Evaluating the Performance and Economics Impact of Bifacial Photovoltaic Modules in Desert Climates

by

Mohamed El Mohamed Elsharif
(2332223094)

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LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
PV	Photovoltaic
GHI	Global Horizontal Irradiance
LCOE	Levelized Cost of Energy
STC	Standard Test Conditions
kWp	Kilowatt peak
kWh	Kilowatt hour
PWF	Present Worth Factor
TLCC	Total Life Cycle Cost
CRF	Capital Recovery Factor
KT	Clearness Index
HRI	Horizontal Reflected Irradiance
RG	Rear Irradiance Gain
BG	Bifacial Gain
Pm	Power Measurement
Vm	Voltage Measurement
Im	Current Measurement
PCU	Power Conditioning Unit

LIST OF SYMBOLS

AH	Ampere-Hour
BIPV	Building Integrated Photovoltaics
BOS	Balance Of System
Ebi	Energy produced from Bifacial PV
Emo	Energy produced from Monofacial
Ereq	Energy required per annum
Em	Energy consumption for month m
Gsc	Solar Constant
GTI	Global Tilted Irradiance
H0	Daily Extra-terrestrial Irradiation on a Horizontal Plane
KT	Daily Clearness Index
LCOE	Levelized Cost of Energy
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
PCM	Phase Change Material
PERC	Passivated Emitter and Rear Contact
RG	Rear Irradiance Gain
SR20-D2	Secondary Standard Pyranometer
STC	Standard Test Conditions
Tamb	Ambient Temperature
Tmod	Module Temperature
ws	Sunset Hour Angle
δ	Declination Angle
ρ	Albedo or Reflectance

Penilaian Prestasi dan Kesan Ekonomi Modul Fotovolta Dwimuka di Iklim Padang Pasir

ABSTRAK

Penyelidikan ini menyiasat prestasi dan daya maju ekonomi modul fotovoltaik (PV) dwimuka di wilayah Alserir di Gurun Sahara Libya, dengan tumpuan pada kecekapannya di bawah keadaan padang pasir yang melampau. Kajian ini menangani keperluan untuk penyelesaian tenaga suria yang boleh dipercayai dan kos efektif di kawasan gersang, di mana suhu tinggi dan pengumpulan habuk memberi kesan ketara kepada prestasi sistem PV. Objektif utama adalah untuk mereka bentuk sistem PV menggunakan kedua-dua modul PV dwimuka dan monomuka, menilai output tenaga mereka, dan meningkatkan prestasi dan kebolehlaksanaan ekonomi mereka dalam iklim padang pasir. Metodologi penyelidikan melibatkan mengumpul dan menganalisis data dunia sebenar, serta menjalankan simulasi lanjutan menggunakan perisian PVSYST, untuk melaksanakan analisis ekonomi yang komprehensif, termasuk pengiraan untuk Kos Tenaga Bertingkat (LCOE) dan pulangan pelaburan (ROI). Penemuan menunjukkan bahawa modul PV dwimuka mengatasi modul monofasial, menjana lebih sedikit tenaga (52,934 kWj/tahun berbanding 52,908 kWj/tahun), dengan potensi meningkatkan pengeluaran tenaga sebanyak 10-20% dan mengurangkan kos sehingga 15%. Keputusan ini menyerlahkan kecekapan unggul modul dwimuka, yang, dengan menangkap cahaya dari kedua-dua belah pihak, meminimumkan sisa tenaga dan memaksimumkan penjanaan kuasa. Kajian itu menyimpulkan bahawa modul PV dwimuka menyediakan penyelesaian yang sangat berkesan dan berdaya maju dari segi ekonomi untuk penjanaan tenaga mampan di kawasan padang pasir. Kecekapan mereka yang lebih baik dan pengurangan kos menjadikan mereka sangat sesuai untuk mengatasi cabaran persekitaran iklim padang pasir, meletakkan teknologi dwimuka sebagai pemacu utama untuk pengembangan tenaga suria dalam persekitaran yang mencabar.

Evaluating the Performance and Economics Impact of Bifacial Photovoltaic Modules in Desert Climates

ABSTRACT

This research investigates the performance and economic viability of bifacial photovoltaic (PV) modules in the Alserir region of the Libyan Sahara Desert, with a focus on their efficiency under extreme desert conditions. The study addresses the need for reliable and cost-effective solar energy solutions in arid regions, where high temperatures and dust accumulation significantly affect PV system performance. The main objectives were to design PV systems using both bifacial and monofacial PV modules, evaluate their energy outputs, and improve their performance and economic feasibility in desert climates. The research methodology involved collecting and analyzing real-world data, as well as conducting advanced simulations using PVSYST software, to perform a comprehensive economic analysis, including calculations for Levelized Cost of Energy (LCOE) and return on investment (ROI). The findings showed that bifacial PV modules outperformed monofacial modules, generating slightly more energy (52,934 kWh/year vs. 52,908 kWh/year), with the potential to increase energy production by 10-20% and reduce costs by up to 15%. These results highlight the superior efficiency of bifacial modules, which, by capturing light from both sides, minimize energy waste and maximize power generation. The study concludes that bifacial PV modules provide a highly effective and economically viable solution for sustainable energy generation in desert regions. Their improved efficiency and reduced costs make them well-suited for overcoming the environmental challenges of desert climates, positioning bifacial technology as a key driver for the expansion of solar energy in such demanding environments.

CHAPTER 1: INTRODUCTION

1.1 Research Background

The demand for renewable energy has surged in recent years, with solar energy standing out as a crucial source due to its reliance on sunlight, a naturally replenished and sustainable resource. Unlike finite fossil fuels, solar energy harnesses sunlight, providing a carbon-neutral energy source. In fact, the Earth receives more energy from sunlight in one hour than the total energy consumed in a year. The solar industry, valued at $7.5 billion, is growing at a rapid rate of 35–40% annually [1]. Solar power is not only utilized for electricity but also for solar-derived fuel from biomass, supporting over a billion people. The sun plays a pivotal role in sustaining life, driving climate and weather patterns. Without it, our planet would be an icy wasteland. The replenishable nature of solar energy distinguishes it from other renewable sources, ensuring a continuous and abundant supply of power.

Photovoltaic technology captures energy from the sun's radiation and converts it into electricity. A photovoltaic system includes solar modules, each made up of multiple solar cells that gather solar radiation and transform it into electricity. The greater the electron movement between layers, the higher the resulting current flow. A Photovoltaic (PV) system, a type of renewable energy technology, directly converts sunlight into Direct Current (DC) electricity. This technology involves PV cells connected in series to form modules, and these modules are then connected in series and parallel to create a PV array.

Power conditioning units (PCUs), including inverters, play a crucial role in a Photovoltaic (PV) system by transforming the electricity generated from solar panels. The solar panels produce (DC) electricity, but most electrical devices use Alternating Current (AC). PCUs, like inverters, are essential because they convert the solar-generated DC electricity into the AC form, making it compatible with common appliances and the

electrical grid.

In simpler terms, power conditioning units act as translators, ensuring that the energy harnessed from the sun can power our homes and be seamlessly integrated into the broader electrical infrastructure. Other devices and components are also incorporated into the system to guarantee the safe and effective functioning of the entire PV system. In essence, power conditioning units make solar energy practical and usable for everyday purposes [2].

Bifacial (PV) modules are a more efficient type of solar panel compared to traditional monofacial ones. It can generate electricity by capturing sunlight on both sides of the panel. Unlike conventional PV cells, the Bifacial model features glass sheets on both sides, allowing it to receive light from the top and also utilize the light reflected off the ground on the backside.

The backside of the panel not only captures reflected light but also allows light to pass through because of its optical transparency. This unique design enables the Bifacial module generates more power without requiring additional physical space or extra silicon. In essence, it maximizes the use of sunlight resources, providing a higher energy output compared to traditional panels. This advantage is particularly beneficial in desert climates, where the reflective ground can further enhance the electricity generation of Bifacial photovoltaic modules without needing more land [3].

The study "Impact of climate change on solar monofacial and bifacial Photovoltaics (PV) potential in Qatar" compares the performance of monofacial and Bifacial solar panels by analyzing their Photovoltaic (PV) yield. To ensure a fair comparison, all results are normalized for a solar panel area of 1 m^2. The analysis incorporates hourly average solar irradiance and ambient temperature, focusing on the month of June as the reference period. Climate model results for future are used to assess the impacts of climate change on the performance and energy yields of the PV systems. The research aims to evaluate and compare the efficiency of monofacial and Bifacial solar panels under changing climate conditions, providing insights into their respective performances and energy outputs [2].

PV deployment in desert climates faces challenges that impact its efficiency:

- Sand Coverage: The accumulation of sand on PV panels poses a significant problem, obstructing sunlight and reducing power output. Sands tend to pile up against the lower edge of the panel frame, partially covering the surface during certain times of the year.
- Temperature Effects: The high temperatures in desert regions diminish the efficiency of PV panels. The intense heat adversely affects the performance of the panels, leading to a decrease in their overall efficiency. These challenges are particularly problematic given the economic considerations tied to electricity demand and pricing.

- Electricity Demand Variation: The mismatch between electricity demand and PV panel efficiency exacerbates the economic impact. The electricity demand and wholesale electricity prices are typically higher during peak sunlight hours. This demand variation results in the average kWh of electricity produced from PV facilities being, on average, only 10% more valuable than that from a pure baseload facility [4]. It's noteworthy that this premium, which might be expected to be higher, is calculated using current prices that reflect systems with very low solar penetration, highlighting the need for strategies to address these challenges in desert climates for more widespread solar adoption [4].

This research delves into the multifaceted aspects of employing Bifacial PV systems in desert areas, specifically focusing on:

- Performance Benefits: The study examines the enhanced electricity generation capabilities of Bifacial PV systems compared to traditional monofacial systems in desert environments. This includes investigating how Bifacial modules mitigate challenges such as sand coverage and temperature effects, leading to increased overall performance.
- Economic Implications: The economic aspect involves a detailed analysis of the financial considerations associated with deploying Bifacial PV systems in deserts. This includes assessing the initial installation costs, maintenance expenses, and potential revenue generated by increased energy production. The study also considers the economic impact of factors like sand mitigation measures and the efficiency gains of Bifacial panels under varying climatic conditions.

- Overall Viability: "Overall viability" encompasses a holistic evaluation, taking into account technological feasibility, cost-effectiveness, and environmental sustainability. This involves determining whether the benefits and economic gains outweigh the challenges, ensuring that the adoption of Bifacial PV systems in desert areas is not only technically feasible but also economically and environmentally sound. The assessment considers long-term viability, considering factors such as the lifespan of the technology and its adaptability to evolving energy and economic landscapes.

1.2 Problem Statement

Given the increasing global importance of solar energy as a sustainable power source, desert regions hold particular significance. These areas exhibit high solar energy potential owing to elevated insolation levels. The efficiency and longevity of Photovoltaic (PV) systems are susceptible to the impact of extreme temperature fluctuations. High temperatures can lead to a decrease in the efficiency of PV panels, as the heat can elevate the semiconductor's intrinsic carrier concentration, affecting the overall performance. Additionally, prolonged exposure to extreme temperatures can contribute to thermal stress, potentially impacting the longevity and structural integrity of PV components.

Studies, such as those conducted by the National Renewable Energy Laboratory (NREL) and other research institutions, consistently highlight the correlation between temperature variations and PV system performance [2]. These findings underscore the need for a comprehensive understanding of temperature effects in optimizing the design, maintenance, and overall performance of PV systems. The efficiency of solar cells, which are inherently sensitive to heat, is further challenged by enormous climatic stress. This stress encompasses not only temperature fluctuations but also factors like humidity and wind. The combined impact of these climatic elements can affect the performance and durability of solar cells, emphasizing the need for resilient design and mitigation strategies in solar energy systems. This could likely cause significant performance degradation, particularly for those installed in hot deserts, where dust accumulation and sand storms are frequent and challenging. Such events can even be observed in large urban areas like the Sahara Desert. The ambient temperature and solar irradiance impact the cell temperature, which negatively affects cell efficiency. In 2020, the highest temperature recorded for monofacial PV cells was 75.6°C. Projections indicate a rise to 76.8°C by 2080 [2]. These figures are based on the latest available data, and the source for the projected increase can be referenced for further verification showing a 1.2 ◦C temperature rise. On the contrary, Bifacial PV, in contrast, experiences a minimal temperature rise of just 0.3°C. This lower increase can be attributed to the design of Bifacial panels, which typically allow for better heat dissipation. The dual-sided nature of Bifacial PV panels enables more efficient cooling, reducing the impact of temperature on their overall performance compared to traditional monofacial counterparts. (86.4°C to 86.7°C by 2080) [2]. This indicates that ambient temperature impacts Bifacial PV less than monofacial PV, as Bifacial PV is transparent and unused radiation passes through the panel. Monofacial and Bifacial (including front and rear) PV efficiencies range from 15.9% to 19.6% and 15% to 19.6% [2]. By 2080, with rising air temperatures, absolute PV efficiency will decrease by 0.1% to 0.2% for both monofacial and Bifacial panels [2].

The combination of strong winds carrying sharp grains of sand can soil and even damage PV modules, particularly the polymer components like the back sheet, the antireflective coating on the front glass, and cables. Additionally, sandstorms deposit thick layers of sun-blocking sand on the surfaces of PV modules, a phenomenon known as soiling. This soiling effect significantly hampers the efficiency of solar panels, as the accumulated sand obstructs sunlight, reducing the power output. In desert conditions, where sand storms are prevalent, the cleaning frequency of PV modules becomes a crucial consideration. Frequent cleaning is often required to maintain optimal performance, and the associated costs, both in terms of labor and resources, can pose challenges to the economic viability of solar installations in these regions, this again highlights the need for efficient maintenance planning. Access to deserts is typically more difficult and requires more time and equipment, increasing plant maintenance costs. On-site 24/7 monitoring, cleaning maintenance, and security at the plant necessitate local staff on-site, which is expensive., albedo variations as well [1]. Bifacial PV modules, designed to capture solar energy from both their front and rear sides, present a promising solution to amplify energy yields, particularly in challenging desert conditions. Unlike traditional monofacial panels, Bifacial modules utilize reflected sunlight from surrounding surfaces and the ground, mitigating the impact of sand soiling common in desert environments. This unique design not only boosts overall efficiency but also provides a potential remedy for maintaining consistent energy production, even in the face of prevalent sand storms. However, it is necessary to comprehensively evaluate their performance in desert climates, considering both technical and economic factors, to ascertain their feasibility over monofacial modules.

1.3 Research Objectives

The research objectives are:

i. To design a standalone PV system for desert climate using bifacial and monofacial PV modules.

ii. To evaluate the energy yield of bifacial PV and Monofacial PV modules in desert climate.

iii. To enhance the performance and economic feasibility of bifacial PV and monofacial PV modules in desert climate.

1.4 Research scope

This research is specifically focused on evaluating the performance of Bifacial photovoltaic (PV) modules in the Alserir area, a section of the Libyan Sahara Desert. The primary objective is to assess and compare the efficiency of Bifacial PV modules with traditional monofacial modules in desert conditions. This includes a detailed examination of the impact of desert-specific factors such as dust accumulation, high temperatures, and variations in solar irradiance.

Additionally, the study aims to investigate the influence of different mounting configurations on Bifacial module performance in arid climates. This involves exploring the effects of tilt angles and tracking systems on the overall efficiency and energy output of Bifacial PV systems.

In terms of economic analysis, the research will conduct a comprehensive evaluation, including calculating the levelized cost of electricity for both Bifacial and monofacial modules. The study will also assess the return on investment for Bifacial PV systems in desert conditions, taking into account installation costs, maintenance expenses, and the potential for increased energy generation over time.

For data collection and analysis, real-world data on PV module performance and associated economic parameters will be gathered using PVSYST software. The findings will be discussed in detail, focusing on the comparative analysis between Bifacial and traditional monofacial module performance in the specified desert environment.

1.5 Research Organization

This research is organized into five chapters, each dedicated to analyzing the characteristics, performance evaluation, and economic impact of Bifacial photovoltaic (PV) modules.

Chapter 1 presents the introduction of the research, including the problem statement, research objectives, and scope.

Chapter 2 provides an overview of photovoltaic technology, performance evaluation of PV modules in various environments, economic analysis of PV systems, and a review of previous studies on Bifacial PV modules in desert climates.

Chapter 3 focuses on the design and study of the desert area, Bifacial PV module technology and specifications, data collection methods, performance evaluation, economic assessment, and data analysis techniques.

Chapter 4 processes the collected data using PVSYST software to compare Bifacial versus monofacial PV module performance. This chapter also investigates the impact of desert specific factors on performance, conducts a comparative analysis of efficiency and energy yield, and explores the economic benefits of Bifacial PV modules in desert areas with cleaning strategies, integrates the findings related to performance and economic aspects, provides policy recommendations, and highlights contributions to the field.

Chapter 5 serves as the conclusion, summarizing key findings and implications for the future of PV technology in desert areas. Recommendations based on the research are also provided.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The inquiry into Bifacial (PV) modules within the context of desert climates marks a pivotal advancement in the quest to optimize the efficiency and economic viability of solar energy systems. This chapter serves as a thorough exploration of existing literature, with a dedicated focus on establishing a nuanced comprehension of the performance and economic implications pertaining to Bifacial PV modules deployed in arid environments.

The delve into the intricacies of off-grid solar energy networks, the narrative intentionally sets the stage for a comprehensive analysis specifically tailored to the challenges and opportunities presented by desert climates. The review prioritizes considerations of reliability, durability, and environmental impact, acknowledging the intersection of PV technology deployment with broader environmental sustainability goals. This literature review further delves into life cycle assessments, recyclability, and ecofriendly manufacturing processes, contextualizing these factors within the unique challenges posed by desert environments.

In the exploration of solar energy network components, this chapter undertakes a meticulous analysis of the technological and systemic elements intrinsic to solar power systems. It goes beyond a generic overview, specifically elucidating the intricate elements that constitute the fabric of solar energy networks in desert climates. This includes a detailed examination of the technological constituents and the systemic interdependencies that define their functionality.