Advanced UAV
http://publish.mersin.edu.tr/index.php/uav
e-ISSN 2822-6976

UAV-based thermal monitoring of solar panels for different topographic conditions

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Cite this study: Akay, S. S., Özcan, O., Özcan, O., & Yetemen, Ö. (2024). UAV-based thermal monitoring of solar panels for different topographic conditions. Advanced UAV, 4 (1), 53-61.

Keywords
UAV
Thermal monitoring
Solar farm
Solar panel
Solar efficiency

Research Article
Received: 02.04.2024
Revised: 17.05.2024
Accepted: 30.05.2024
Published: 14.06.2024

Abstract

The unmanned aerial vehicles (UAVs) can be used to monitor photovoltaic (PV) systems, specifically focusing on their integration with thermal imaging technology. The process involves equipping UAVs with integrated thermal cameras to capture aerial photographs, which are then used to generate thermal orthomosaic. These thermal data play a crucial role in efficiency calculations for solar panels in solar farms. The integration of UAVs with thermal imaging technology offers several advantages. It provides a rapid and cost-effective solution for monitoring solar farms where human resources may be limited. The use of thermal orthomosaic instead of multiple thermal aerial photographs streamlines the data collection process, allowing for efficient temperature and efficiency calculations. The temperatures and efficiencies of solar panels in different geographic directions in solar farms were rapidly examined using UAV. It has been calculated that temperatures vary more significantly based on direction than efficiencies. Although solar panels have regional temperature differences of approximately 1 to 8°C, panel efficiency was within 1%. Therefore, there might be directional temperature differences in solar farm, panel efficiencies were similar during winter months.

1. Introduction

Monitoring solar panels is critical to maintaining their efficiency and identifying faults. Traditionally, the temperatures of solar panels were measured using human-based solutions and conventional methods such as ground-based sensors and weather station data. hotspots and potential defects were detected with terrestrial thermal cameras, wired and wireless sensor, temperature measurement device. Terrestrial thermal images to identify areas of abnormal heat distribution, indicative of malfunctioning cells or panel degradation. Additionally, temperature data is collected by measurement devices attached to each panel, and calculations are made for each panel. In this context, both taking individual photos for each solar panel and the increased cost and time associated with installing devices on each panel indirectly make it difficult to control and identify faulty and low-efficiency panels in solar farms [1-3].

The integration of thermal imaging technology with Unmanned Aerial Vehicles (UAVs) has revolutionized various industries by providing unique advantages in aerial surveillance and data collection. This innovative combination leverages the capabilities of thermal cameras to detect heat variations and visualize temperature differences from an aerial perspective, offering significant benefits in numerous applications, such as search and rescue, agriculture, infrastructure inspection, and environmental monitoring. The integration of thermal imaging technology with UAVs has significantly advanced various fields, including surveillance, environmental monitoring, and disaster management. UAVs equipped with thermal cameras offer a unique capability to detect temperature variations and provide critical insights that are not visible to the naked eye or standard optical cameras. This technology has proven invaluable in search and rescue operations, where it enhances the ability to locate missing persons in challenging terrains or under low-visibility conditions, such as at night or through smoke. Moreover, thermal imaging UAVs are increasingly utilized in agriculture for crop monitoring, allowing farmers to identify areas affected by pests, diseases, or water stress, thereby enabling precise intervention and resource management. In the realm of infrastructure inspection, these UAVs help in identifying faults in electrical installations, pipelines, and buildings by detecting anomalies in heat patterns, thus ensuring timely maintenance and preventing potential failures. As the technology evolves, the applications of UAV-based thermal imaging continue to expand, driven by advancements in sensor technology, data processing algorithms, and autonomous navigation systems [4-8].

The growing demand for renewable energy sources has spurred advancements in solar energy technology. Photovoltaic (PV) systems, which convert sunlight into electricity, are a cornerstone of this renewable energy revolution. The rapid expansion of PV solar power plants necessitates innovative methods for efficient maintenance and monitoring to ensure optimal performance. Traditional methods of monitoring and maintaining solar panels are often time-consuming and labor-intensive. One such advanced technique is the use of UAVs equipped with thermal cameras. UAVs offer significant advantages in inspecting large-scale solar installations due to their ability to cover extensive areas swiftly and access hard-to-reach locations without human intervention. UAV-based thermal monitoring provides critical insights into the operational status of PV modules by detecting temperature anomalies indicative of defects such as hotspots, broken cells, and malfunctioning bypass diodes. This method enhances detection accuracy and reduces inspection times compared to traditional ground-based thermographic inspections. Consequently, the integration of UAVs with thermal imaging technology is revolutionizing the maintenance practices in the solar energy sector, leading to improved efficiency, reduced operational costs, and extended lifespan of PV systems [9-12]. UAV thermal monitoring is used to detect and analyze temperature anomalies in PV systems, highlighting its potential for preventive maintenance. Similarly, UAVs are realized to monitor the performance of solar panels, finding that thermal imaging could effectively identify areas with reduced efficiency due to temperature variations [13, 14]. The thermal performance of solar panels is a critical factor influencing their overall efficiency. Higher temperatures typically lead to lower efficiencies. Understanding and managing these temperature effects are crucial for optimizing solar energy production [15].

It is important to increase the efficiency of solar power plants and detect potential failures. This study examines the comparison of temperature and efficiency values by UAV-based thermal orthomosaic in a solar farm. The temperature and efficiency of solar panels in different directions were analyzed using the thermal orthomosaic. The efficiency coefficient and average panel temperatures were used to calculate the efficiencies of panels in different geographic orientations. This method allowed for a rapid assessment of panel performance, highlighting areas with significant temperature variations and corresponding efficiency levels.

2. Study area and method

Türkiye is observed to have high efficiency in terms of solar energy, with high solar efficiency seen from central Anatolia towards the south. In this context, a study has been conducted in the district of Alanya, which situated on the southern coast of Türkiye, is not only renowned for its picturesque beaches and historical sites but also for its potential in harnessing solar energy. Alanya which is a coastal town, has a large mountainous and rural area. Alanya has high levels of solar irradiance due to its geographical location and topography. Solar farm are established in mountainous and unsuitable agricultural areas to benefit from solar energy and, the annual photovoltaic power potential is between 1600 and 1800 kWh/kWp [16-20]. Alanya boasts ample sunlight throughout the year, making it an ideal candidate for solar energy harnessing. The region's high solar irradiance levels, particularly evident in its southern expanse, present a prime opportunity for photovoltaic systems and solar thermal applications. Recognizing the dual benefits of tourism and solar energy, Alanya has embarked on a multifaceted approach to integrate renewable technologies into its hospitality sector [20, 21].

In February 2023, a study was conducted at the solar farm located at 36.7006° N latitude and 31.9192° E longitude. The solar farm is situated in a mountainous area with an altitude of 927 meters, approximately 19 km from the center of Alanya. Also, the annual photovoltaic power potential of the solar farm is 1692 kWh/kWp [19]. PV power potential of Türkiye and the location of the solar farm are demonstrated in Figure 1. Especially in the southeastern region of Türkiye, but also in the southern region, there is a high potential for solar energy production, with values ranging approximately between 1500 and 2000 kWh/kWp. The lowest solar energy potential is observed in the northeastern region. Therefore, it is seen that Türkiye is suitable for solar energy production starting from the Central Anatolia region (Figure 1). The study area is 7.14 hectares and contains 4576 solar panels. Optical and thermal images of the study area are shown in Figure 2. In the solar farm, it is observed that solar panels extend towards the west in the north and south, while panels are arranged in a symmetrical manner closer to the center of the farm (Figure 2).

The solar panels are P-Serie 265 model panels produced by Solar Fabrik GmbH. The size of the solar panel is 1667x998x35 millimeters which contains 60 cells. The characteristics of the solar panels at standard test condition

(STC) are shown in Table 1 as provided by the Solar Fabrik GmbH. As producer information, it is observed that at 25 °C the efficiency of the panels is 15.9%, with a maximum power of 265 Wp. [22].

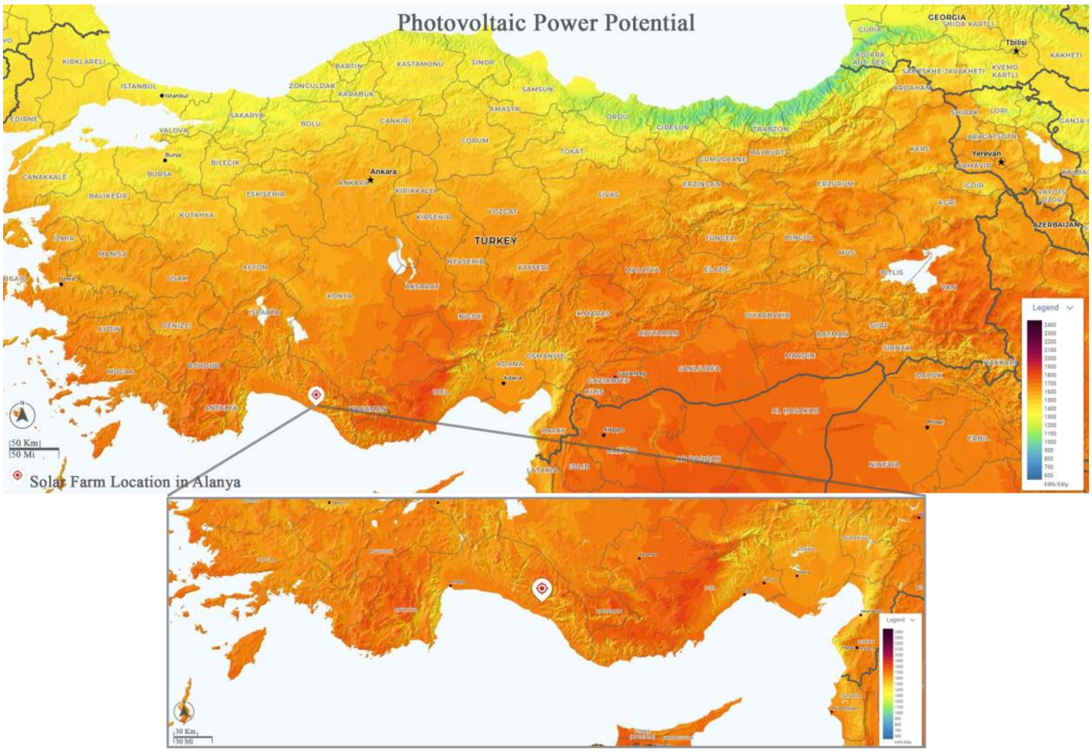

Figure 1. Demonstration of the solar farm location and PV power potential map of Türkiye [19].

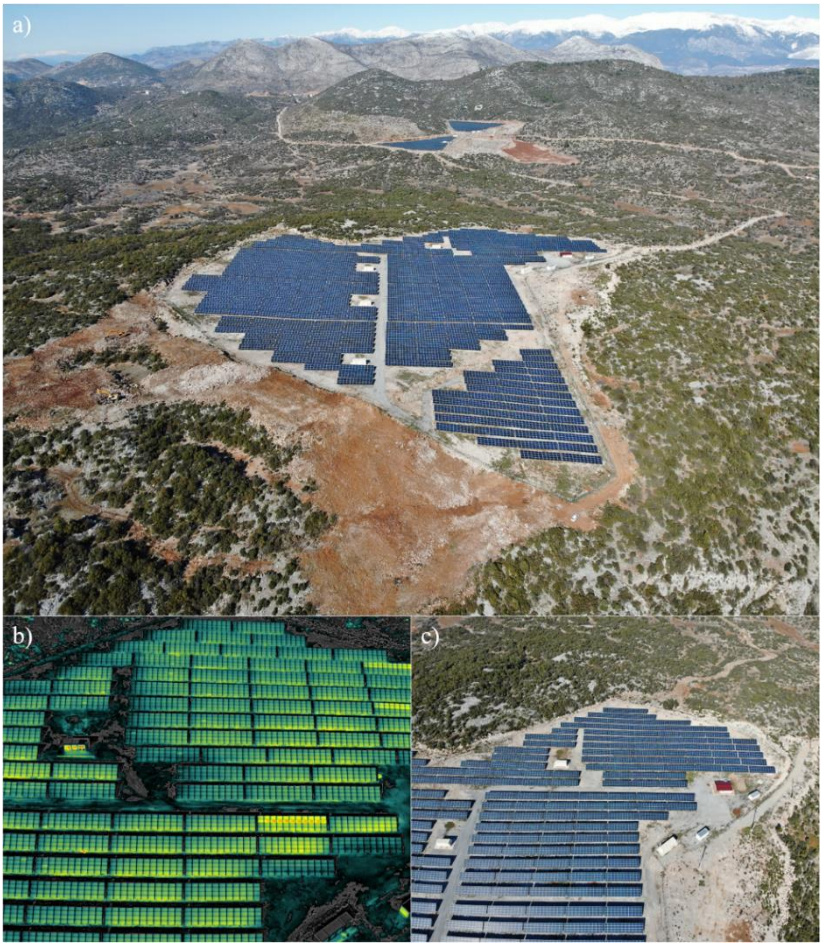

Figure 2. Demonstration of the a) study area, b) thermal aerial image of solar farm and c) optic images of the solar farm.

Table 1. The characteristics of the solar panels on Standard Test Conditions (STC - (25°C temperature 1,000 W/m^2 solar radiation, and 1.5 Air Mass) [22].

Features	Value
Maximum Power	265 Wp
Open circuit voltage	38.1 V
Voltage at maximum power	31 V
Short circuit current	9.2 A
Current at maximum power	8.55 A
Module efficiency	15.9 %
Temperature coefficient	-0.43 %/°C
Weight	18.5 kg

The study aimed to examine the temperature and efficiency of the solar panels during the winter months using a UAV integrated with a thermal camera to perform photogrammetric flights. The UAV flight was carried out to investigate the efficiency of solar farms on February 11, 2023. The multirotor UAV employed in the study, a DJI Matrice 300 RTK, is equipped with an advanced DJI Zenmuse H20T camera (featuring both optical and thermal sensors) and a Real-Time Kinematic (RTK) positioning system, which were utilized to measure the temperatures of the solar panels. The thermal camera is capable of providing thermal images with a resolution of 640x512 pixels, and temperature ranges from -40 to 150 °C in thermal imaging [23]. During UAV flights for thermal imaging, aerial photos were taken parallel to the flight plan. In this context, the recommended overlap ratios are a minimum front overlap 70% and a side overlap of 20% for thermal photogrammetric flight [24]. Thermal aerial photos were captured in R-JPG format with UAV photogrammetric flights at an altitude of 50 m with a 90 % overlap rate and RTK in this study. Thermal photos in R-JPG format cannot be directly used in photogrammetric data production processes. Thermal aerial photos had temperature values and which these values were transformed into reflection values to produce orthomosaic. Thermal data production processes proceed similarly to optical imaging processes. After the format conversion of thermal images in R-JPG format, the photos are integrated to software and alignment process is started. Features are matched to generate point clouds and then thermal orthomosaic data are produced similarly optic imaging process. Thermal photos whose value type has been changed can be used in the data production stage by converting the image format to TIFF format. Transformed thermal aerial photos were integrated to photogrammetric software to produce 2D and 3D data. The SfM (Structure from Motion) method was carried out to process thermal aerial photos and thermal orthomosaic were produced to examine the efficiency analysis on solar panels (Figure 3). When examining the thermal orthomosaic, it was observed that the temperature ranged from -17.1 to 97.9 °C. Moreover, the hottest area was in the solar panels at the center of the solar farm. The north and south of the solar farm were colder compared to other directions. It was also observed that the colder areas were generally the shaded areas underneath the panels.

The temperature and efficiency values of the solar panels were determined using thermal orthomosaic. Thermal orthomosaic of the solar farm is shown in Figure 3. Since the topography of the solar farm area does not have a symmetrical shape, the solar panels in the center of the solar farm were selected based on their alignment to achieve symmetry and conduct a regional study. It was observed that solar panel temperatures were warmer in the lines at the center of the solar farm, with maximum temperatures reaching up to 97.6 °C. Additionally, the northern part of the solar farm was cooler compared to the southern part, and when DEM data was examined, the northern region had higher elevation than the southern region.

The aspect, or the direction a solar panel faces, significantly affects its performance. Solar panels oriented towards the equator generally receive maximum sunlight intensity and duration throughout the day, optimizing energy production. For instance, in the Northern Hemisphere, panels facing south tend to generate more electricity compared to those facing other directions [25]. Moreover, the topography of the land on which a solar farm is situated can introduce variations in solar panel efficiency. Aspects and gradients of the terrain influence the incident solar radiation received by the panels [26]. Therefore, understanding the interplay between geographic orientation, topographic features, and panel performance is critical for the efficient design and operation of solar farms. Integrating UAV-based thermal imaging with traditional efficiency analysis methods offers a comprehensive approach to studying the impact of geographic orientation of the underlying topography on the performance of solar panels. In the study, to conduct regional temperature and efficiency analyses at the solar farm, panels from different aspects were selected, and their boundaries were digitized. In this context, panels from eight different directions were chosen, which were north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), and northwest (NW). The locations of the panels are also shown in Figure 3. In the solar farm, each solar panel array consists of four columns of solar panels. In the study, for each direction, the second row of solar panels from the top was selected from the outermost column, and their temperature and efficiency values were analyzed. In the selected area of the solar farm, the topographic variations range between 4 and 8 meters, and the aspect of the solar panels is consistent in the same direction. The solar panels were positioned facing the equator, specifically oriented towards the south. Therefore, the study focused on examining the temperature and efficiency of solar panels based on their geographic orientation in a solar farm with similar topographic and aspect characteristics.

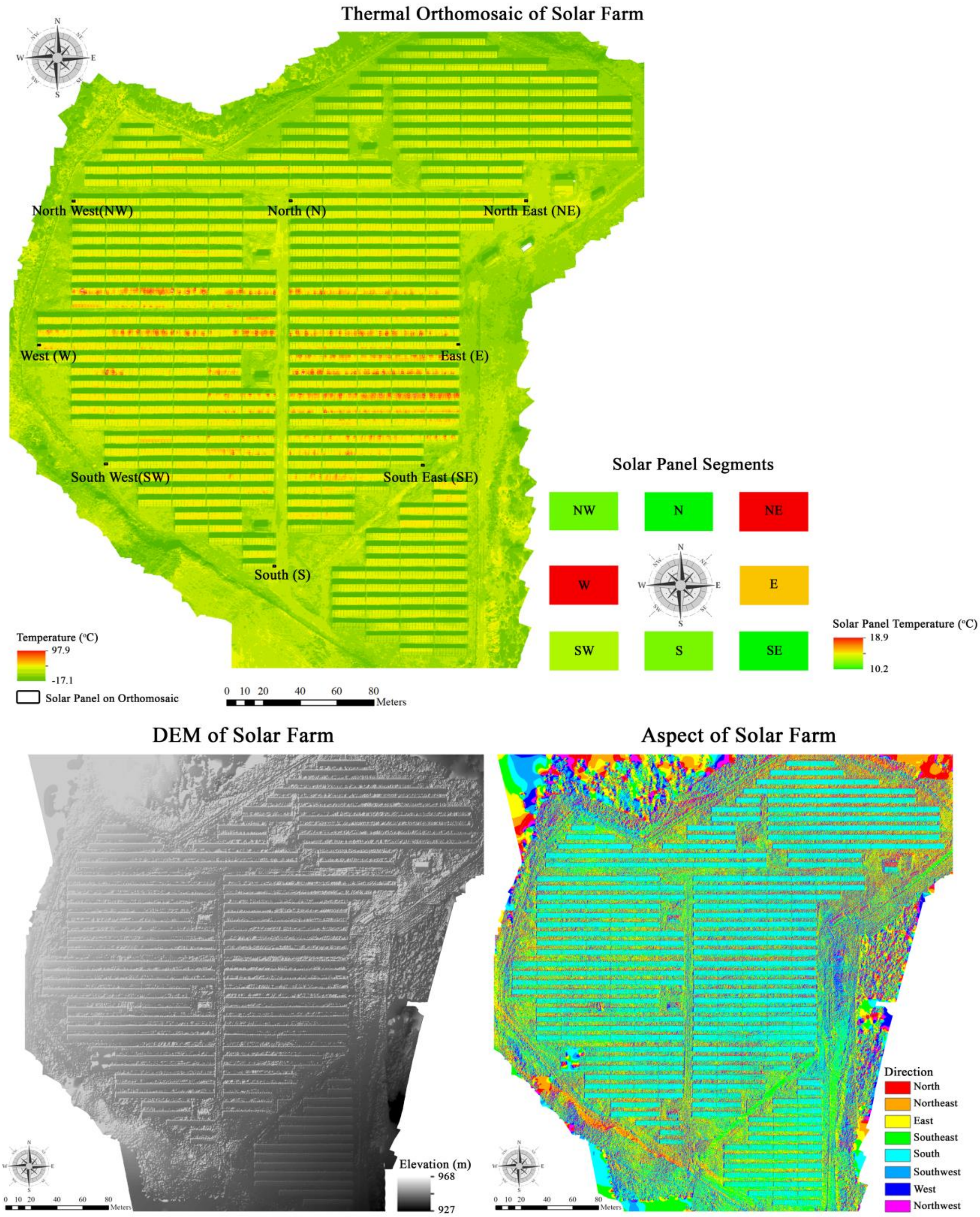

Figure 3. UAV-based data (orthomosaic, DSM, aspect) for solar farm and selected panel temperatures in different directions.

The instantaneous efficiencies of solar panels were determined by detecting panel temperatures. Temperature-based efficiency analyses were performed for selected panels. In this context, the efficiency of the solar panels was determined using the reflectance values, which included the average thermal values from the thermal orthomosaic. Taking into account STC, it is possible to calculate the instantaneous working PV efficiency of solar panels based on their instantaneous temperatures and panel efficiency values [27]. Table 2 shows the formulation and values related to temperature and PV efficiency within the scope of calculations. Efficiency analyses were conducted for the 8 selected solar panels based on the manufacturer's information.

Table 2. PV efficiency formula [27].

Features	Statement
n_{ref}	Efficiency at the reference temperature
n_c	Panel efficiency
T_{ref}	Reference temperature at 1,000 W/m^2 solar radiation
T_c	Panel temperature
B_{ref}	Temperature coefficient of the panel
PV efficiency formula	$n_c = n_{ref}\,[1 - B_{ref}(T_c - T_{ref})]$

3. Results

In efficiency analysis of solar farms, terrestrial temperature measurements and efficiency analyses take a long time, while UAV mapping provides a fast solution for solar farms. In this context, UAV flights can be conducted at any time of day, allowing temperature detection with a single orthomosaic. The temperatures of the solar panels selected in 8 different directions were measured using the orthomosaic for solar farm. For each panel, minimum, maximum, and average temperature values were measured. The average panel temperatures were used for panel efficiency analysis. Upon examining the temperatures, the maximum temperature ranges from 11.7 to 24.4°C, while the minimum temperature ranges from 1.9 to 11.7°C. The maximum temperature of 24.4 °C is in the W panel, while the minimum temperature of 1.9°C is in the SE panel. The average temperatures of the panels range from 10.2 to 18.9°C. It was observed that the panel in the NE has the highest average temperature. The panel in the west, which had the highest at maximum temperature, also had an average temperature of 18.8°C.

When comparing panels in the same direction, the average temperature difference between NE and NW, which had similar latitude values, was the highest at 5.6°C. The lowest average temperature difference was 2.5°C between E and W. In this context, when examining the temperatures of panels at the same longitude, the highest average temperature difference was 8.7°C between NE and SE. The lowest average temperature difference was 1.1°C between NW and SW. There was a 1.2°C difference between S and N.

In order to calculate the efficiency of panels regarding temperature, the efficiency and temperature coefficient of the panels, along with the average panel temperatures were used to calculate the efficiencies of panels in different directions in February. In Figure 4, temperature and efficiency values for each panel can be seen. The efficiency calculations for the panels resulted in very close values, ranging from 16.3 to 16.9%. The highest efficiency was 16.9% in the SE, while the lowest was 16.3% in the NE. The efficiency difference between NE and SE, where the temperature difference was the highest, was 0.6%. It has been observed that the efficiency difference between the S and NW panels, which had a 0.2°C difference in temperature values, was 0.01%. Except for the NE panel, it had been observed that the efficiency of panels increases from west to east (from SW to S and from S to SE; from NW to N; from W to E). Also, the efficiency difference between N and W was 1%. As a result, the panel with the lowest temperature exhibits the highest efficiency. Additionally, it has been observed that the temperatures and efficiencies of solar panels in different directions vary, but despite the significant temperature differences, the efficiency differences were not very high. Panels in the SE region exhibited the highest efficiency, while those in the NE showed the lowest efficiency. The temperature differences were more pronounced than the efficiency differences, indicating that other factors, such as panel quality and installation, also play a role in determining efficiency. For the analysis of temperature and efficiency values and their variations using boxplot analyses, the variability of the values was low, and no outliers were detected. The median of the temperature values was close to the lower values, whereas the median of the efficiency values was close to the higher values. It was observed that there was an extremely low value in the temperature data, and the other values were close to the maximum da value. In the efficiency data, the values were concentrated towards the minimum data value.

Solar panel efficiency fluctuates with temperature changes throughout the day and can be impacted by weather factors such as cloud cover, fog, dust, and others. When the meteorological report for Antalya Airport for the day and time of the flight was examined, it was observed that the air temperature was 13°C, wind speed was 14.8 km/h, and the sky was clear with visibility exceeding 10 km [28]. Therefore, there was no cloud cover during the flight that would affect panel temperature, and the panels were mapped under similar weather conditions. It has been observed that panel temperatures and efficiencies vary directly based on their geographical orientations.

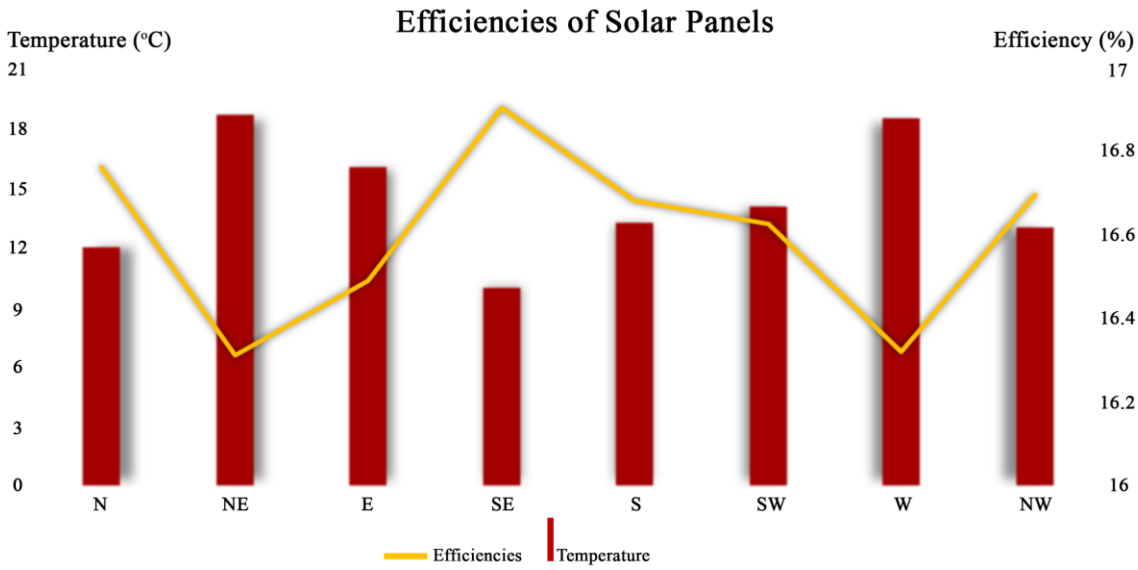

Figure 4. Efficiency and temperature values of solar panels.

4. Discussion and conclusion

The integration of UAVs with thermal imaging technology provides a powerful tool for the rapid assessment of solar panel performance in PV systems. By capturing high-resolution thermal images and creating thermal orthomosaic maps, it is possible to identify temperature variations and facilitate the efficient calculation of panel efficiencies. This approach not only enhances the monitoring and maintenance of solar farms but also contributes to the optimization of solar energy production. The study focused on using UAVs for swift and effective evaluation of solar farm energy efficiency. These UAVs gathered high-resolution thermal data for assessing the solar farm's performance. This research demonstrates the suitability of UAVs for solar farm monitoring and their utility in efficiency calculations. Analyzing high-resolution UAV-based data revealed rapid insights into solar farm efficiency. Regional variations in panel temperatures were observed to exhibit significant fluctuations at extreme temperatures, yet their energy efficiencies were found to be less than 1%. However, due to the absence of meteorological events (cloud, fog, dust etc.) in the study area, a direct relationship between temperature and efficiency has been established. The analysis revealed that while temperatures varied significantly across different geographic regions, the efficiencies of the solar panels were relatively similar during the winter months. In the winter months, it has been observed that the temperatures of solar panels vary regionally, yet the panel efficiencies are above the manufacturer's efficiency values and there are no issues with energy production. Despite the panels being at different topographic elevations, it has been found that the topography does not significantly affect their temperatures. Since the solar panels face south, it can be inferred that their temperatures differ due to their positions within the farm.

The study demonstrates that temperatures and efficiencies in different directions within solar farms can be rapidly calculated using UAVs, also suggesting the possibility of examining the topographic characteristic of these solar farms. It is considered that topographic factors such as the slope angle and aspect of the solar farm can also affect panel temperatures and efficiencies. Additionally, it is hypothesized that regions with diverse topographic features could exhibit variations in both the temperature and efficiency of the panels. Therefore, it is proposed that the imagery obtained during UAV thermal imaging studies and the generated DSM data should be incorporated into efficiency analyses.

UAVs can provide significant advantages in monitoring solar farms through thermal imaging. Specifically, to offer a quick solution in terms of time and cost where human resources may be insufficient, thermal imaging with UAVs will be advantageous. Utilizing a single thermal orthomosaic instead of multiple thermal aerial photos for temperature and efficiency calculations will enable institutions and organizations to take rapid actions. Furthermore, this integrated approach facilitates quick actions and decision-making by institutions and organizations involved in solar energy management and control. It is possible to identify damaged or less energy-producing panels and detect issues in the panels by monitoring efficiency and temperatures with drones on an hourly or daily basis. With these hourly or daily detections, operators can ensure their earnings increase or remain stable without any decrease. By leveraging UAV technology and thermal imaging, it becomes possible to enhance the utilization and management of solar energy as a sustainable and renewable energy source.

In conclusion, renewable energy has gained importance nowadays; therefore, the efficiency and control of the produced energy are also crucial. In this context, UAV-based monitoring will increase in controlling efficiency losses in clean energy production. With the analysis of fast and high-temporal resolution data, the control of clean energy will also be improved. The integration of UAVs with thermal imaging technology presents a promising avenue for improving temperature and efficiency calculations in solar panel systems. This innovative approach contributes to the advancement of solar energy technology and its widespread adoption in renewable energy applications. Renewable energy has gained importance nowadays; therefore, the efficiency and control of the produced energy are also crucial. In this context, UAV-based monitoring will increase in controlling efficiency losses in clean energy production. With the analysis of fast and high-temporal resolution data, the control of clean energy will also be improved. It is anticipated that with machine learning and artificial intelligence, the autonomy level of drone flights and the processing speeds of image analysis will increase, enabling independent controls without human intervention.

Acknowledgement

We would like to thank the Earth3Bee Lab -3D Earth Modeling Laboratory for acquiring thermal aerial photos and processing of the data.

Funding

This research received no external funding.

Author contributions

Semih Sami Akay: Conceptualization, Methodology, Software, Writing-Original draft preparation, Visualization
Orkan Özcan: Data curation, Software, Validation, Investigation, Writing-Reviewing and Editing.
Okan Özcan: Investigation, Writing-Reviewing and Editing.
Ömer Yetemen: Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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