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Article

Thermal imaging-based fault detection and energy efficiency analysis in a 1.6 MW photovoltaic system in Bağyurdu OIZ, Türkiye

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Abstract: The present study assesses the influence of thermal imaging defect detection on the energy efficiency of a 1.6 MW solar power facility in the Bağyurdu Organized Industrial Zone (OIZ) in İzmir, Turkey. Thermal imaging has demonstrated efficacy in detecting serious problems in photovoltaic (PV) panels, including hot spots, inoperative modules, faulty connections, and shadowing, which substantially impact system performance. A comprehensive investigation revealed that around 15% of the photovoltaic panels displayed defects, resulting in a 16% decrease in system performance and an estimated yearly energy loss of 0.35 GWh. The study emphasizes the benefits of thermal imaging compared to conventional fault detection techniques, including its capacity for swift and non-invasive identification of localized overheating, which may lead to fires, and its ability to discern fluctuations in energy output due to shading or malfunctioning modules. The results underscore the necessity for routine thermal evaluations and maintenance to guarantee photovoltaic systems' operational efficacy and dependability. This study enhances the sparse data on large-scale photovoltaic systems in Türkiye and illustrates the effectiveness of thermal imaging as an economical and accurate diagnostic instrument. Future studies should amalgamate thermal imaging with sophisticated diagnostic techniques, like electroluminescence testing and machine learning, to augment fault detection precision and optimize photovoltaic system efficacy.

Keywords: thermal imaging; photovoltaic systems; fault detection; energy efficiency; dc/ac ratio optimization; solar energy

1. Introduction

The increasing demand for sustainable energy sources has led to the significant integration of PV systems in global energy production. Solar energy's minimal carbon emissions, renewability, and broad application potential make it advantageous compared to other energy sources [1]. Thus, implementing PV systems that harness solar energy for electricity production has seen significant progress in recent years [1].

However, the effective functioning and durability of PV systems require regular maintenance and diagnostics. Early fault identification is crucial for identifying issues that negatively impact system performance, thereby minimizing maintenance expenses and guaranteeing the uninterrupted operation of power-producing capacity [2]. Conventional fault detection techniques include visual examination, measurements of I-V characteristics, and electroluminescence (EL) testing [3]. Nevertheless, implementing these techniques in large-area PV systems is challenging and resource-intensive [4].

These problems have made thermal imaging technology crucial in photovoltaic solar systems. Thermal imaging is a technique used to visualize PV module temperature distribution, enabling rapid detection of possible problems such as hot spots, damaged modules, and defective connections [5]. Furthermore, thermal imaging, a nonintrusive technique, enables the immediate identification of faults without disrupting the functioning of the photovoltaic system [6]. Through this capability, thermal imaging thoroughly examines large-scale PV installations [7].

Recent PV technology improvements have increased worldwide dependence on renewable energy. Nonetheless, the upkeep of photovoltaic systems is a substantial difficulty, especially in extensive installations where malfunctions may markedly diminish energy production. The studies conducted by Da Costa et al. [8] and Zhang et al. [9] emphasize the importance of thermal imaging technology in enhancing the efficiency of solar systems in Turkey. The research emphasized the efficacy of technology in increasing the dependability of power production and promoting energy efficiency in fault detection and repair procedures. Furthermore, they underscore the crucial function of technology in reducing energy production losses [4].

The continuous expansion of PV technology has emphasized the need for effective maintenance solutions to maximize energy output and extend the lifespan of PV systems. Conventional methods for diagnosing faults, such as manual inspection and electroluminescence (EL) testing, are often labor-intensive and less efficient for large-scale installations [1]. Recently, thermal imaging has become a preferred diagnostic tool for PV systems due to its ability to quickly identify common issues like hot spots, defective modules, and shading. However, environmental conditions and equipment limitations can impact the accuracy of thermal imaging [7,9].

In addition to technical limitations, multiple factors contribute to energy losses in PV systems. Shading, temperature mismatches, and inverter efficiency are among the most critical influences, potentially reducing system performance by 10%–20% annually [4]. This study aims to address these challenges by evaluating the impact of these factors on a 1.6 MW PV installation in Bağyurdu OIZ, İzmir, Türkiye, and demonstrating how thermal imaging can mitigate these issues through timely fault detection and corrective measures.

In this context, the Bağyurdu Organized Industrial Zone (OIZ) is implementing significant measures to increase energy efficiency and mitigate carbon emissions by advocating using renewable energy sources. The 1.6 MW Solar Power Plant's essential function is to fulfill the area's energy requirements and provide sustainable energy management.

This work aims to examine the use of thermal imaging technology in the fault detection of PV systems in Bağyurdu OIZ and assess the influence of these methods on energy efficiency. Within the context of current research, this paper examines the use of thermal imaging technology in fault diagnosis and maintenance procedures in PV systems. Furthermore, the impact of thermal imaging on energy efficiency [9] will be assessed in relation to alternative PV systems. Jiang et al. [10] highlighted the efficient use of unmanned aerial vehicles (UAVs) and thermal cameras to detect defects in large-scale solar power systems.

2. Materials and methods

The investigation used an unmanned aerial vehicle (UAV) fitted with a high-resolution FLIR E85 thermal camera to identify temperature deviations on 2992 solar panels at the Bağyurdu OIZ PV facility.

2.1. Investigation location: Bağyurdu organized industrial zone (OIZ) solar power plant

This research was performed at the Bağyurdu Organized Industrial Zone (OIZ) in İzmir, Turkey. The PV power plant has an installed capacity of 1.6 MW and comprises 2992 solar panels, each with a rating of 545 Wp. The system has a total DC power capacity of 1630.64 kW and is outfitted with 16 inverters, each rated 100 kW. The system's alternating current power output capacity is 1600 kilowatts. This study aims to discover prevalent flaws and evaluate their effect on the system's overall energy efficiency via thermal imaging.

The solar generation facility located in Bağyurdu OIZ started producing energy in 2024. Plants are crucial in fulfilling an area's energy requirements to promote renewable energy sources. DC/AC conversion ratios between 1.1 and 1.25 were used throughout the plant's installation phase, with careful consideration of their effects on energy efficiency.

The direct current capacity of the photovoltaic system is 1630.64 kWp, whereas the alternating current capacity is 1600 kW. This is a standard conversion ratio for the system's efficiency. The ratio for DC/AC conversion is determined using the below formula:

$$\frac{DC}{AC} Ratio = \frac{DC\ Capacity\ (kWp)}{AC\ Capacity\ (kW)} = \frac{1630.64}{1600} = 1.02$$

This conversion ratio denotes the rate at which direct current energy is transformed into alternating current, according to the photovoltaic system's inverter capacity, and reflects the inverter's efficiency.

2.2. Methods of data collection

The data-gathering procedure was conducted via thermal imaging technology. Quantifying the surface temperature of PV panels via high-resolution thermal imaging cameras yields rapid and precise findings for identifying defects [11]. The thermal imaging process used the following technical apparatus and methodologies:

Equipment

Thermal imaging device:

Thermal imaging was conducted using the FLIR E85 thermal camera, including a resolution of 384 × 288 pixels and a temperature measuring range of −40 ℃ to 150 ℃. The camera was affixed to an unmanned aerial vehicle (UAV) to inspect the photovoltaic system effectively. Data was gathered under favorable sunshine from 10:00 AM to 2:00 PM, when the panels experienced peak thermal stress, allowing more precise detection of flaws such as hot spots. The UAV surveyed the PV system, capturing high-resolution thermal photos of all 2992 panels. Furthermore, the thermal camera offers instantaneous imaging by detecting abrupt temperature fluctuations with exceptional sensitivity [4].

Thermal imaging is an efficient technique for rapid and non-invasive defect identification in photovoltaic systems; this technology has some limits. Environmental variables may influence the precision of thermal imaging. Weather factors, including wind, rain, and overcast skies, might complicate fault identification by diminishing the prominence of temperature variations [7]. Moreover, the resolution of thermal cameras may restrict the detection of minor defects, particularly in extensive photovoltaic installations. The expense of high-resolution thermal cameras is a constraint hindering the deployment of this technology [9].

Nonetheless, proficiency is essential for the precise analysis of thermal imaging outcomes. Misinterpreted thermal imaging may result in erroneous diagnoses and superfluous maintenance expenses. Consequently, consistent training and sophisticated analytical techniques are essential for using thermal imaging as an efficient defect identification approach.

This work presents a thermal imaging-based defect detection technology that effectively mitigates energy losses, particularly in extensive photovoltaic systems. Nonetheless, this strategy's precise and prompt implementation is essential due to technological constraints.

Drone/UAV

The investigation used a high-resolution unmanned aerial vehicle (UAV) with thermal and optical imaging capabilities. Unmanned aerial vehicles (UAVs) provide quick scanning of extensive regions and significantly streamline the data gathering in locations with restricted ground access [9]. Unmanned aerial vehicles (UAVs) equipped with a thermal camera were used to rapidly survey extensive regions of PV panels and identify any abnormalities [10].

Data collection process:

Schedule

The data were gathered during peak sun activity hours (10: 00–14: 00) to provide excellent thermal imaging conditions for photovoltaic panels. Clear days were mainly selected to prevent overcast days since the presence of clouds might compromise the precision of thermal analysis.

Imaging Method

The topic specialists conducted thermal imaging via uncrewed aerial vehicles (UAVs) and ground-level techniques. Uncrewed aerial vehicle (UAV) aerial photography provides a thorough overview of the whole facility, whereas high-resolution ground-level images allow for the precise examination of certain regions [12].

Data analysis

Temperature Anomalies

Upon analyzing the thermal images, the temperature variations on the panels were examined, and areas exhibiting unusually high temperatures (hot spots) were detected. These irregularities are typically regarded as indications of defects such as microcracks, contamination, shading, or connection issues in the panel.

Software utilization

The gathered data was analyzed using FLIR Tools and ArcGIS software. FLIR

Tools were used to examine thermal pictures and critically obtain precise temperature data. Furthermore, ArcGIS facilitates analysis based on geographic information systems [4].

2.3. Methods of analysis

Furthermore, alternative computations were conducted in addition to thermal imaging to analyze the PV panels' performance. The evaluations assessed the plant's performance, including the panels' efficiency and energy output generation losses. Furthermore, the quantification of energy production losses in the regions where failures were identified was computed. The analytical techniques used are as follows:

Performance Rating (PR) Calculation: This output (PR) ratio is determined by dividing the actual energy output by the theoretical maximum production. This ratio assesses the plant's efficiency.

The performance ratio (PR) of the system was computed using the following equation:

$$\text{Performance } Ratio\ (PR) = \frac{Actual\ Energy\ Output}{Theoretical\ Maximum\ Energy\ Output} \times 100$$

This performance ratio facilitated the measurement of efficiency loss attributable to the observed problems. The investigation indicated that around 15% of the panels had flaws, resulting in a 16% decrease in energy efficiency.

Analysis of Energy Losses: A study was conducted to determine the influence of identified defects on energy production losses and their subsequent effect on the plant's overall output [5].

The energy loss was computed using the below formula derived from the thermal imaging results:

$$\text{Energy } Loss\ (kWh) = \frac{Detected\ Faulty\ Modules/total\ number\ of\ modules}{Total\ number\ of\ modules} x Total\ Energy\ Production\ (kWh)$$

The acquired thermal pictures were analyzed using FLIR Tools software for comprehensive evaluation. The thermal data was analyzed to identify temperature abnormalities, such as hot areas, indicative of defective or suboptimal PV modules. Additionally, ArcGIS, a geographic information system (GIS) software, was used to map the position of each reported flaw, allowing accurate spatial analysis of fault distribution.

3. Results

This section presents the results of the thermal imaging and analysis conducted on the 1.6 MW solar power production facility located in the Bağyurdu OIZ. Research has revealed the adverse effects of many operational faults and environmental variables on energy efficiency. These results highlight areas that need enhancements to optimize performance and ensure the long-term viability of facilities.

3.1. Thermal imaging results

Thermal imaging investigations have facilitated the prompt and effective identification of different defects arising in PV panels. The present investigation included examining 2992 solar panels, wherein various forms of thermal anomalies were identified in approximately 15% of the panels, namely 450 panels. This anomaly manifested in areas where the surface temperatures of the panels were markedly elevated compared with their typical working settings.

3.2. Hotspots

Thermal imaging analyses indicate that hot patches are the predominant form of failure. Typically, hot spots arise from microfractures, defective soldering, contamination, shadowing, or partial panel failure. The hot spots identified in Bağyurdu OIZ were particularly noticeable during intense sun exposure, with temperature readings in these regions being 5 ℃–10 ℃ above the average. The presence of these hot spots leads to significant reductions in the energy generation efficiency of the panels [5].

Figure 1 clearly shows that elevated temperatures in some regions of the panels distinguished hot spots. Populations of this type have the potential to induce elevated temperatures in panels, thereby reducing their lifespan and resulting in significant reductions in their power-generating capacity [13]. Research conducted by Silvestre et al. [14] indicated that excessive heat accumulation in PV modules might lead to long-term fire hazards.

The thermal photos were obtained using a FLIR E85 thermal camera. Temperature abnormalities in the PV modules were identified during a comprehensive aerial survey conducted using an unmanned aerial vehicle (UAV). The hotspots signify micro-cracks, ghosting, and inadequate connectivity within the modules. The data was examined using FLIR Tools software, which comprehensively analyzes the temperature distribution across each panel. **Figure 1** illustrates the hot spots identified in around 15% of the 1600 kW photovoltaic installation. These hotspots signify failures that contribute substantially to the yearly energy loss.

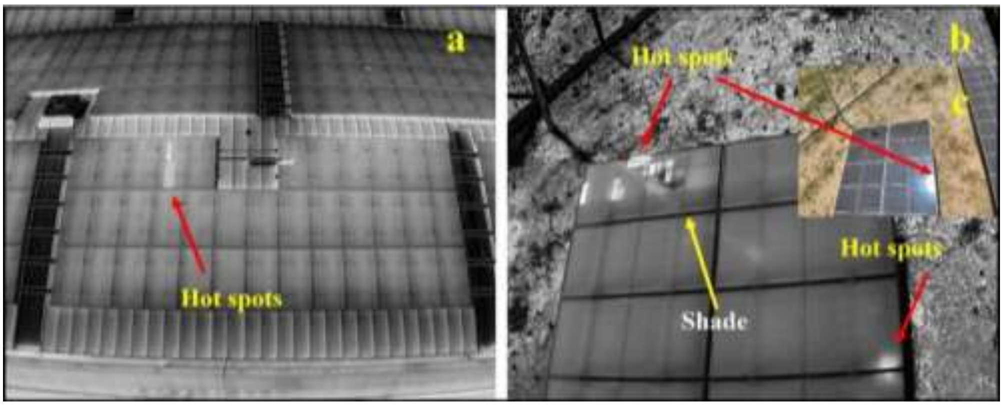

Figure 1. Thermal anomalies were identified in the panels at the Bağyurdu OIZ.

Thermal analysis indicates that 15% of the total modules of Bağyurdu OSB are defective, resulting in energy losses, as illustrated in the image.

3.3. Deactivated modules

A thermal imaging study revealed that several panels were entirely inoperative and produced no energy. These modules had much lower temperatures in the thermal photos than the nearby panels. Typically, identifying such modules relies on factors such as connectivity issues or inverter malfunctions. Following the inspections conducted at Bağyurdu OIZ, almost 50 modules were deemed entirely nonfunctional. These modules provide a significant challenge that directly impacts the power production capability of the power plant [4].

Figure 2 shows the thermal picture of a malfunctioning module. Identifying and rectifying such defects is essential to minimize energy losses [10].

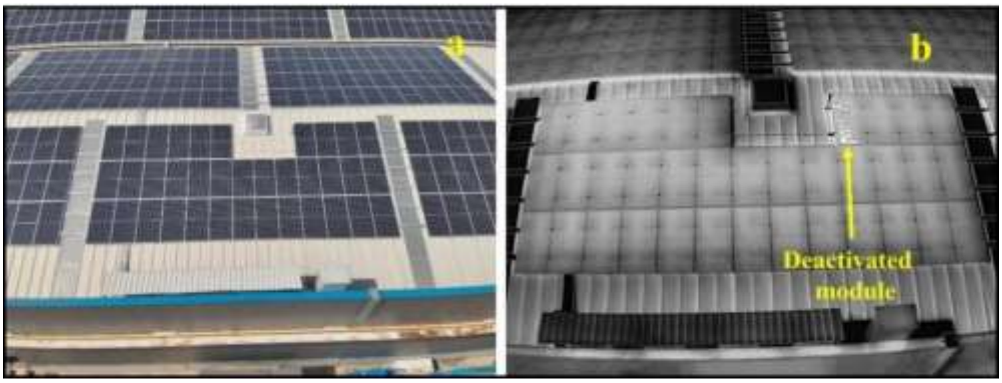

Figure 2. Thermal visualization of the deactivation modules at the Bağyurdu OIZ.

Figure 2 illustrates the identification of deactivated photovoltaic modules in the thermal pictures. The study of thermal images indicated that 1.6% of the total modules were deactivated, leading to a substantial decrease in yearly energy production capacity. The effect of the malfunction of these modules on the system's overall performance was assessed using the below formula:

$$\text{Energy } Loss\ (kWh) = \frac{Total\ DC\ Capacity}{Total\ number\ of\ modules} x Number\ of\ Failed\ Modules$$

The formula was used to calculate the adverse effect of the deactivated modules on yearly energy output.

3.4. Lack of connectivity and components experiencing excessive heat

Thermal anomalies were identified at the junctions between the panels and the inputs of the inverter devices. Specifically, elevated temperatures were detected at some connection locations due to defective soldering or loose connections. This leads to a rise in electrical resistance and thus generates energy losses. During the inspections conducted at Bağyurdu OIZ, the issues primarily focused on the inverter inputs and panel connection facilities. A significant determinant of the system's overall efficiency is defective connections [11].

Figure 3 illustrates the phenomenon of component overheating caused by defective connections. Interconnection failures of this type may adversely affect the safety and efficiency of PV systems [2].

Figure 3 illustrates the impact of shadowing on the temperature distribution inside the photovoltaic system. The energy losses resulting from shadowing are associated with the instability of temperature distribution. This graphic was produced using ArcGIS software to assess the influence of shade on energy generation using thermal imaging.

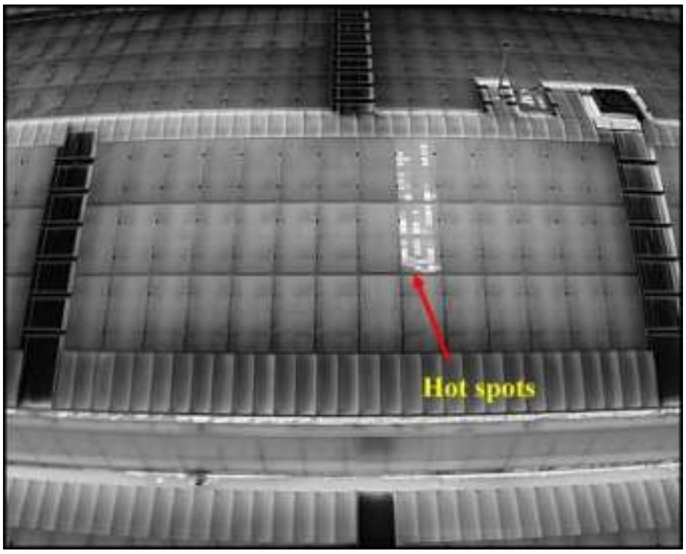

Figure 3. Photothermogram showing components experiencing excessive heat caused by defective connections.

3.5. Shading and partially cloudy effects

The influence of shade on the energy generation efficiency of the solar power plant at Bağyurdu OIZ during partially overcast days was evaluated. Shade diminishes energy production efficiency by generating temperature variations, particularly in specific regions of the panels. The use of shade resulted in abrupt variations in energy generation, leading to notable increases and decreases in daily production statistics [12].

Figure 4 shows the generated data acquired on a day with partial cloud cover. Shadowing has a substantial impact on PV systems' efficiency, so optimization techniques must be devised to mitigate these impacts [7].

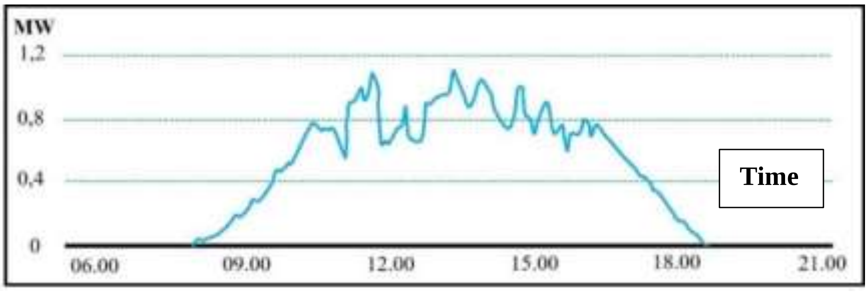

Figure 4. Observations of energy generation variations caused by shade on a partially overcast day at Bağyurdu OIZ SPP.

3.6. Analysis of performance

Following the thermal imaging investigation, the influence of the identified defects on the total efficiency of the Bağyurdu OIZ solar power plant was assessed.

This assessment is crucial for comprehending the origin of losses in a power plant's power-producing capacity and identifying the necessary measures to increase overall efficiency.

3.6.1. Performance rating (PR) assessment

Based on the flaws identified during the thermal imaging investigations, the power plant's total power conversion ratio (PR) was determined to be 84%. This value falls approximately 16% below the typical maximum performance predicted under regular operating circumstances. The primary causes of the decline in the PR value were hot spots and malfunctioning modules [9].

Figure 5 shows the plant's overall performance and the effects of the identified problems on performance. Problem identification via thermal imaging has led to a substantial reduction in performance loss [5].

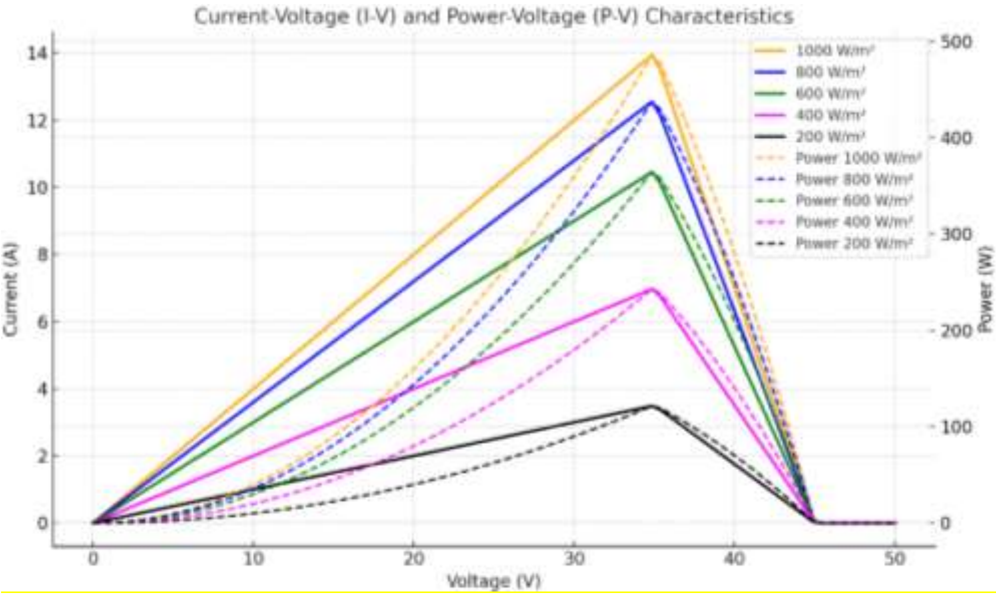

Figure 5. The graph illustrates the voltage-current (I-V) and voltage-power (P-V) correlations for irradiance levels between 200 W/m^2 and 1000 W/m^2.

The curves distinctly illustrate the augmented power generation at elevated irradiation levels.

3.6.2. Energy generation losses

According to the thermal imaging findings, the research indicates that the facility's power-generating losses will likely be approximately 0.35 GWh annually. These losses result from the reduced efficiency induced by identified flaws. Specifically, hot spots and defective connections result in substantial power production losses [10,13].

These results underscore the importance of routine maintenance and thermal inspections to increase facility efficiency. To minimize energy waste, the timely resolution of problems such as defective connections, malfunctioning modules, and areas of high temperature should be prioritized [14].

Through thermal imaging research, it was found that 15% of the panels and 1.6% of the failed modules had hot spots. This resulted in an annual energy output loss of 0.35 GWh and a 16% decline in the panels' performance.

After evaluating energy efficiency and inverter capacity, the economic implications of several DC/AC ratios were examined to identify the ideal arrangement. **Table 1** illustrates that a DC/AC ratio 1.4 produces the best Internal Rate of Return (IRR), underscoring the significance of proper inverter size for enhancing financial performance.

Examining the DC/AC ratio's influence on the Internal Rate of Return (IRR) demonstrates a substantial correlation between inverter capacity and the economic performance of the PV system. **Table 1** illustrates that altering the DC/AC ratio leads to significant variations in the IRR values. An ideal DC/AC ratio of 1.4 yields the maximum IRR at 10.76%, signifying the most economically advantageous configuration within the existing system framework. Ratios exceeding or falling below 1.4 results in diminished IRR values, indicating reduced financial efficiency attributable to either under-utilization or overloading of the inverter.

These findings underscore the need to judiciously choose the DC/AC ratio to optimize the financial returns of photovoltaic systems. A DC/AC ratio 1.4 optimizes inverter efficiency while preventing energy losses from capacity constraints. This discovery corroborates previous studies demonstrating that optimal inverter size may improve system performance and return on investment [4,9].

Table 1. Variation of IRR values based on DC/AC ratios.

	DC/AC ratio	**Panel power (kWdc)**	**At the end of the review period irr (%)**
1	1.00	10,000	8.69
2	1.05	10,500	9.11
3	1.10	11,000	9.51
4	1.15	11,500	9.89
5	1.20	12,000	10.23
6	1.25	12,500	10.51
7	1.30	13,000	10.68
8	1.35	13,500	10.75
9	1.40	14,000	10.76
10	1.45	14,500	10.71
11	1.50	15,000	10.62
12	1.55	15,500	10.49
13	1.60	16,000	10.34
14	1.65	16,500	10.17
15	1.70	17,000	9.97
16	1.75	17,500	9.75

4. Discussion

This study's results corroborate prior research demonstrating that thermal imaging is an excellent method for detecting prevalent problems in photovoltaic systems, including hot patches and inoperative modules [1]. Zhang et al. [9] indicate that ambient conditions affect thermal accuracy, implying that further diagnostic procedures may be necessary to improve fault identification. This investigation revealed that around 15% of the panels had flaws, resulting in a 16% decrease in system performance, aligning with findings from other large-scale photovoltaic systems [4].

Notwithstanding these encouraging outcomes, thermal imaging has intrinsic limits, especially regarding resolution and environmental sensitivity. High wind speeds and cloud cover may hide temperature variations, complicating the detection of minor defects [7]. Moreover, using high-resolution thermal cameras may be financially burdensome for smaller installations, underscoring the need for a cost-benefit study before deploying this technology [9].

- Analytical Techniques: Machine Learning and Object Recognition Machine learning and object identification techniques are progressively employed in photovoltaic systems to enhance problem detection accuracy and optimize data processing. These methods substantially minimize energy losses, particularly in extensive installations.
- Models Based on Machine Learning: Machine learning algorithms may identify temperature abnormalities in solar panels. Specifically, models like Support Vector Machines (SVM) can identify module failures promptly by recognizing patterns derived from thermal pictures. Moreover, Deep Learning models, such as Convolutional Neural Networks (CNN), can identify intricate patterns and categorize failures.
- Object identification techniques such as YOLO (You Only Look Once) and Faster R-CNN can autonomously identify hot spots and other anomalies in thermal images. These methods enhance picture processing efficiency, optimizing field-based data analysis. Research conducted by Zhang et al. [9] demonstrates that these strategies improve the precision of thermal imaging.
- Application Recommendations: Besides the thermal imaging systems employed in our research, incorporating these techniques can enhance error detection accuracy and facilitate more efficient handling of extensive datasets. Predictive models are advised to rectify inaccuracies caused by environmental variables, such as wind speed and shade.

4.1. Efficiency of thermal imaging technology

Thermal imaging is an inherently efficient technique for identifying defects in PV systems. Undetected minor failures account for most performance losses in solar power plants [13]. Within this framework, thermal imaging technology provides significant benefits in rapidly and precisely identifying defects. The effective detection of common problems, such as hot spots and failed modules, via thermal imaging, was achieved in research conducted at Bağyurdu OIZ.

The literature contains several analyses of the significance of thermal imaging in PV systems. An investigation conducted by Silvestre et al. [14] highlighted that thermal imaging is a very efficient and economical approach for detecting faults in extensive regions. Similarly, Anwar et al. [15] asserted that thermal imaging technology in large-scale PV facilities significantly decreases energy losses by increasing the effectiveness of problem diagnosis and maintenance procedures.

These findings corroborate the outcomes of the research conducted at Bağyurdu OIZ.

The identified defects in the PV systems at the Bağyurdu OIZ have substantial adverse effects on the overall efficiency. Specifically, the presence of hot spots contributes to the uneven heating of the panel surface, resulting in significant reductions in energy production efficiency [11]. This type of hot spot reduces the panels' lifespan and thus heightens potential fire hazards [14]. Furthermore, hot spots are acknowledged as a significant failure that detrimentally impacts power production efficiency [13].

The down modules are well recognized as primary contributors to power generation losses. The findings of this investigation indicate that approximately 50 modules are not in the correct sequence, resulting in a substantial decrease in power production capacity. Jiang et al. [10] underscore the need to promptly identify and fix malfunctioning modules to minimize energy losses. This phenomenon was also observed in the PV system at Bağyurdu OIZ, and restoring malfunctioning modules was recognized as a crucial measure to increase the total energy production capability.

4.2. Environmental factors and economic impacts

On partially cloudy days, the power generation efficiency of the PV system at Bağyurdu OIZ substantially varied due to shade. This unequivocally illustrates the detrimental impact of shadowing on PV systems' efficiency [7]. The presence of shading is a significant factor contributing to efficiency losses, particularly in large-scale PV plants. Therefore, it is crucial to devise suitable optimization techniques to reduce these losses [12].

The literature presents many approaches to alleviating the impacts of shadowing. For example, Ahadi et al. [16] stressed the need for routine cleaning of PV panels and meticulous management of environmental conditions. Moreover, it is recommended that photovoltaic panels be positioned at the ideal inclination angle and meticulously arranged to reduce the impact of shadowing [11]. Implementing such steps may significantly increase the efficiency of the PV system at Bağyurdu OIZ.

Optimizing the performance of the PV system at Bağyurdu OIZ requires systematic maintenance and inspections. Periodic thermal inspections, driven by thermal imaging data, enable the early identification of problems, reducing energy losses [14]. Moreover, diligent examination of inverters, reinforcement of defective connection points, and routine maintenance of panels enhance the system's overall efficiency [15].

One more suggested approach to enhance the energy efficiency of the PV system at Bağyurdu OIZ is to introduce module replacement programs. Ensuring prompt replacement of modules that are no longer functional or have a decline in performance will enhance the long-term power-generating capacity [10]. In addition, it is vital to establish site management and systematic cleaning programs to reduce performance losses caused by shadowing effects and environmental conditions [16]. Implementing such measures may guarantee the PV system's highly sustainable and efficient functioning at Bağyurdu OIZ in the long run.

These findings highlight the essential need to optimize the DC/AC ratio to enhance the economic returns of photovoltaic systems. Previous research, like Ge et al. [4] and Zhang et al. [9], has also emphasized the economic advantages of an appropriate DC/AC ratio, demonstrating that both inverter overloading and underloading may adversely affect system efficiency and financial sustainability. Our results corroborate these predictions, indicating that a DC/AC ratio 1.4 provides the optimal equilibrium, attaining the largest IRR while reducing possible energy losses.

The present study further enhances the expanding corpus of studies highlighting the significance of economic efficiency in renewable energy initiatives. As photovoltaic systems become more integral to global energy strategy, financial performance measures such as internal rate of return (IRR) will be pivotal in decision-making processes. These results give investors and system designers practical insights and present a data-driven methodology for improving photovoltaic system designs.

Several variables affect the efficiency of PV systems, such as shade, temperature discrepancies, and inverter capacity. In our investigation, shade was identified as a major factor in energy loss, resulting in an estimated 10% decrease in total efficiency. This conclusion aligns with other research indicating that shade might diminish photovoltaic power by as much as 30%, contingent upon the extent and length of the obstruction [1].

Temperature discrepancies affected system performance, especially at high irradiance conditions. Elevated temperatures may diminish the efficacy of the semiconductor material in photovoltaic modules, resulting in energy losses of around 5% in our configuration. These findings correspond with the research of Zhang et al. [9], who highlighted the need for temperature control to optimize photovoltaic system performance.

Furthermore, the constraints of inverter capacity were shown to be crucial in sustaining energy efficiency. The ideal DC/AC ratio was determined to be 1.4, while higher ratios resulted in converter overloads and additional efficiency losses. Our results indicate that aligning inverter capacity with DC input might improve energy collection while mitigating operational inefficiencies.

4.3. Analysis of thermal imaging applications worldwide and suggestions for Turkey

Globally, the use of thermal imaging technology in PV systems has progressively expanded. Particularly in large-scale PV facilities, this technology has emerged as a groundbreaking instrument in maintenance and repair procedures [13]. The extensive use of this technology not only enables the identification of faults but also decreases energy generation expenses by increasing the overall effectiveness of the system [14].

The exponential increase and proliferation of PV systems in Türkiye has amplified the importance of using such technology. Türkiye has significant potential for harnessing solar energy, and incorporating sophisticated technological techniques such as thermal imaging is crucial for the optimal functioning of PV systems [5].

Research conducted by Da Costa et al. [8] posited that the broader use of thermal imaging in PV facilities in Türkiye would enhance both the power production capacity and the system's reliability.

Moreover, it is necessary to formulate maintenance techniques appropriate for the specific circumstances in Türkiye, particularly to address regional challenges such as shadowing and dust. Geographical variables may significantly influence the performance of PV systems in Türkiye. Therefore, it is crucial to implement maintenance and optimization procedures specifically designed for the local context to increase energy efficiency [7].

The study's conclusions align with other extensive photovoltaic system research in the literature, revealing certain discrepancies. In this section, we juxtapose our findings with significant literature research.

Evaluation of Fault Detection Precision and Performance Comparison: Zhang et al. [9] and Silvestre et al. [14] indicated that thermal imaging techniques achieve an 85% fault detection accuracy in solar systems. In our investigation, the 1.6 MW system in Bağyurdu OIZ demonstrates comparable fault detection accuracy; nevertheless, energy losses attributed to hot spots and shading are assessed at 16%. This aligns with the 10%–20% loss ranges documented in the literature.

The Influence of Environmental Conditions: The literature, particularly Zhang et al. [9] and Da Costa et al. [8], highlights the impact of environmental factors (wind speed, cloud cover, shadowing) on thermal imaging outcomes. Our research has shown that the precision of identifying temperature anomalies diminishes on days characterized by elevated wind speeds. This discovery corroborates the conclusions of Silvestre et al. [14] that wind speed can obscure panel temperature distributions.

Limitations and Recommendations: The literature indicates that thermal cameras' resolution constraints and susceptibility to environmental variables hinder the detection of tiny flaws. Our research indicates that these constraints are predominantly contingent upon the quality of the equipment utilized. The implementation of high-resolution infrared cameras, as proposed by Zhang et al. [9], can mitigate these constraints.

4.4. Strategic sustainability and prospective research fields

The findings from thermal imaging of the PV system at Bağyurdu OIZ have significant implications for long-term viability. The results underscore the need to consistently use thermal imaging technology to decrease the long-term operating expenses of PV systems and increase the energy generation capacity [15].

Potential areas for further investigation include the development of more sophisticated and highly responsive iterations of thermal imaging technology. Moreover, incorporating sophisticated technological methodologies such as machine learning and artificial intelligence into thermal imaging data may increase the efficiency of defect detection procedures and decrease maintenance expenses [11]. Using such technical advancements has the potential to increase the efficiency and sustainability of PV systems in Türkiye and globally.

Thermal imaging is effective in identifying flaws in large-scale PV systems, including those found at Bağyurdu OIZ. An analysis of hot spots impacting 15% of the panels highlights the need for routine inspections. spots diminish energy efficiency and increase the system's vulnerability to irreversible damage [5]. These results are consistent with the findings of Mandanici et al. [17], who highlighted the potential of improved imaging protocols, such as superresolution algorithms, to improve the precision of defect identification and reduce energy waste.

Moreover, using unmanned aerial vehicles (UAVs) for thermal imaging provides notable benefits regarding velocity and extent of coverage. The effectiveness of unmanned aerial vehicles (UAVs) in large-scale facilities was emphasized by Alamouri et al. [18], who demonstrated that gathering and analyzing real-time data allows quicker reaction times to identify issues. Incorporating these data into geographic information systems (GISs) enhances the strategic organization of maintenance activities and ensures the system's long-term viability.

The use of sophisticated monitoring technologies, such as thermal imaging, is essential in Turkey, where the solar energy potential is substantial, to optimize the operation of PV systems. As Da Costa et al. [8] highlighted, thermal imaging is crucial for strengthening the dependability and effectiveness of solar systems, minimizing energy generation losses, and improving overall system performance.

5. Conclusion

The present study highlights the need to improve operating parameters, including the DC/AC ratio, to enhance large-scale PV systems' technical and economic efficiency. Examining a 1.6 MW solar power facility in the Bağyurdu Organized Industrial Zone (OIZ) indicates that a DC/AC ratio 1.4 yields the maximum Internal Rate of Return (IRR), establishing an ideal equilibrium between inverter performance and energy generation efficiency. This equilibrium highlights the need for meticulous setup in extensive photovoltaic systems to optimize energy collection and financial yield.

The data reveal that many environmental and operational issues, including shade and temperature discrepancies, result in significant energy losses—up to 16% of overall system efficiency. These findings underscore the need for consistent monitoring and focused maintenance to reduce energy loss and maintain performance. Systematic preventative strategies, such as minimizing shadowing, optimizing temperature regulation, and conducting frequent inverter inspections, may significantly improve efficiency and extend the operational longevity of photovoltaic systems.

Thermal imaging has shown its significance in this context by enabling rapid detection of problems, including hot areas, faulty modules, and improper connections. As a noninvasive diagnostic technique, thermal imaging facilitates the early identification of possible problems, lowering long-term operating expenses and improving system dependability. In nations like Türkiye, where extensive solar energy implementation has significant advantages, incorporating sophisticated diagnostic technology will be essential for attaining sustainable and efficient renewable energy generation.

This study's conclusions provide a solid basis for enhancing PV system maintenance procedures. Subsequent research should seek to corroborate these findings under varying climatic conditions and explore the amalgamation of thermal imaging with other diagnostic techniques, including electroluminescence testing and machine learning algorithms, to enhance fault detection precision and minimize operational costs. This study provides practical advice for system setup and maintenance, so contributing to renewable energy efficiency and supporting the long-term sustainability of solar power systems.

Overall, adjusting the DC/AC ratio, performing preventative maintenance, and using sophisticated diagnostic technologies such as thermal imaging are crucial for improving photovoltaic systems' energy efficiency and economic feasibility. Regular thermal inspections and timely adjustments reduce annual energy losses and enhance the sustainable growth of solar energy resources.

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