV system interconnection to comprehensively comprehend the implications of the PV plant on the utility. This study is a robust foundation for advancing PV system performance and guides future research trajectories in renewable energy within the Sudanese context.

Contribution of Researchers

A.H. ALI contributed to the methodology, evaluation of the results, writing of the study.

A. NAJAFI contributed to the literature review, reviewing and editing of the study.

Conflict of Interest

No conflicts of interest have been declared by the authors.

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