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Assessment of Solar Photovoltaic System Performance under Real Environmental Conditions

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Abstract. Solar photovoltaic (PV) systems are a key solution for reducing the environmental impact of conventional energy generation, although their real performance often differs from nominal values under standard test conditions. This study evaluates the effect of environmental and operational factors on PV system output using weather-related correction coefficients. A simulation-based analysis of a 10 kW solar power plant considers irradiation, temperature, dust, incidence angle, and electrical losses. The results indicate that the output power decreases from 7,28 kW under ideal conditions to 6,48 kW in real operation, corresponding to a total loss of 11,3%. Temperature rise and module mismatch are identified as the dominant loss factors. The findings underline the importance of accounting for real operating conditions in PV system assessment and design.

INTRODUCTION

One of the major factors contributing to global environmental pollution is the generation of electrical energy based on conventional fossil fuels. The limited availability of these resources, along with their significant negative impact on the environment, has led to a growing demand for cleaner and more sustainable energy sources. In this context, renewable energy technologies, particularly solar photovoltaic systems, have attracted increasing attention worldwide. Solar photovoltaic cells generate electrical energy directly from solar radiation. Solar energy is considered an inexhaustible and renewable resource; however, its effective utilization largely depends on the performance characteristics of photovoltaic systems. These include the efficiency and productivity of solar cells, their operational lifetime, and the conditions under which maintenance is carried out. In addition to technical performance, the economic feasibility of energy generation using photovoltaic technologies plays an important role in their large-scale deployment [1].

Solar radiation originates from the sun and delivers approximately 1367 W/m² of energy at the outer boundary of the Earth's atmosphere. At present, the total amount of solar energy absorbed globally is estimated to be close to 1,8 × 10^{11} MW, which is sufficient to meet current worldwide energy demands, amounting to approximately 580 million terajoules. This highlights the significant potential of solar energy as a primary source of sustainable power. Over the past decade, the efficiency of solar panels has improved considerably. At the same time, their cost has decreased by more than 80% over the last eight years. These trends have transformed photovoltaic systems into economically attractive investment options and have accelerated their adoption in both developed and developing countries [2]. The efficiency and operational performance of solar power plants are influenced by several interrelated factors, which can be grouped into four main categories: natural, technical, operational, and geographical factors. Each of these categories plays a specific role in determining the overall effectiveness of a solar photovoltaic system. Natural factors, including climatic and environmental conditions, are associated with the characteristics of the region where the solar power plant is installed. These factors include the level of solar irradiation, weather conditions, ambient temperature, wind speed, airborne dust concentration, and overall air pollution [3-8].

Technical factors refer to the type of photovoltaic panels used, their orientation and tilt angle, the quality of inverters, and the compatibility of all system components. Operational and organizational factors include regular cleaning and maintenance of panels, installation quality, electrical transmission losses, and equipment aging. Geographical factors are related to the installation site, such as latitude and longitude, terrain features, and the presence of shading caused by surrounding objects or landscape conditions [3,4]. Among these factors, natural conditions are largely uncontrollable and cannot be directly influenced by human intervention. Therefore, it is essential to examine how such natural factors affect the efficiency and performance of solar power plants, which is the focus of the following analysis.

EXPERIMENTAL RESEARCH

Solar irradiation represents the amount of solar energy incident per unit area and is considered one of the most critical factors affecting the performance of PV panels. The electrical energy generated by PV systems is directly dependent on the level of solar irradiation received by the panel surface. Throughout the day, the apparent movement of the sun leads to continuous changes in irradiation intensity. Solar irradiation varies depending on geographical location, time of day, and atmospheric conditions. Higher irradiation levels allow PV panels to absorb more energy, resulting in an increased conversion efficiency and higher electrical output.

When nearby objects cast shadows on PV panels, accurate estimation of their performance becomes more complex. However, appropriate selection of the panel tilt angle makes it possible to maximize solar radiation absorption. During summer, the optimal tilt angle differs from the site latitude, while in winter the tilt angle typically requires an adjustment of approximately 15 degrees [5,6]. According to approximate assessments, a deviation of the panel azimuth angle by 1 degree from true south may result in an irradiation loss of about 0,08%. For this reason, the use of solar tracking systems is recommended. Solar trackers follow the sun's trajectory and maintain the panel in an optimal position relative to solar rays, thereby enhancing irradiation capture and improving overall system performance.

Humidity has a relatively minor direct influence on the efficiency of PV panels. Under high temperature conditions, moisture may form dew or thin film layers on the panel surface; however, the resulting performance reduction is generally limited. For example, a decrease in relative humidity from 60% to 48% may increase panel efficiency from 9,7% to 12,04%. Conversely, an increase in humidity by 20% can reduce the panel output power by approximately 3,16 W. Air quality, however, plays a more significant role. In polluted environments, suspended particles and aerosols reduce the amount of solar radiation reaching the panel surface, leading to lower electricity generation. This effect is particularly pronounced in industrial zones and densely populated urban areas with high levels of air pollution [1, 3-5].

The efficiency of solar panels is strongly influenced by temperature. Although increased solar irradiance leads to higher energy production, elevated operating temperatures negatively affect PV performance. Most commercial solar panels are designed to operate within a temperature range of -40 °C to +80 °C. Lower temperatures generally improve efficiency, while higher temperatures result in performance degradation. The nominal power of PV panels is typically measured at an optimal temperature of +25 °C. In the absence of cooling mechanisms, each 1 °C increase in panel temperature leads to an efficiency reduction of approximately 0,03-0,05%. For instance, when panel temperature rises to 56 °C, efficiency may decrease by about 3,13%. At temperatures around 64 °C, efficiency losses can reach up to 6-9%. Ambient temperature also affects the output voltage of PV modules: as temperature increases, output voltage decreases, further reducing electrical performance. This behavior is associated with increased electrical resistance at higher temperatures, which slows current flow. Conversely, lower temperatures reduce resistance and contribute to higher energy output [7].

Wind speed, defined as the velocity of air movement in a specific direction, significantly affects convective heat transfer from PV panels and thus influences their operating temperature. Higher wind speeds enhance heat dissipation, leading to reduced panel temperature and improved system efficiency. In hot climates, achieving higher PV performance requires installing panels a few centimeters above the ground or roof surface to allow sufficient airflow and prevent excessive overheating. Consequently, both wind speed and direction play an important role in PV system performance. However, strong winds may also cause adverse effects, such as increased accumulation of dust and snow, as well as potential mechanical damage to panel modules [8].

Dust accumulation on the surface of PV panels causes partial shading and significantly reduces the amount of solar radiation reaching the photovoltaic cells, leading to notable energy losses. Experimental studies conducted in Isfahan, Iran, over a 70-day period investigated the impact of dust deposition on glass transmittance [9]. The results showed that dust accumulation reached 4,0599 g/m² on surfaces oriented at 90° toward the northwest, while surfaces tilted at 15° toward the north accumulated up to 10,3129 g/m² of dust. Consequently, glass transmittance decreased by 15% and 24,83%, respectively. In desert regions, high dust concentration can reduce effective solar radiation by up to 40%

[6,8]. Studies conducted in Saudi Arabia indicate that pollution has a severe impact on photovoltaic power plant performance. If PV panels are not cleaned for a period of six months, dust accumulation may lead to output power losses of up to 50% [11].

Recent research has identified a linear relationship between dust density and the efficiency of PV modules. According to this relationship, when dust density reaches 10 g/m², the maximum power output of PV modules may decrease by approximately 34% [10]. These findings clearly demonstrate the critical impact of dust on PV system performance, particularly in arid and desert environments.

The total energy production of a solar photovoltaic (PV) panel, taking into account atmospheric and weather-related factors, can be estimated using the following expression:

$$E = H \cdot A \cdot \eta \cdot C_{weather} \quad (1)$$

where

E - is the daily energy output (kWh),

H - is the daily solar irradiation (kWh/m²/day),

A - is the active area of the PV panel (m²),

η - is the panel efficiency (typically in the range of 0,15-0,22), and

$C_{weather}$ - is the coefficient accounting for the combined influence of weather and atmospheric conditions (0,4-1,0).

The values of the weather influence coefficient $C_{weather}$ are summarized in Table 1, which presents the contribution of individual atmospheric factors.

TABLE 1. Weather-related factors and their influence coefficients ($C_{weather}$)

Factor	Influence coefficient (reduction factor)
Cloud cover	C_{cloud}=0,5-0,9
Atmospheric pollutants	$C_{pollution}$=0,85-0,95
Humidity	$C_{humidity}$=0,9-0,98
Dust	C_{dust}=0,7-0,95
Wind speed	C_{wind}=1,0

As shown in Table 1, the overall weather coefficient is determined by cloud cover, atmospheric pollution, humidity, dust deposition, and wind speed. When their combined effect is considered, the coefficient can be calculated as [8-11]:

$$C_{weather} = C_{cloud} \cdot C_{pollution} \cdot C_{humidity} \cdot C_{dust} \cdot C_{wind} \quad (2)$$

The nominal efficiency of solar PV modules is defined under Standard Test Conditions (STC), which provide a controlled and repeatable laboratory environment for evaluating and comparing different modules. STC parameters are highly standardized and include a solar irradiance of 1000 W/m², a cell temperature of 25 °C, and an air mass (AM) value of 1,5. These parameters represent ideal operating conditions and are used primarily for reference and comparison purposes. In real-world applications, however, it is not possible to maintain such ideal conditions. Variations in temperature, irradiance, angle of incidence, and environmental factors lead to deviations from nominal performance. Therefore, it is necessary to assess how changes in these influencing factors affect the actual power output of PV systems.

RESEARCH RESULTS

This section presents the results obtained from the simulation-based analysis of a 10 kW solar photovoltaic system under real operating conditions. The main loss mechanisms affecting the system performance were identified and quantified based on environmental and technical factors. A summary of the individual loss contributions is provided in Table 2, which illustrates the relative impact of each factor on the overall power reduction.

TABLE 2. Main loss factors affecting the performance of a 10 kW solar photovoltaic system

Loss factor	Description	Power loss (%)
Temperature increase	Module temperature rise from 25 °C to 47,9 °C	2,9
Module quality	Manufacturing tolerances and material imperfections	0,7
Module mismatch	Electrical mismatch among individual PV modules	2,9
Incidence Angle Modifier (IAM)	Solar radiation incidence angle of 40°	1,6
Connection resistance	Electrical interconnection losses	0,0

Taking all these losses into account, the total peak power of the PV array decreases from the nominal value of 7,28 kW to 6,46 kW. This corresponds to an overall power loss of approximately 11,3% under real operating conditions.

Figure 1 illustrates the current-voltage (I-V) characteristics of the photovoltaic module represented by curves of different colors. Each curve corresponds to a specific type of loss affecting the module performance. The associated loss types and their magnitudes are summarized in Table 3.

TABLE 3. Types of losses corresponding to the I-V characteristic curves

Color	Type of loss	Loss magnitude
Black	Standard condition at 25 °C	Peak power: 7,28 kW
Red	Module quality loss	-0,7%
Blue	Module mismatch loss	2,9%
Green	Incidence Angle Modifier (IAM) losses (diffuse + beam, 40°)	1,6%
Magenta	Module temperature at 47,9 °C	-7,9%
Cyan	Electrical connection resistance (227 mΩ)	0,0%

As shown in Table 3 and Figure 1, the black curve represents the reference I-V characteristic of the PV module under standard test conditions (25 °C), where the peak power reaches 7,28 kW. Deviations from this reference curve illustrate the impact of individual loss mechanisms on the electrical behavior of the module.

Module quality losses, represented by the red curve, result in a relatively small reduction in output power (0,7%), reflecting manufacturing tolerances and material imperfections. The blue curve corresponds to mismatch losses arising from non-uniform electrical characteristics among individual modules, leading to a more noticeable reduction of 2,9%.

Losses associated with the incidence angle of solar radiation are shown by the green curve. At an incidence angle of 40°, including both diffuse and direct components, the reduction in effective irradiance leads to a power loss of approximately 1,6%. Temperature-related effects are illustrated by the magenta curve, where an increase in module temperature to 47,9 °C causes a significant power reduction of about 7,9%, confirming the strong negative influence of elevated temperatures on PV performance.

Finally, the cyan curve represents losses due to electrical connection resistance. In this case, the impact of interconnection resistance (227 mΩ) is negligible, resulting in no measurable power loss.

Overall, the comparison of I-V characteristics under different loss conditions clearly demonstrates that temperature and mismatch effects are among the dominant factors influencing PV module performance, while connection resistance plays a minor role in the analyzed system.

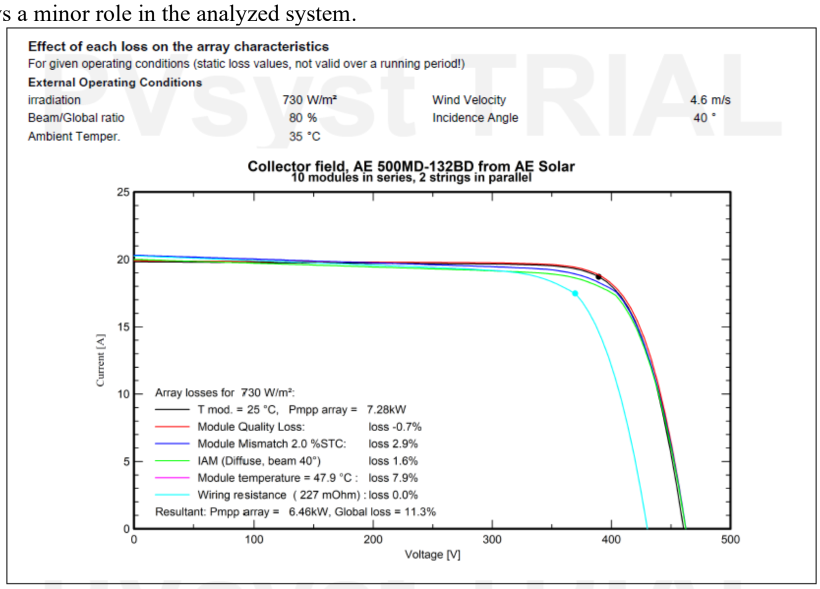

FIGURE 1. Variation of the electrical power output of a solar photovoltaic power plant as calculated using the PV system simulation software, taking into account the influence of key operating and environmental factors)

CONCLUSIONS

In conclusion, under ideal operating conditions-namely a module temperature of 25 °C, full solar irradiance, and the absence of system losses-solar photovoltaic panels are capable of delivering a maximum output power of 7,28 kW. However, under real operating conditions, the combined influence of various environmental and technical factors reduces the actual output power to approximately 6,48 kW. This corresponds to an overall power loss of about 11,3%.

The observed losses are primarily associated with several key factors. First, temperature increase has a significant negative impact on PV performance. As the operating temperature of solar panels rises, their electrical efficiency decreases, resulting in lower power output. Second, variations in panel quality and manufacturing tolerances lead to performance differences among individual modules. Since PV systems operate as interconnected units, even small deviations in module characteristics can reduce the overall system efficiency.

In addition, electrical losses occur during power transmission from the panels to the inverter through connecting cables. These losses become more pronounced when cable lengths are excessive or conductor cross-sections are insufficient. Another contributing factor is the presence of diffuse solar radiation. Under cloudy or dusty atmospheric conditions, solar radiation reaches the panel surface in a scattered form rather than as direct beam radiation, which leads to reduced energy conversion efficiency.

Therefore, proper system design, optimal installation, regular cleaning of panel surfaces, and careful consideration of environmental conditions play a crucial role in maintaining the performance of solar photovoltaic systems. Efficient utilization of solar energy is not only economically beneficial but also essential for ensuring long-term environmental sustainability and reducing the negative impact of conventional energy generation on the ecosystem.

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