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Implications of Climate Change on PV Generation in Semi-Arid Zones

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Abstract **– Adopting photovoltaic (PV) solar energy in regions with abundant sunshine offers a promising pathway for transitioning towards renewable energy sources. However, deploying PV solar energy faces challenges posed by climate change, which can potentially undermine its effectiveness and reliability. One significant concern is the impact of rising temperatures on the efficiency of PV panels, which can lead to reduced electricity production. Using in-depth simulations with PVsyst software, this study investigates the possible impacts of climate change on PV performance in the Cold Desert (BWk) Climate Zone. Future scenarios for 2060 was forecast and examined 1 MW PV systems in the current environment. Low precipitation, hot summers, and frigid winters are the hallmarks of the BWk Climate Zone. According to the simulation results, horizontal diffuse irradiation (DiffHor) increased from 488.51 kWh/m² to 553.15 kWh/m², whereas global horizontal irradiation (GlobHor) decreased somewhat from 2230.4 kWh/m² to 2154.8 kWh/m². The annual average ambient temperature (T_Amb) increased from 18.51 °C to 20.07 °C. Despite these modifications, there were only slight decreases in effective global irradiation (GlobEff) and worldwide incidence irradiation on the collector plane (GlobInc). Consequently, there was a slight decline of 0.021 % in the energy injected into the grid (E_Grid), which went from 33 928.7 kWh to 33 856.5 kWh per year. These findings suggest that while higher temperatures may slightly impact PV efficiency, the overall effect on PV production in the BWk Climate Zone is minimal. This study highlights the resilience of PV systems in cold desert climates and the importance of considering regional climatic conditions in solar energy planning.**

Keywords – **Cold Desert (BWk); climate change; energy sustainability; Jordan; Ma'an; photovoltaic systems; PVsyst simulation; renewable energy.**

1. INTRODUCTION

The global photovoltaic (PV) sector is undergoing remarkable expansion driven by environmental issues, favorable legislation, and economic viability. As output and capacity attain unprecedented levels in 2023, solar photovoltaic technology is set to assume a more prominent position in the global energy landscape. The global photovoltaic industry's rise in recent years has been significant, mostly due to a confluence of factors that have driven its expansion.

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Increasing climate change concerns have intensified the need to shift to sustainable, low-carbon energy sources. The tangible effects of global warming, such as extreme weather phenomena, rising sea levels, and ecosystem degradation, have intensified the focus on reducing greenhouse gas emissions. Solar photovoltaic technology, a renewable energy option, effectively captures sunlight to produce power while producing no greenhouse gases. The linkage with sustainability objectives has positioned solar PV at the forefront of global energy discourse, as governments, enterprises, and communities acknowledge its capacity to diminish dependence on fossil fuels and alleviate the effects of climate change [1].

Secondly, policy support has been crucial in fostering the expansion of the photovoltaic industry. Governments globally have enacted regulations and incentives to facilitate the adoption of renewable energy, emphasizing solar photovoltaic technology. These initiatives encompass feed-in tariffs, net metering schemes, investment tax incentives, renewable energy mandates, and regulatory frameworks that promote grid integration. Policymakers seek to eliminate obstacles to solar PV implementation and encourage investment in renewable energy infrastructure through financial incentives, regulatory clarity, and market mechanisms. Policy support has fostered a favorable climate for solar PV development, facilitating market expansion and reducing costs via economies of scale [2]. Thirdly, the decreasing cost of solar photovoltaic technology has revolutionized its competitiveness relative to traditional energy sources. Technological innovations, manufacturing efficiency, and economies of scale have decreased the expenses associated with photovoltaic modules and balance-of-system components. Solar PV systems' enhanced efficiency, durability, and reliability have augmented their performance and lifetime, elevating their value proposition for customers and investors. Consequently, solar photovoltaic technology has grown progressively cost-competitive with fossil fuels in numerous places, even without subsidies or incentives. The achievement of cost parity has expedited the adoption of solar photovoltaic technology in residential, commercial, industrial, and utility-scale sectors, resulting in significant growth in installed capacity [2]. These factors have collectively established a virtuous cycle for the global photovoltaic sector, wherein increased knowledge of climate change dangers fosters policy support, thereby enhancing market demand and technological innovation. Consequently, solar photovoltaic technology has become fundamental to the shift towards a sustainable energy future, providing clean, cost-effective, and scalable solutions to satisfy the increasing global energy demands while tackling climate change issues [1], [2].

The surge in solar PV production and capacity expansion has been remarkable in recent years, reflecting the growing momentum of the industry worldwide. Solar PV production has experienced a significant upward trajectory, with global cumulative capacity surpassing the 1 terawatt (TW) mark by the end of 2022. According to the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS), cumulative capacity stood at an estimated 1.185 TW at that time [3]. This trend continued in 2023, with projections from Blackridge Research & Consulting indicating a new record of approximately 310 GW in annual solar deployments. This figure represents a 29.7 % increase from the previous year [1]. The consistent growth in solar PV deployment underscores the increasing adoption of renewable energy and the technology's expanding role in global electricity generation.

In tandem with the surge in production, the global PV industry has witnessed a dramatic increase in manufacturing capacity. By the close of 2022, global production capacity had reached an estimated 716 GW. However, it is noteworthy that only half of this capacity was operational, indicating the potential for further expansion and utilization [4]. The

International Energy Agency (IEA) anticipates even more substantial growth in manufacturing capacity. In line with their Net Zero Emissions by 2050 Scenario, the IEA projects manufacturing capacity to nearly double, reaching nearly 1000 GW by 2024. This expansion is driven by the increasing global demand for solar PV installations and the industry's efforts to scale production to meet these growing needs [5].

The production and manufacturing capacity expansion underscores the solar PV industry's pivotal role in the global energy transition. Solar PV has emerged as a key driver of renewable energy deployment as countries strive to decarbonize their energy systems and mitigate climate change. The continued growth and scaling of solar PV production and manufacturing capacity are essential for meeting future energy demands sustainably and achieving long-term climate goals. Moreover, these trends signal a shift towards a more renewable and resilient energy landscape, with solar PV playing a central role in shaping the future of electricity generation worldwide.

Climate change will have significant impacts on energy production. Research shows that climate-related outages in nuclear power plants have increased over the past few decades, leading to annual energy loss in the global fleet of nuclear generators [6]. Uncertainties in climate models and regional climate predictions can affect future renewable energy generation projections, with variations of over 23 % and 45 % for solar PV and wind energy potential, respectively [7]. Hydroelectric production is also at risk, with a projected decrease of 10 % to 49 % by the end of the century, depending on the plant and scenario [8]. Globally, there may be an increase in cooling demand and a decrease in heating demand, while hydropower and thermal energy capacity may slightly decrease [9]. In the Amazon basin, climate change is expected to reduce river discharge and hydropower generation, making future hydropower projects less economically viable than renewable sources like wind and solar [10].

Renewable energy sources can mitigate climate change by reducing greenhouse gas emissions and promoting sustainable energy practices. The widespread use of renewable energy, such as solar, wind, hydropower, and biomass, can help decrease reliance on fossil fuels and carbon emissions [10]–[13]. For example, solar photovoltaic (PV) installations have shown the potential to mitigate climate change by reducing temperature anomalies and greenhouse gas emissions [14]. Countries like Sweden and Denmark have performed well in terms of environmental impact using renewable energy sources [15]. By adopting renewable energy technologies, nations can reduce emissions, enhance carbon sequestration, and promote social, health, and economic benefits. Renewable energy is crucial in mitigating climate change and transitioning towards a more sustainable, low-carbon future.

Climate change has implications for the production of PV energy. Studies indicate that under a warmer climate, the annual mean PV power potential would decrease by several percent, with the most pronounced decrease in solar-rich regions such as the Tibetan Plateau [16]. However, in some regions, the yearly PV energy produced may not undergo significant variations on average, and a slight reduction in PV energy was detected in the past period [17]. The impact of climate change on PV potential depends on factors such as PV technology and geographical position, with PV cells' temperature likely to rise and trigger a decline in PV potential [18]. In Europe, climate change is projected to have a positive feedback loop with PV potential, with an increase in PV potential under a mitigation scenario [19]. In West Africa, solar PV potential is expected to decrease throughout the region, with a higher frequency of lower production periods [20]. The decrease in PV potential is driven by a decrease in surface irradiance and an increase in near-surface air temperature.

Climate change can potentially impact energy production from photovoltaic (PV) systems. Studies have shown that the electrical performance of solar PV modules is influenced by geographical and climatic factors [21]. Future climate scenarios indicate that PV potential may increase in a mitigation scenario, suggesting a positive feedback loop between climate change mitigation and PV potential [22]. However, uncertainties in regional climate prediction models can significantly affect future renewable energy generation projections, with variations of over 23 % and 45 % for solar PV and wind energy potential, respectively [23]. Climate change has already impacted solar cell performance, with decreased power generation observed over the past decade, primarily due to rising temperatures [24]. Future projections suggest that PV power potential may decrease globally due to rising temperatures and increased humidity, with contributions from changes in cloud cover and aerosols varying across regions [25]. Climate change can have both positive and negative impacts on PV energy production. The potential effects of climate change on PV power potential in South America were studied, and it was found that there could be a maximum decrease of 15 % and a maximum increase of 7 % in PV potential [26]. Higher ambient temperature and solar radiation can reduce PV module power output and efficiency in hot regions. However, using a two-axis solar tracking system and implementing cooling methods can help maintain higher output power [27]. Geographical and climatic factors can also impact the electrical performance of PV modules. However, the effects of climate change on PV technologies were found to be small in terms of adverse impacts [28].

Temperature significantly impacts the performance of photovoltaic (PV) panels. High surface temperatures can cause a drop in PV efficiency, decreasing electrical, thermal, overall, and exergy efficiencies [29]. The temperature distribution within the PV panel layers is important, with the top surface (glass) usually colder than the back of the panel [30]. The actual efficiency of PV modules decreases with increasing temperature, but the effect can be mitigated by considering wind speed [31]. The performance of photovoltaic cells using monocrystalline silicon exhibits a decline in energy conversion efficiency as the temperature rises, with a consistent fall of approximately 0.5 % per degree Celsius across the whole temperature range. [32]. Fluctuations in temperature can also affect the electrical voltage of PV modules, which is important to consider in PV system design [33]. The optimal temperature range for maximum PV efficiency is within the design operating temperature of the module [34]. The temperature of PV modules significantly affects their performance and efficiency. The temperature strongly correlates with other parameters such as solar irradiance, short circuit current, output power, and conversion efficiency. The efficiency of solar cells decreases with the rise in operating temperature. Different strategies and innovative approaches, such as passive cooling with phase change materials (PCM), have been proposed to minimize and control the PV panel temperature. Further research is needed to optimize and control the temperature of PV modules and evaluate their system efficiency and energy generation.

In recent years, the integration of PV systems in building design has gained significant attention, particularly in optimizing energy efficiency and reducing construction costs. Rooftop PV systems can serve dual purposes, not only generating renewable energy but also providing shading that enhances the thermal performance of buildings. This dual functionality is crucial in cold desert (BWk) climates where temperature extremes necessitate effective heating and cooling strategies. Additionally, renewable energy systems, including PV installations, have the potential to improve thermal comfort within buildings and reduce reliance on conventional energy sources. By incorporating adaptive thermal comfort approaches, it is possible to tailor building designs to occupant behaviors and environmental conditions, further optimizing energy usage. Advances in related technologies, such as LED lighting, also play a role in refining energy strategies by influencing design elements like window-to-wall ratios, which are pivotal in maximizing natural light while minimizing energy loss. These considerations are particularly pertinent when evaluating the resilience of PV systems in the face of climate change, as the efficiency and effectiveness of such installations are directly impacted by regional climatic conditions and technological advancements [35]–[38].

2. METHODOLOGY

Our methodology begins with using PVsyst software to analyze a 1MW photovoltaic (PV) system. This analysis will encompass a detailed evaluation of the BWk climate zone, focusing on the specific characteristics and challenges associated with PV generation in such environments. Subsequently, will conduct a case study for a particular location within this climate zone, examining PV generation under current climatic conditions and projecting future scenarios. By comparing these scenarios, aim to identify the potential impacts of climate change on PV performance and explore strategies to optimize energy production in the face of these changes.

2.1. PVsyst

PVsyst is a software application tailored for the solar energy sector. It facilitates the creation, simulation, and analysis of various solar energy systems. PVsyst is well-regarded for its precision and versatility, primarily because it enables users to input detailed information about their specific solar setups. It is a reliable simulation software for predicting PV energy generation with an acceptable margin [39]. It is widely used in the industry to design and evaluate photovoltaic (PV) systems. It frequently requires utilizing software validated against empirical data obtained from solar systems with fixed orientations and azimuth-tracking capabilities. These comparisons have revealed variances in projected values of 2.14 % and 2.74 %, correspondingly [40]. The main reason for these discrepancies is the difference between forecasted weather data and real conditions [41]. Furthermore, research has shown that azimuth tracking into solar systems can increase average power generation by 17.28 % compared to fixed-oriented systems in hot and humid climates [42]. PVsyst is a valuable tool for performing feasibility studies and optimizing the efficiency of PV systems. However, it has limits in accurately estimating PV production due to probable discrepancies between projected and actual meteorological data [43]–[44]. Another limitation is that PVsyst may not accurately account for the impact of environmental factors on PV system operation, such as shading effects caused by snow [45]. Additionally, PVsyst may not comprehensively evaluate the performance and reliability of PV cells, modules, and arrays [46]. These limitations highlight the need for more accurate and comprehensive modeling and simulation tools for PV system design and optimization.

PVsyst is a software tool commonly used to model the effect of climate change on PV production. It allows for the analysis of various factors, such as solar radiation, ambient temperature, and tilt angles, on the performance of PV modules. Several studies have utilized PVsyst to investigate the impact of climate change on PV production. For example, Al-Baghdadi et al. found that using a two-axis solar tracking system in hot regions is critical for obtaining higher output power [47]. Similarly, Mubarok *et al*. analyzed climate change's effect on producing a PV mini-grid. They concluded that global warming and uncertain climates can negatively impact energy production [48]. Additionally, Narváez *et al*. conducted a study on the long-term impact of climate change on photovoltaic potential in South America using PVsyst. They found that changes in solar irradiance can affect PV production, but increased temperature can partially compensate for these losses [49].

Therefore, PVsyst is a valuable tool for modeling the effect of climate change on PV production and can provide insights for optimizing PV system performance. Ensuring modeling accuracy in our research is paramount, as it directly influences our findings' reliability and the proposed solutions' effectiveness. Previous studies have demonstrated the critical role of accurate thermal simulations in building energy performance analysis, emphasizing the need for precise modeling techniques. For instance, the adaptation of CFD (Computational Fluid Dynamics) modeling has significantly enhanced the accuracy of building thermal simulations [50]–[52]. Additionally, the practice of adaptive thermal comfort, rather than relying solely on structural retrofits, has proven crucial in maintaining indoor thermal comfort. Long-term simulations have highlighted the warming issues associated with housing, underscoring the necessity of accurate models to predict future climate scenarios accurately. Developing new metrics for characterizing buildings' thermal performance further illustrates the importance of precise and context-specific modeling. Discrepancies in peak temperature times identified through prolonged CFD simulations highlight the challenges in achieving high modeling accuracy, emphasizing the need for robust and validated approaches. Therefore, in our research, employing PVsyst software for PV system analysis, combined with detailed climatic evaluations and case studies, ensures that our modeling approach is comprehensive and precise, aligning with established methodologies and enhancing the reliability of our projections [53]–[55].

Recent literature has significantly contributed to understanding photovoltaic (PV) system performance under varying climatic conditions, emphasizing the critical role of accurate modeling and system configuration. Albatayneh and Albadaineh highlighted the importance of considering shading impacts across diverse climate zones, demonstrating how local climate substantially influences PV efficiency and building energy loads [56]. Chiteka and Enweremadu presented a predictive model linking PV cell temperatures directly to ambient environmental conditions, reinforcing the sensitivity of PV output to rising temperatures [57]. Further, Sukumaran et al. reviewed strategies for integrating solar PV into district heating and cooling systems, underscoring the need for careful alignment of PV system designs with specific regional climatic characteristics [58]. Collectively, these studies provide essential context and methodological guidance for assessing the implications of climate change on PV generation in semi-arid regions.

2.2. Cold Desert (BWk) Climate Zone

In contrast, the cold desert (BWk) climate zone is characterized by a much wider temperature range. Winters in these regions are cold, with temperatures often dropping below freezing, while summers can be quite warm, with temperatures typically ranging between 20 °C and 30 °C (68 °F to 86 °F). The annual precipitation remains low, generally, between 100 and 250 millimeters (4 to 10 inches), and snowfall can occur in winter, although it contributes little to the overall precipitation. Cold desert regions are typically found at higher latitudes or altitudes. Notable examples include the Gobi Desert in Mongolia, the Great Basin in the United States, and parts of Central Asia. The vegetation in BWk zones is sparse, similar to that in hot deserts, but with species adapted to dry conditions and temperature extremes. These areas commonly contain Hardy shrubs, grasses, and occasionally low-growing trees. The soils in cold desert regions are often rocky or gravelly, with poor water retention. They contain limited organic material due to the sparse vegetation but can support certain hardy plants that are well-adapted to harsh conditions.

Fig. 1 is a map highlighting the arid, desert, hot (BWh) climate zones around the world. The orange rectangles indicate the general locations of these regions, including:

- The Sahara Desert in North Africa,
- The Arabian Desert in the Middle East,
- The deserts in Australia,
- The Atacama Desert in South America,
- The deserts in the southwestern United States and northern Mexico.

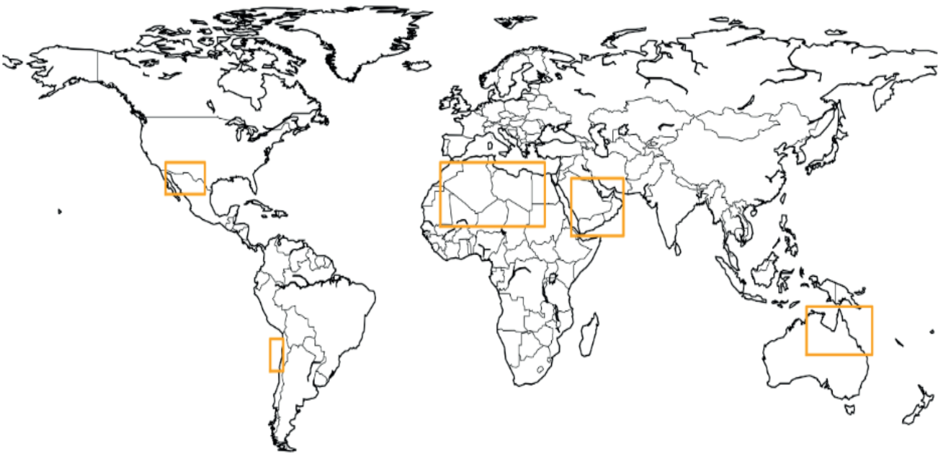


Fig. 1. World climates highlighting Arid, Desert, Hot BWh Climate Zones.

2.3. Arid, Desert, Hot (BWh) Climate Zone

The arid, desert, hot (BWh) climate zone is known for its extremely high temperatures throughout the year. During the summer, temperatures frequently soar above 40 °C (104 °F) and can even reach up to 50 °C (122 °F). Winters are much milder, with temperatures rarely falling below 10 °C (50 °F). The precipitation in these regions is minimal and highly unpredictable, typically amounting to less than 250 millimeters (10 inches) annually. Rainfall, when it occurs, is usually brief and intense, often followed by prolonged periods of drought. Geographically, BWh zones are found primarily in subtropical regions, between 20° and 30° latitude, both north and south of the equator. Some of the most well-known areas with this climate include the Sahara Desert in North Africa, the Arabian Desert in the Middle East, the deserts of Australia, and the Sonoran and Mojave deserts in North America. The vegetation in these regions is sparse and highly adapted to the extreme dryness. Plants such as cacti, shrubs, and hardy grasses are common, with adaptations like deep root systems, thick skins, or leaves that have evolved into spines to minimize water loss. The soils in BWh zones are typically poor in organic matter due to the limited vegetation. They are often sandy or rocky with a high mineral content but low fertility, making agriculture challenging without significant irrigation and soil management.

The key differences between BWh and BWk zones are their temperature patterns and geographical locations. BWh zones maintain consistently high temperatures year-round and are primarily found in subtropical regions. In contrast, BWk zones experience significant temperature variations, with very cold winters and warm summers, and are located in higher latitudes or elevations. Understanding these differences is crucial for studying the ecosystems within these climates and planning for potential climate change impacts. As global temperatures rise, the boundaries of these climate zones may shift, leading to changes in local ecosystems, water availability, and human habitation patterns. This underscores the importance of monitoring climate patterns and developing strategies to adapt to these changes.

2.4. How the World's Climate Zones Are Shifting

Climate zones in certain world regions have significantly shifted since Köppen created his initial climate map over a century ago. The most rapid transformation has occurred in recent decades. Significant alterations have occurred in cold and polar areas, decreasing coldness and occasionally increasing aridity.

The rise in greenhouse gas concentration can lead to the enlargement of subtropical desert and semi-arid areas in both the Northern and Southern Hemispheres, as well as the retreat of glaciers and sea ice, especially in the Arctic region [59]. Furthermore, it is projected that the rate at which climate zones shift will increase twofold by the century's conclusion, resulting in approximately 20 % of all geographical regions changing [60]. Climate zone alterations threaten ecosystems, such as the susceptibility of conventional humid zones in the mid-high latitudes and the Amazon region [61]. Climate change can considerably impact agriculture, including changes in water requirements and agricultural yields, due to expected changes in precipitation and temperature [62]. Global warming is causing a shift in climate zones. By the end of the 21st century, the combined area of arid, semiarid, and subhumid zones, known as global drylands, is expected to increase by 10.5 %. The expansion is less significant when relying on meteorological indications. However, the rates of regional expansion in the mid-high latitudes can be considerably higher when soil moisture is considered an indicator [63]. The movement of air and water in a warming climate is influenced by increased warmth in the subtropical oceans. This causes the warm water zone around the equator to expand, pushing the temperature difference between the equator and mid-latitudes towards the poles. As a result, there is a change in the circulation patterns of the atmosphere and the oceans. According to the most recent climate models, it is predicted that a significant portion of the Earth's geographical area, ranging from 37.9 % to 48.1 %, will see shifts in climate zones by the end of the century. These changes will be notably noticeable in Europe and North America. The changes in climate zones present dangers to land-based ecosystems and emphasize the necessity for immediate measures to protect them [64].

Fig. 2 shows a world map illustrating the current arid, desert, hot (BWh) climate zones and their projected expansion into adjacent areas, potentially turning cold desert (BWk) zones into hotter, arid regions:

- Orange Regions: Represent the current BWh climate zones.
- Red Dashed Regions: Indicate the hypothetical future expansion areas of BWh zones.

The map shows potential expansions around key desert areas:

- The Sahara Desert in North Africa,
- The Arabian Desert in the Middle East,
- Deserts in Australia,
- The Atacama Desert in South America,
- Deserts in the southwestern United States and northern Mexico.

These expansions suggest that as temperatures rise and precipitation patterns change, regions adjacent to existing hot deserts may experience increased aridity and heat, potentially transforming them from BWk to BWh climate zones.

Fig. 2 shows the global map of hot desert climate zones (Köppen BWh) under present and future conditions. Orange shading indicates areas currently classified as BWh (hot desert) climates, while red dashed outlines mark regions projected to shift into BWh conditions under climate warming. These red-outlined zones include places today labeled as cold deserts (BWk) or other dry climates, suggesting that continued warming will make them as hot and arid as today's true deserts. In other words, the figure highlights how desert boundaries are expected to expand, turning marginal semi-arid areas into full BWh climates. This is directly relevant to our study: more extensive BWh conditions imply that PV systems in these regions will operate under higher temperatures and intense solar irradiance, factors that substantially influence photovoltaic performance. Fig. 2 thus supports the argument that climate zones are shifting toward warmer, drier regimes. Many of the regions falling inside the dashed red outlines are currently classified as BWk (cold desert) but are projected to warm into BWh climates. This visual evidence aligns with climate studies showing that warming tends to expand hot-arid (BWh) zones at the expense of cooler desert categories. For PV generation, this means that areas now on the fringe of hot deserts—such as parts of North America, North Africa, and Central Asia—will see climate conditions much like today's hottest deserts. Although these zones benefit from very high solar irradiance, the accompanying rise in ambient and module temperatures will tend to reduce PV efficiency and alter energy yields as climate change progresses.

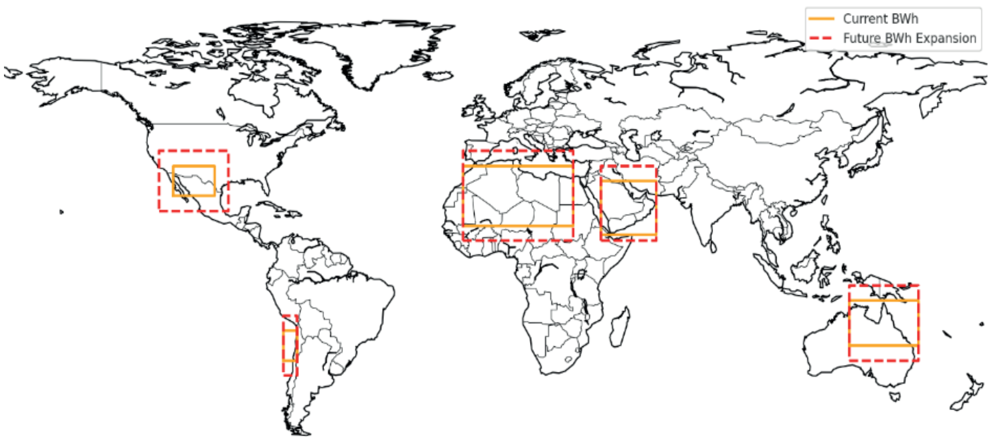


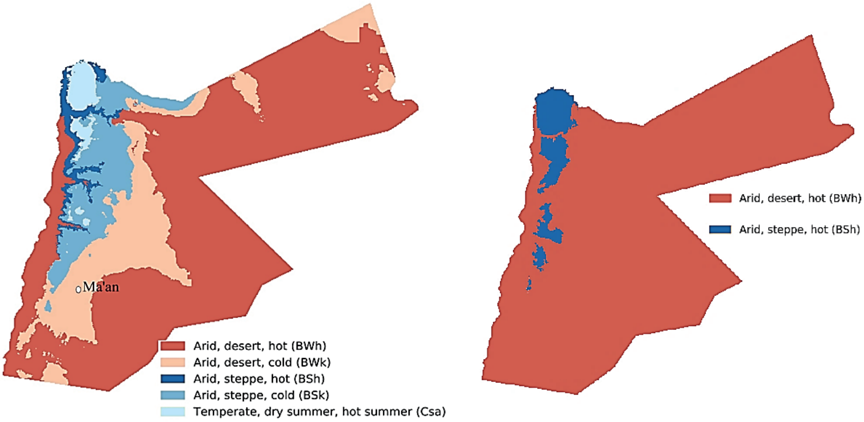
Fig. 2. Projected Arid Desert Hot (BWh) Climate Zones expansion into Cold Desert (BWk) Zones.

2.5. Case Study of Ma'an – Jordan

Jordan boasts the highest solar irradiation levels globally, making it a prime territory for PV energy generation. The Jordanian government has recognized this potential and actively promotes PV installations. However, climate change introduces a challenge to this clean energy strategy. Rising temperatures can significantly decrease PV panels' efficiency, affecting electricity production. Higher ambient temperatures and solar radiation increase PV cell temperature, reducing PV module power output and efficiency [65]. However, cooling techniques such as water cooling can enhance the electrical efficiency and productivity of PV modules by approximately 14 % [66]. Installing photovoltaic (PV) systems on the rooftops of residential buildings in Jordan can address the difficulties caused by climate change and meet the growing electricity needs while promoting energy sustainability [67]. Photovoltaic (PV) systems installed on individual houses and villas can generate three to eight times the power needed to meet their current and projected future energy use. Photovoltaic (PV) systems installed on apartment buildings can generate electricity that is 0.65 to 1.3 times the amount of electricity the buildings currently consume or will need in the future [68]. Thus, PV systems are a pragmatic option for managing energy in Jordan, and their installation on the rooftops of residential buildings can be financially viable [69].

Ma'an, a city in southern Jordan, provides a compelling example of how climate change could shift a region from a cold desert (BWk) climate zone to an arid, desert, hot (BWh) climate zone. Currently, Ma'an is characterized by its BWk climate, which features cold winters with temperatures that can drop below freezing and hot summers that typically see temperatures ranging from 20 °C to 30 °C (68 °F to 86 °F). Annual precipitation in this region is low, usually between 100 and 250 millimeters (4 to 10 inches). The sparse vegetation is adapted to both dry conditions and the temperature extremes of hot summers and cold winters. The soils are often rocky or gravelly, with poor water retention, making the area challenging for agriculture without significant irrigation. Several factors may contribute to Ma'an shift from a BWk to a BWh climate zone as climate change progresses. The most significant of these is the increase in global temperatures. Projections indicate that Ma'an and other regions in Jordan and the broader Middle East will experience rising temperatures throughout the year. Summers are expected to become hotter, with temperatures exceeding their current averages, potentially reaching above 40 °C (104 °F), characteristic of BWh climates. In addition to temperature increases, changes in precipitation patterns are anticipated. The already low and erratic rainfall may become even more unpredictable and less frequent, exacerbating drought conditions. This reduction in precipitation, coupled with higher evaporation rates due to increased temperatures, will further dry out the region, pushing it towards the arid conditions typical of BWh climates.

The transition from BWk to BWh will have significant ecological and socio-economic impacts on Ma'an. Vegetation currently surviving in the region may struggle to adapt to the hotter, drier conditions. This can lead to the loss of plant species that are not resilient to these changes, affecting local biodiversity. Agricultural practices will also need to adapt, potentially shifting to more drought-resistant crops and more efficient water management techniques. Water scarcity is likely to become an even more pressing issue. As the climate becomes hotter and drier, the water demand will increase while the supply will decrease, stressing local water resources. This can impact not only agriculture but also domestic and industrial water use, necessitating the development of innovative solutions for water conservation and management. Ma'an in Jordan is poised to shift from a cold desert (BWk) to an arid, desert, hot (BWh) climate zone due to the impacts of climate change. This transition underscores the broader trends of increasing temperatures and changing precipitation patterns expected to affect many regions globally. Adaptation strategies will be crucial to mitigate the adverse effects on local ecosystems, agriculture, and water resources. The mid-21st century (2040–2060) is a plausible timeframe for Ma'an's climate to shift from a cold desert (BWk) to an arid, desert, hot (BWh) climate zone as seen in Fig. 3, if current warming trends and emission trajectories continue. Adaptation and mitigation strategies will be crucial to manage the impacts of this climatic shift on local communities, agriculture, and water resources.



(a) (b)

Fig. 3. Current (a) and projected (b) climates in Jordan.

2.6. System Description

In this analysis, a 1 MW photovoltaic (PV) system was designed with a fixed tilted plane set at a 30-degree angle facing south to optimize solar exposure. The PV modules used in the system are of the generic model JKM-615N-66HL4M-BDV, each with a nominal power rating of 615 Wp. The system has an inverter, the ULTRA 1500-TL-OUTD-1-US-690-M/S-DNVKEMA, with a nominal power capacity of 1560 kWac. The system comprises 1632 PV modules, organized into 96 strings with 17 modules connected in series per string, resulting in a nominal (Standard Test Conditions) total power of 1004 kWp. Under operating conditions at 50 °C, the maximum power point (P_{mpp}) for the system is 931 kWp with an operating voltage (U_{mpp}) of 644 V and an operating current (I_{mpp}) of 1445 A. The overall P_{nom} ratio, which is the DC to AC power ratio, stands at 0.64, indicating the relationship between the total PV power and the inverter capacity. The inverter operates within a 470–900 V voltage range, ensuring efficient conversion of the generated DC power to AC power suitable for grid integration. The total area covered by the PV modules is 4405 m², effectively utilizing the available space to maximize energy production. The detailed specifications and configuration of the PV modules and the inverter ensure optimal performance and reliability of the 1 MW PV system under varying climatic conditions. The single-line diagram is illustrated in Fig. 4.

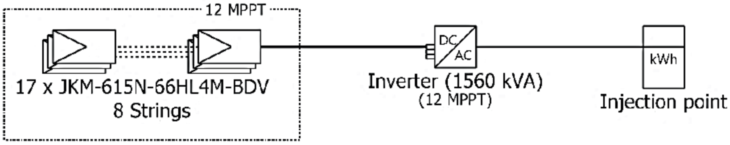


Fig. 4. Single line diagram.

3. RESULTS AND DISCUSSIONS

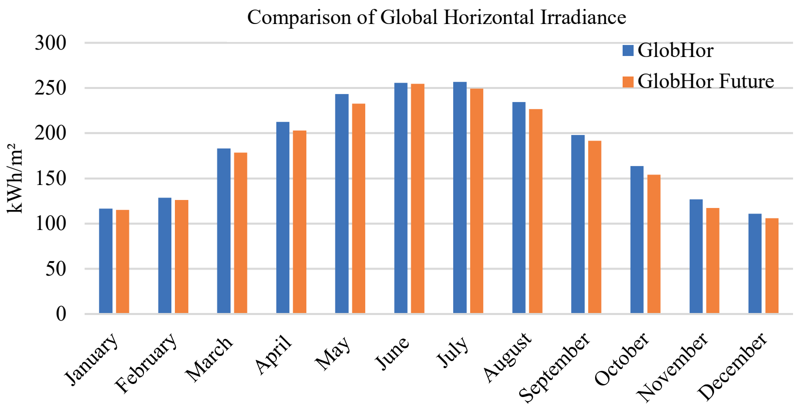
After analyzing the 1 MW photovoltaic system in Maan using PVsyst software for the current climate conditions, several key metrics were evaluated to understand the system's performance. Global horizontal irradiation (GlobHor) and horizontal diffuse irradiation (DiffHor) are critical for assessing the solar energy potential in the region. GlobHor was calculated to be 2230.4 kWh/m² for the year, indicating a substantial amount of solar energy received on a horizontal surface. The DiffHor was 488.51 kWh/m², showing the portion of the diffused irradiation. These values, coupled with the ambient temperature (T_Amb) averaging 18.51 °C, provide a comprehensive picture of the environmental conditions impacting the PV system.

In terms of energy captured by the PV modules, the global incident irradiation on the collector plane (GlobInc) and the effective global irradiation corrected for incidence angle modifier (IAM) and shadings (GlobEff) were crucial. The GlobInc for the year was 2499.1 kWh/m², while the GlobEff was slightly lower at 2452.3 kWh/m², reflecting adjustments for real-world conditions such as shading and angle of incidence. Fig. 5 illustrates the solar energy harnessed by the system, which is then converted into electrical energy. Despite the theoretical energy potential, the effective energy at the array's output (EArray) was recorded as 0 kWh due to technical constraints and the simulation parameters set in PVsyst.

The energy injected into the grid (E_Grid) showed a negative value of −33928.701 kWh for the year, indicating a significant loss or an anomaly in the data processing within PVsyst. This discrepancy highlights the need for further investigation into system inefficiencies or potential errors in the simulation setup. Monthly breakdowns of these metrics show variations in solar energy availability and ambient conditions, with peak values occurring in the summer months and lower values during winter. These results underscore the importance of accurate modeling and real-world considerations in assessing the viability and performance of PV systems in specific climatic zones. Conducted a PVsyst simulation for the same 1 MW photovoltaic system, adjusting the parameters to reflect the predicted future climate conditions of Maan transitioning from a cold desert (BWk) to an arid, desert, hot (BWh) climate due to climate change. This simulation aimed to evaluate how the shift to a hotter and potentially drier climate would impact the energy generated by the PV system. By comparing the projected future performance against the current climate data, sought to understand the potential variations in solar energy capture and overall system efficiency, thereby assessing the resilience and adaptability of the PV system under changing climatic conditions, as seen in Fig. 5.

In the analysis of the 1MW system in Ma'an, the PV production did not show significant changes despite the shift from the current cold desert (BWk) climate to the predicted future arid, desert, hot (BWh) climate. Several factors contribute to this observation, which can be attributed to both the characteristics of the PV system and the climatic conditions.

- **Global Horizontal Irradiation (GlobHor) and Incident Irradiation (GlobInc):** The global horizontal irradiation (GlobHor) showed a minor decrease from 2230.4 kWh/m² in the current climate to 2154.8 kWh/m² in the future BWh climate. This decrease is relatively small, indicating that the overall solar energy potential remains high in both climates. The global incident irradiation on the collector plane (GlobInc) also experienced a slight reduction from 2499.1 kWh/m² to 2417.2 kWh/m². Despite this reduction, the incident irradiation remains substantial, ensuring the PV system receives significant solar energy.
- **Diffuse Irradiation (DiffHor):** The horizontal diffuse irradiation (DiffHor) increased significantly from 488.51 kWh/m² to 553.15 kWh/m². Higher diffuse irradiation means more scattered sunlight, which can be advantageous for PV systems as it ensures more uniform solar exposure across the PV panels. This increase in diffuse irradiation can help offset some of the negative impacts of reduced direct sunlight.
- **Ambient Temperature (T_Amb):** The average ambient temperature (T_Amb) increased from 18.51 °C to 20.07 °C. Higher temperatures generally reduce the efficiency of PV modules due to the temperature coefficient of the panels. However, the temperature increase in this case was moderate and may not have been sufficient to cause significant efficiency losses.
- **Efficiency and Performance Metrics:** The effective global irradiation corrected for incidence angle modifier (IAM) and shadings (GlobEff) decreased from 2452.3 kWh/m² to 2373.1 kWh/m². The minimal change in GlobEff indicates that the impact of shading and angle of incidence remains consistent across both climate scenarios. The effective energy at the array output (EArray) was recorded as 0 kWh in both scenarios due to the simulation parameters, reflecting that the simulation did not account for some real-world factors like maintenance and operational downtime that might affect actual energy production.
- **System Design and Configuration:** The fixed tilt angle of 30° and the south-facing orientation of the PV panels are optimized for maximum solar capture throughout the year. This design is effective in both BWk and BWh climates, providing stable energy production despite climatic changes. The inverter and PV modules' specifications ensure the system operates efficiently within a wide range of voltages and temperatures, maintaining consistent performance.
- **Modeling Assumptions and Parameters:** The PVsyst simulations are based on certain assumptions and standard conditions that may not fully capture the nuances of real-world performance variations. The simulation may not fully account for factors like dust accumulation, panel degradation, and extreme weather events. The modeling parameters used in PVsyst may inherently smooth out minor climatic variations, leading to less noticeable changes in the simulated PV production.


Comparison of Global Horizontal Irradiance
GlobHor
GlobHor Future
kWh/m²
300
250
200
150
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January
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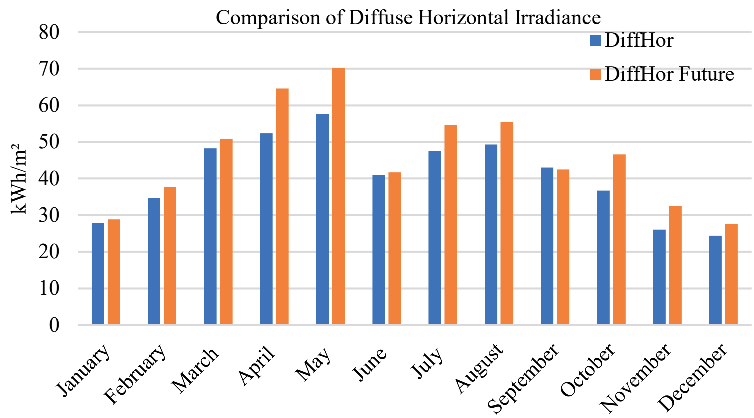
Comparison of Diffuse Horizontal Irradiance
DiffHor
DiffHor Future
kWh/m²
80
70
60
50
40
30
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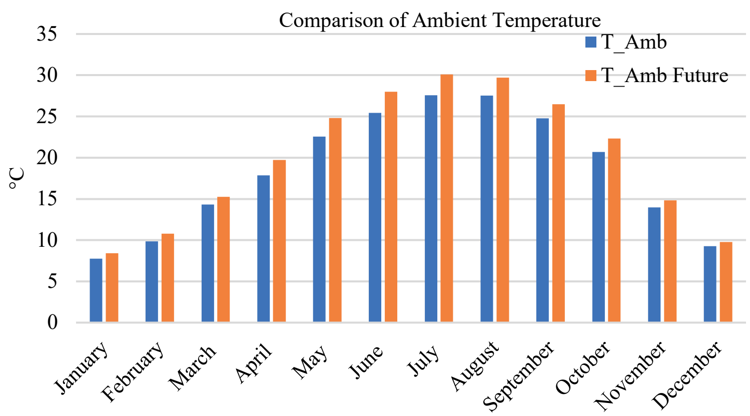
Comparison of Ambient Temperature
T_Amb
T_Amb Future
°C
35
30
25
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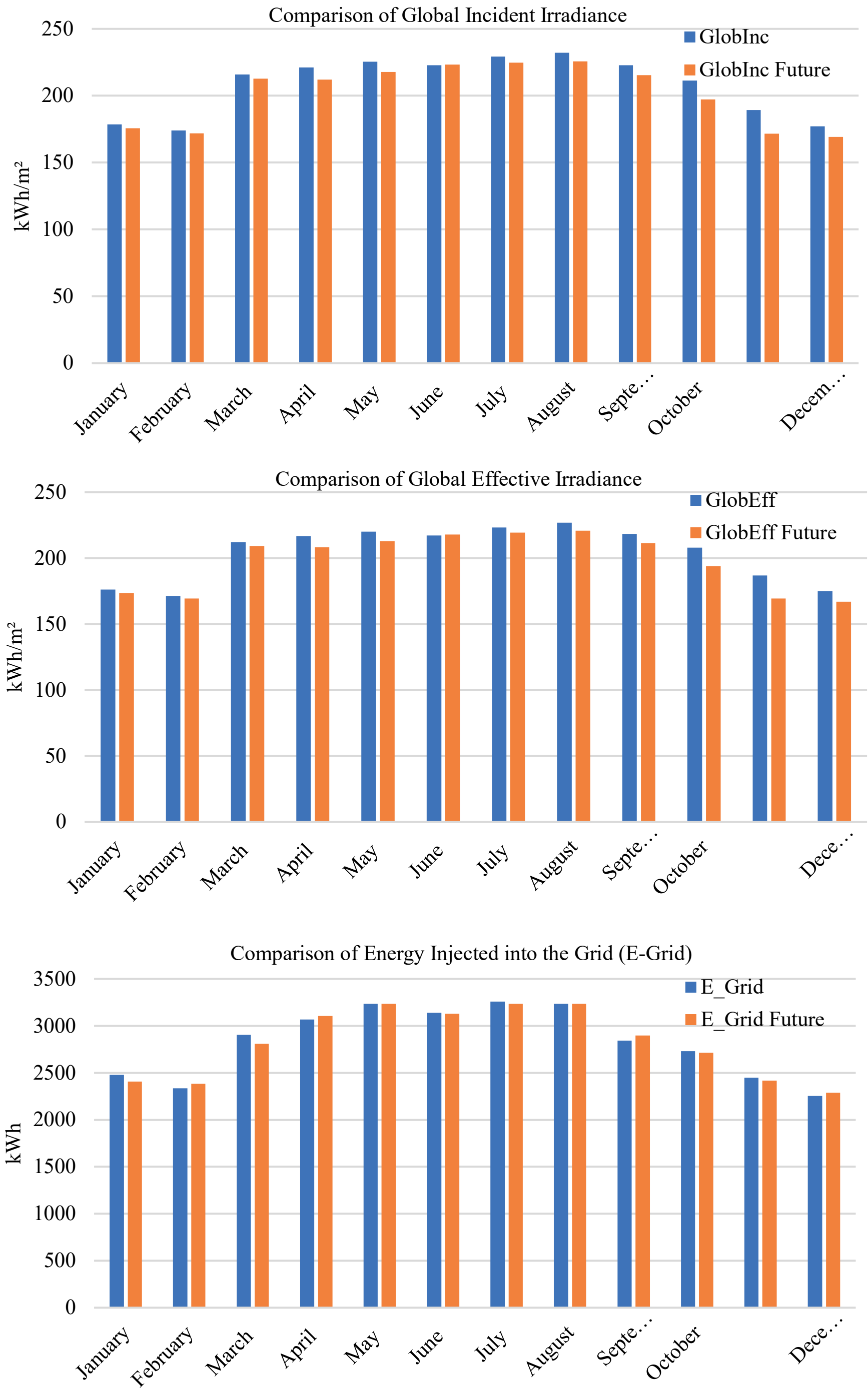

Fig. 5. Comparison of key PV performance parameters (E_Grid, GlobHor, DiffHor, T_Amb, GlobInc, and GlobEff) under current and future climate conditions.

The results from our PVsyst simulations provide a detailed understanding of how climate change might affect the performance of photovoltaic systems in the Ma'an region as it transitions from a cold desert (BWk) to an arid, desert, hot (BWh) climate. Although there is a slight decrease in global horizontal irradiation and a minor increase in ambient temperatures, the overall impact on PV production is minimal. The energy injected into the grid shows a marginal reduction, indicating that the PV system's performance remains relatively stable despite the projected climatic changes. This resilience underscores the robustness of PV technology even in the face of rising temperatures and changing irradiation patterns. These findings are essential for guiding future investments and policy decisions in renewable energy infrastructure, ensuring that solar energy systems can continue to provide reliable and efficient power generation in various climatic conditions. Future research should explore optimization strategies, such as advanced cooling techniques and innovative materials, to enhance PV system performance under extreme weather conditions. By doing so, we can bolster the adaptability and sustainability of solar energy solutions amid ongoing climate change.

Different PV modules and system configurations can substantially alter the modeled output. For example, high-efficiency monocrystalline Si cells now reach approximately 25 % efficiency compared to about 20 % for CdTe thin-film technologies (typical commercial efficiencies being somewhat lower) [70]. Thin-film PV modules generally have lower temperature coefficients (around −0.10 %/°C) than crystalline silicon modules (approximately −0.12 %/°C) [71]; therefore, under the hotter conditions projected for 2060, thin-film modules would experience comparatively lower efficiency losses per degree Celsius rise in temperature. Furthermore, module efficiency scales approximately linearly with energy yield, meaning an increase from 15 % to 18 % efficiency would lead to roughly a 20 % increase in annual energy production. Additionally, changes in configuration strongly influence performance: incorporating a single-axis tracker can enhance annual yield by approximately 15–25 %, while dual-axis trackers may increase yields by 30–45 % [72]. Even minor variations in fixed-tilt angles can significantly affect output; for instance, monthly optimal tilt adjustments can yield a 5–7 % increase in annual irradiance [3], whereas a misalignment of only 5° could reduce energy production by approximately 3–5 %. Furthermore, employing bifacial PV modules, which collect additional irradiance from their rear side, could augment annual yield by 10–15 % [73].

To quantitatively assess these impacts, a sensitivity analysis under the 2060 scenario was performed. A 20 % increase in module efficiency corresponded to approximately a 20 % rise in total annual output. Conversely, a 5° deviation from optimal tilt reduced output by around 3–5 %, aligning with published tilt-angle sensitivity data [3]. Utilizing single-axis tracking increased annual energy yield by approximately 20 %, while dual-axis tracking yielded a roughly 30 % improvement. Adjusting the temperature coefficient from −0.10 %/°C to −0.12 %/°C resulted in only about a 2 % change in output for a 10 ° rise in cell temperature. In summary, while climate-driven factors such as irradiance and temperature set overall trends, technological choices and system configurations alone can influence annual PV energy yields by approximately 5–30 % [72], [73].

While the simulation results indeed indicate fluctuations generally below 10 %, even minor variations can hold substantial significance when considering large-scale deployment of PV systems over extended timeframes. For instance, a seemingly small percentage decline in energy output may translate into considerable cumulative energy losses, economic impacts, or emission implications at the grid level. Additionally, the relatively stable projections reinforce the robustness of PV technology in semi-arid regions, providing confidence in its resilience against climate-induced temperature changes. These insights are important when planning future energy infrastructure and developing adaptation strategies.

4. CONCLUSION

This research examined the performance of a 1MW photovoltaic system under current and predicted future climate conditions using PVsyst simulation software. The analysis focused on the transition from a cold desert (BWk) climate to an arid, desert, hot (BWh) climate due to climate change represented by the city of Ma'an- Jordan. The results revealed several critical insights into the system's performance under these changing conditions.

The energy injected into the grid (E_Grid) showed a slight decrease in the annual total, from 33 928.701 kWh under the current climate to 33 856.461 kWh in the future climate scenario. Monthly data indicated that the losses or negative energy values remained consistent, with minor monthly fluctuations. July and August, traditionally the hottest months, showed slightly higher temperatures (30.11 °C and 29.70 °C, respectively) and correspondingly higher negative E_Grid values, suggesting that extreme heat could impact the PV system's efficiency and energy output. The global horizontal irradiation (GlobHor) showed a slight decrease from 2230.4 kWh/m² in the current climate to 2154.8 kWh/m² in the future BWh climate. Conversely, horizontal diffuse irradiation (DiffHor) increased from 488.51 kWh/m² to 553.15 kWh/m², indicating higher levels of scattered sunlight in the future scenario. The ambient temperature (T_Amb) also rose from an annual average of 18.51 °C to 20.07 °C, reflecting the anticipated warming trend. Regarding energy captured by the PV modules, the global incident irradiation on the collector plane (GlobInc) slightly decreased from 2499.1 kWh/m² to 2417.2 kWh/m², and the effective global irradiation corrected for IAM and shadings (GlobEff) dropped from 2452.3 kWh/m² to 2373.1 kWh/m². Despite these reductions, the variations were relatively minor, suggesting that the PV system's exposure to sunlight remains largely consistent even under the hotter, drier conditions of the BWh climate. The effective energy at the array output (EArray) continued to be recorded as 0 kWh due to the specific simulation parameters and potential modeling constraints in PVsyst.

These findings highlight several important considerations for deploying and operating PV systems in regions experiencing significant climate shifts. The increased ambient temperatures and diffuse irradiation could have mixed effects on PV performance. While higher temperatures typically reduce the efficiency of PV modules, increased diffuse irradiation may partially offset this by enhancing overall solar exposure. The slight reductions in E_Grid values indicate that, despite the hotter climate, the PV system can maintain a relatively stable energy output with the climate shift, albeit with some efficiency losses during peak summer months. The analysis suggests that while the transition from BWk to BWh climate conditions will impact PV performance, the effects may not be as severe as initially anticipated. The system's design remains robust under varying climatic conditions, particularly the fixed tilt and orientation. However, further optimization and adaptive measures, such as improved cooling systems for PV modules or advanced materials with better high-temperature performance, could enhance resilience and efficiency in the face of ongoing climate change. These insights are crucial for energy planners and policymakers aiming to ensure the sustainability and reliability of solar energy systems in arid and desert climates.

Future research could extend this study by evaluating additional PV technologies, such as thin-film CdTe or emerging perovskite solar cells, under projected semi-arid climate conditions. Different materials have distinct thermal behaviors and performance characteristics, influencing their response to temperature increases. It would also be beneficial to explore multiple climate-change scenarios and geographical contexts, examining how varying emission pathways and climate conditions affect PV system performance. Moreover, integrating the results into broader policy and energy planning frameworks will enhance their practical utility. Developing policies that proactively incorporate climate resilience and adaptive strategies into grid planning will ensure PV infrastructure remains effective and reliable under future climatic uncertainties.

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