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Thermal Analysis of Photo Voltaic System for Impact Assessment on Seasons for Power Generation

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

In photovoltaic systems the performance is basically influenced by various factors, including temperature, irradiance, and seasonal changes. In this study the thermal behavior of PV systems and assesses the impact of seasonal variations on their power generation efficiency at the designated power plant has been studied. By analyzing temperature fluctuations over different seasons, we aim to better understand the relationship between ambient temperature, surface temperature of PV panels, and their electrical output. Seasonal changes, particularly the higher temperatures in summer and lower temperatures in winter, significantly influence the efficiency of photovoltaic systems. The results show that while PV systems generate more power during high-irradiance months, their efficiency can be compromised by elevated temperatures. The findings provide valuable insights for improving PV system efficiency in varying climatic conditions and guide the development of more sustainable and reliable energy generation solutions.

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Keywords: Temperature; PV systems; energy; seasonal changes.

1. INTRODUCTION

Energy plays a crucial role in driving both economic and social progress. India is the sixth-largest energy consumer globally, accounting for approximately 5% of the world's total annual energy consumption. However, the per capita energy consumption in India remains relatively low at 1020 kWh, compared to the global average of 6000 kWh. To achieve the targets of sustainable development, this figure needs to rise. Since gaining independence, India's power generation capacity has expanded by many times, reaching a total installed capacity. Despite this growth, the country still faces a peak demand shortage of about 6% and an energy deficit of 5%. To address the energy gap, especially in electricity, it is imperative not only to increase energy production capacity but also to promote efficient utilization and conservation of energy. (Anand et al., 2015).

Photovoltaic (PV) systems have emerged as a leading solution for harnessing solar energy, offering a clean, sustainable, and renewable alternative to conventional fossil fuel-based power generation. As global energy demands continue to rise and the urgency of combating climate change becomes more pressing, PV technology plays a central role in efforts to decarbonize the power sector. However, the performance of photovoltaic systems is highly influenced by environmental factors, especially temperature and solar irradiance. The efficiency and energy output of PV panels are subject to variations in ambient temperature, which can fluctuate significantly over different seasons, impacting their overall effectiveness. This interplay between environmental conditions and PV system performance highlights the importance of thermal analysis in assessing the seasonal impacts on power generation.

Thermal analysis in PV systems refers to the study of the heat flow and temperature distribution across the PV module during operation. Temperature influences the efficiency of photovoltaic cells since elevated temperatures can reduce the ability of the semiconductor material to generate electrical energy from sunlight. While higher irradiance generally leads to more power generation, the associated rise in temperature can counteract this benefit by increasing resistive losses within the PV module. The temperature of a PV panel is a critical factor because it governs the electrical output, with a decrease in efficiency of approximately 0.4% to 0.5% per degree Celsius increase in temperature. This phenomenon is especially pronounced in regions with high ambient temperatures, where PV systems tend to operate at suboptimal temperatures, reducing their overall performance.

The impact of seasonal variations on PV system performance has been the subject of numerous studies, but a comprehensive understanding of the combined effect of irradiance and temperature throughout the year is still limited. In different seasons, the intensity and duration of sunlight exposure change, influencing both the energy generated by PV systems and the temperature at which they operate. In regions with significant seasonal temperature differences, such as those with temperate or polar climates, the efficiency of PV systems can vary considerably from summer to winter. For instance, in summer, the higher ambient temperatures can lead to substantial efficiency losses, despite longer hours of sunlight. Conversely, in winter, while the irradiance might be lower due to shorter days and possible cloud cover, the cooler ambient temperatures help maintain higher efficiency levels, albeit with reduced energy generation.

Additionally, the impact of local climatic factors, such as humidity, wind speed, and air quality, can further exacerbate or mitigate the thermal performance of PV systems. Wind, for example, can help reduce the surface temperature of PV modules by enhancing heat dissipation. In contrast, high humidity levels can increase the thermal load on the system, leading to a greater risk of overheating and reduced efficiency. As such, understanding the thermal dynamics of PV systems across different seasons and climates is crucial for optimizing their design and operation.

This study aims to provide a thorough investigation into the seasonal thermal performance of PV systems. By conducting both experimental and simulation-based thermal analyses, the research evaluates how temperature and irradiance interact throughout the year and assesses their combined impact on power generation. The findings will not only enhance our understanding of seasonal variability but also offer practical insights for the development of improved PV systems, including thermal management strategies, that can perform efficiently across different climatic conditions. Moreover, the study will help optimize PV installations for maximum energy yield and contribute to the broader goal of maximizing the reliability and sustainability of solar energy as a primary power source in varying environments.

The global adoption of photovoltaic (PV) systems as a sustainable energy solution has intensified in recent years due to their potential to mitigate environmental challenges associated with conventional energy sources. However, the efficiency of PV systems is strongly influenced by thermal conditions, with ambient temperature being a critical factor affecting performance. Studies have demonstrated that elevated temperatures can reduce the efficiency of PV cells by increasing their operating temperature and altering the semiconductor properties (Sun et al., 2022; Sanusi et al., 2011; Hasan et al., 2021).

Seasonal and climatic variations further compound the impact of temperature on PV performance. In regions with distinct seasonal changes, the interaction between ambient temperature, solar irradiance, and wind conditions plays a pivotal role in determining the energy output of PV systems. Research has shown that during hotter months, PV efficiency declines, while colder seasons may enhance energy generation but introduce challenges such as snow accumulation and reduced sunlight availability (Bevilacqua et al., 2020; Sanusi et al., 2011; Sarmah et al., 2023). The need for efficient thermal management strategies to maintain optimal operating conditions is particularly evident in extreme weather conditions (Parthiban & Ponnambalam, 2022; Vasisht et al., 2016).

Researchers have explored various approaches to mitigate thermal losses, including passive and active cooling techniques, advanced heat dissipation materials, and innovative system designs. For instance, integrating heat pumps with PV systems has shown promise in stabilizing temperatures while enhancing overall system efficiency (Lorenzo & Narvarte, 2019). Furthermore, advancements in PV material technology aim to improve resilience to temperature fluctuations, thereby enhancing seasonal adaptability (Sun et al., 2022; Hasan et al., 2021; Perrakis et al., 2019).

This paper examines the thermal behavior of PV systems under diverse climatic and seasonal conditions, leveraging insights from extensive studies on their thermal performance and management strategies. By evaluating these impacts, the work seeks to highlight the importance of thermal optimization in enhancing PV system efficiency across different seasons and regions.

2. ANALYSIS

2.1 Thermal Impacts on PV Performance

Thermal conditions significantly affect the performance of photovoltaic (PV) systems. Studies indicate that the power output of PV modules decreases with rising cell temperatures due to increased resistive losses and reduced open-circuit voltage. This phenomenon is quantified using the temperature coefficient (β), which represents the percentage change in efficiency per degree Celsius rise in temperature. β typically ranges between −0.4% to −0.5%/°C for crystalline silicon PV cells.

Mathematically, the relationship can be expressed as:

$$P_T = P_{STC} \times [1 + \beta \times (T_C - T_{STC})],$$

Where:

- P_T: Power output at cell temperature T_C.
- P_{STC}: Power output under Standard Test Conditions (STC)
- β: Temperature coefficient
- T_C: Cell temperature
- T_{STC}: Temperature at STC (25°C)

1. **Given Data**:

   - P_{STC} = 300 W: The rated power under standard test conditions.
   - $\beta = -0.4\% /^{\circ}C$: The temperature coefficient of power. Converting to a decimal, β = −0.004.
   - $T_c = 45^{\circ}C$: The cell temperature during operation.
   - STC assumes a cell temperature of $25^{\circ}C$.

2. **Formula**: The power at temperature T_C is calculated using the formula: $P_T = P_{STC} \times [1 + \beta \times (T_C - 25)]$

3. **Substitute Values**:

   $P_T = 300 \times [1 + (-0.004) \times (45 - 25)]$

4. **Simplify**:

   o $(T_C - 25) = 45 - 25 = 20$
   o $\beta \times (T_c - 25) = -0.004 \times 20 = -0.08$
   o $1 + (-0.08) = 0.92$

$P_T = 300 \times 0.92$

3. RESULTS

$P_T = 276$ W

3.1 Monthly Power Generation Trends

PV system at GKVK campus demonstrates peak energy production in January, coinciding with cooler ambient temperatures. Using data from studies on tropical regions, the observed efficiency during winter can be attributed to reduced thermal losses.

Monthly Power Output Trends: The following graph compares the GKVK campus monthly power generation trends with reference studies, highlighting the seasonal impact:

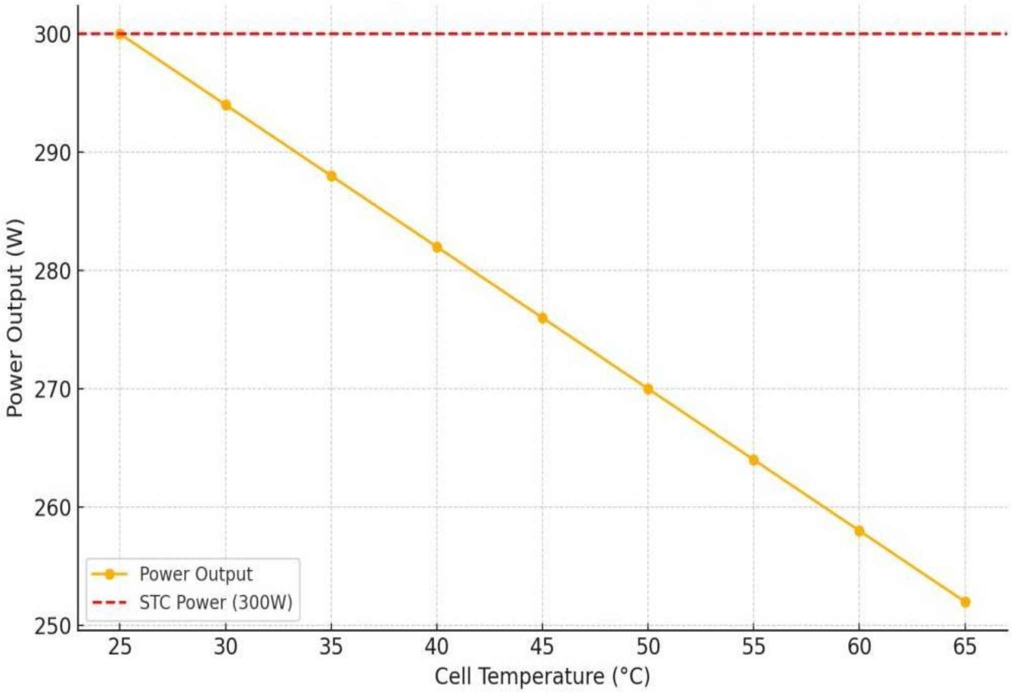

Fig. 1. Temperature vs. Power output

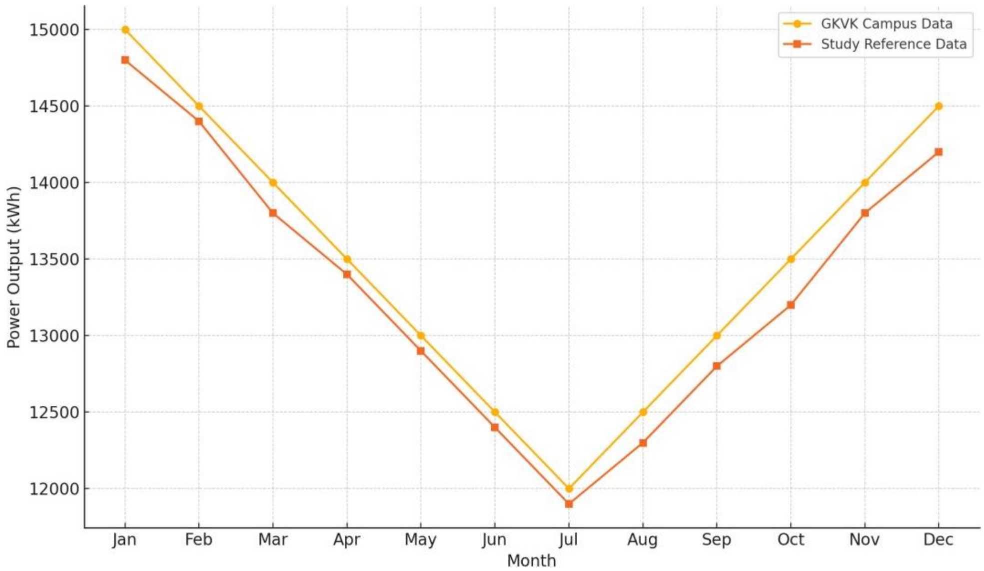

Fig. 2. Monthly Power Output Trends

3.2 Seasonal Efficiency Variation

Seasonal efficiency trends can be modeled using meteorological and operational parameters:

1. **η (Efficiency under given conditions)**
   The system's efficiency at the current temperature and operating conditions.
2. **ηSTC (Efficiency under STC)**
   The system's efficiency under **Standard Test Conditions (STC)**, which typically include:

- Ambient temperature: 25°C
- Irradiance: 1000 W/m²
- Air mass (AM): 1.5

3. **Tambient (Ambient temperature)**
   The surrounding air temperature where the system is operating.
4. **ΔT (Temperature rise due to irradiance)**
   The additional temperature increase caused by solar irradiance.
5. **β (Temperature coefficient)**

Represents the sensitivity of the system's efficiency to changes in temperature. It is often expressed as a negative value, indicating that efficiency typically decreases as temperature increases.

$\eta = \eta_{STC} \times [1 + \beta \times (T_{ambient} + \Delta T - T_{STC})]$,

- **Tambient + ΔT − TSTC:**
  The difference between the operating temperature and the reference temperature under STC.
- **β × (Tambient + ΔT − TSTC):**
  The relative change in efficiency is due to the temperature difference.
- **Final Efficiency (η):**
  Efficiency is scaled by ηSTC after adjusting for temperature effects.

The study conducted at the UAS Bangalore campus in the year 2013 has potential of producing 110Kwh of power in an hour, where average energy produced in the tropical country like India is around 4.6 kwh per day. However, due to tropical climatic condition which is having four seasons comprising summer, rainy season, autumn and spring. Hence, Solar Energy available in the year 2013, as been restructured to have data's in the months accounting for the power generated in the Fig 3.

The illustrated data in the bar graph above clearly demonstrate the power generation pattern in the gkvk campus in the year 2013, monthly which is clearly earmarked. The power generation in the 110 kwh solar PV system is not as asumed or designed. It is clearly the demonstration of thermal efficiency of solar PV system and its impact on the solar panels including the vapor.

Alternative Energy Sources in the present era is getting more attention than early is due to its economic benefits. Any Energy Sources utilized for power generation is always concerned with the Apparent Power [KVA] and Power Produced [Kwh]. The apparent power is the maximum demand which as been substituted from the alternative sources of energy from the conventional sources of energy, where as any energy sources utilized for the power generation is measured in terms of units [Kwh] produced. In the Fig. 3 above demonstrates the economic benefits produced from the Solar PV system installed at the GKVK campus, interms of Maximum Demand which is 960KVA/Annum and Power Produced by Solar PV System is 1,49,720 units. Here both Maximum Demand as well as Power Produced by Solar PV system as brought revenue Rs. 10,54,720/- to the University per annum.

Fig. 3. Monthlywise Power Generation pattern in KWH [Units] for the year 2013

Table 1. Economic evaluation economic evaluation

Month	Maximum Demand [KVA]	Units Produced [KWH]	Cost of KVA @ Rs 180/KVA	Cost of KWH @ Rs. 5.90/Kwh	Total Savings /Month [INR]
January	80	16056	14400	94730	109130
February	80	14380	14400	84842	99242
March	80	14880	14400	87792	102192
April	80	13160	14400	77644	92044
May	80	13270	14400	78293	92693
June	80	10350	14400	61065	75465
July	80	9380	14400	55342	69742
August	80	10880	14400	64192	78592
September	80	11230	14400	66257	80657
October	80	11842	14400	69868	84268
November	80	12370	14400	72983	87383
December	80	11680	14400	68912	83312
Total	**960**	**149478**	**172800**	**881920**	**1054720**

4. CONCLUSION

The conclusion of solar thermal studies at the GKVK campus for power generation highlights the significant potential of solar energy as a sustainable and viable solution for meeting the energy demands. The studies demonstrate that solar thermal systems installed at the campus have proven effective in harnessing solar power, offering a reliable source of energy with minimal environmental impact with a caution on solar efficiency of the panels. The results indicate that solar thermal technology can substantially contribute to reducing dependency on conventional energy sources while supporting the campus's efforts in energy conservation and sustainability. Additionally, with proper maintenance and optimal usage, the solar thermal systems have the capacity to generate sufficient power, thereby enhancing energy efficiency and promoting renewable energy adoption in the region.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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