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A Measurement Framework for Assessing Temperature and Power Output on Biosolar Roof Systems

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Abstract

Biosolar roofs, which combine photovoltaic (PV) panels with green roof, offer a way to connect renewable energy generation with benefits such as reduced surface temperatures and improved urban microclimates. Despite growing interest, practical field data from Central Europe remain limited. This study introduces a measurement strategy developed at the Faculty of Civil Engineering, TUKE, to evaluate thermal and electrical behavior of systems. The setup includes two identical PV panels with the same orientation and tilt-one installed above a sedum green roof and the other above an asphalt roof. Temperature sensors placed on the panel surfaces, beneath the modules, and on both roof types record thermal conditions, while weather data are collected from a nearby station. Electrical performance is monitored through periodic I–V curve measurements using a portable tester. The methodology provides a consistent basis for comparing roof types and supports future simulation and BIM-based modeling in temperate climates.

Keywords: green roof, vegetation, solar panel, photovoltaic panel, energy efficiency

1 Introduction

Biosolar roof systems, which integrate photovoltaic (PV) panels with vegetated roof layers, have recently gained attention as an effective strategy for combining renewable electricity generation with environmental benefits in urban areas. In addition to producing energy, these hybrid systems help mitigate heat stress on buildings by moderating rooftop temperatures and improving the microclimate above the roof surface [1]. Numerous studies have documented that vegetation can lower roof surface temperatures and reduce the thermal load experienced by PV modules, which in turn supports higher electrical efficiency [2,3]. This cooling effect results from several mechanisms: vegetation increases surface reflectivity, plants release moisture through evapotranspiration, and a ventilated air layer can form beneath the panels, enhancing convective heat removal. Together, these processes contribute to decreasing the operating temperature of PV modules, particularly on their rear surfaces, where heat accumulation is most significant [4,5]. The magnitude of these benefits, however, varies widely across published research. Factors such as regional climate, plant species, substrate thickness, and the geometry of PV installation, including mounting height and tilt angle, play a major role in determining system performance. Some studies report noticeable gains in electrical output, while others observe far smaller improvements, often tied to site-specific weather patterns or roof design characteristics [6,7,8]. Recent field investigations have explored these variations in detail. For example, a large biosolar installation in Barangaroo, Sydney, demonstrated a 3–4% improvement in PV energy yield compared with a conventional roof surface [1]. Experimental and modeling studies in Delft similarly concluded that vegetation characteristics and installation geometry strongly influence the cooling potential through evapotranspiration and shading interactions [6]. Additionally, measurements reported by Alshayeb et al. [9] confirmed that PV modules situated above vegetated roofs operate several degrees cooler than those above dark roof membranes, which can result in improved electrical performance during high-temperature summer periods. Despite the growing amount of international research, there remains a clear demand for standardized and reproducible experimental procedures that allow for meaningful comparison of biosolar systems installed in different environments. Key components of such a methodology include parallel measurements on two identical PV modules positioned above contrasting roof surfaces (e.g., vegetation vs. asphalt), continuous monitoring of surface and rear-side temperatures, and integration of meteorological variables such as solar radiation, air temperature, and wind speed [10,11]. To complement the thermal data, electrical performance should be characterized through I–V curve measurements and other output parameters, collected simultaneously with climatic data to reveal the relationship between temperature fluctuations and energy production [12]. Numerical tools such as EnergyPlus or DesignBuilder can then build upon these measurements, enabling simulation studies that test alternative vegetation types, panel configurations, or roof structures. Coupling such simulations with Building Information Modeling (BIM) can further support the design and planning of future biosolar roof applications [13]. In the context of Central Europe - where significant seasonal temperature differences and variable weather conditions are typical - there is still a limited number of field experiments providing high-quality datasets for this type of research. The present study addresses this gap by introducing a detailed experimental setup designed to evaluate the thermal and electrical behavior of two identical PV panels, one mounted above a sedum green roof and the other above an asphalt surface. The methodology includes a description of sensor placement, data acquisition strategy, measurement frequency, and procedures for capturing I–V characteristics. The collected dataset will be used to compare the performance of both systems and will serve as a foundation for future simulation work and the development of BIM-based predictive models [13,14,15,16]. This paper therefore focuses on outlining the full experimental methodology created for evaluating biosolar roof performance under Central European climatic conditions. The following sections describe the arrangement of the test panels, the placement and function of temperature sensors, and the integration of meteorological and electrical measurements. The aim is to offer a clear, replicable procedure for data collection and analysis that supports further research on the thermal and electrical characteristics of biosolar roofs.

2 Methods

This chapter presents the methodological approach developed for assessing both the thermal behavior and electrical output of photovoltaic panels installed over two contrasting roof types: an extensive green roof planted with Sedum species and a traditional asphalt roofing membrane.

The objective of the experiment is to enable a reliable comparison of these configurations under real outdoor conditions characteristic of the Central European climate. The sections that follow provide a detailed description of the experimental site and its environmental setting, the layout and operating parameters of the photovoltaic installation, and the measurement equipment selected for monitoring temperature and electrical characteristics. In addition, the procedures for collecting, organizing, and evaluating the recorded data are explained. Finally, the chapter outlines how the obtained measurements are intended to be incorporated into numerical simulations and Building Information Modeling (BIM) workflows for further analytical and design-oriented applications.

2.1 Experimental site

The experimental campaign is designed to take place on the roof of the main campus building of the Technical University of Košice in eastern Slovakia. This region experiences a temperate continental climate, marked by relatively warm summers—often reaching average daytime temperatures of about 28 °C—and cold winter periods, during which temperatures can drop below –5 °C. The university building features a recently implemented extensive green roof, planted predominantly with Sedum species. This vegetation layer, established within a lightweight growing medium, represents a typical Central European green roof system known for its low maintenance requirements and resilience to drought. It provides an ideal real-world setting for observing thermal effects and microclimatic interactions associated with vegetated roofs. Directly next to the green roof section, part of the same rooftop remains finished with a conventional bitumen/asphalt waterproofing layer. The close proximity of the vegetated and non-vegetated zones allows for direct side-by-side comparison of the two surface types under identical environmental conditions. The configuration of this rooftop environment is illustrated in Figure 1.

Figure 1: View of the main TUKE building rooftop, illustrating the adjacent green-roof section and the asphalt-covered surface

For reference, meteorological data were collected from a nearby weather station located about 200 meters from the testing area, operated by the university. Its close location guarantees that the recorded climate parameters accurately reflect the conditions on the rooftop throughout the monitoring period.

2.2 Experimental setup

To assess how the type of roof surface affects photovoltaic (PV) performance, two identical 260 Wp polycrystalline PV panels were installed side by side on the roof. One panel was placed above the green roof (Sedum vegetation), while the other was mounted over an asphalt surface. Both panels, depicted in Figure 2, face south and are tilted at an identical angle of 26° to ensure similar exposure to solar radiation. Each panel is supported by a specially designed frame providing mechanical stability and uniform geometry. The first frame is entirely made of aluminium, whereas the second combines aluminium with wooden supports to compensate for missing parts. Both setups maintain adequate spacing between the panels and the roof to allow natural airflow. Temperature and electrical output measurements are scheduled to be recorded following installation.

Figure 2: Installed PV panels

The setup of the experiment was arranged to allow simultaneous monitoring of environmental and electrical parameters for both systems under the same weather conditions.

2.3 Thermal monitoring setup

A total of eight temperature sensors were deployed to monitor the thermal behavior of the photovoltaic modules and their supporting roof surfaces:

- Two sensors were installed on the rear side of each PV panel - one at the top and one at the bottom. A schematic representation of the sensor arrangement is shown in Figures 3 and 4.
- Two sensors were positioned directly on the roof surface beneath the panels (one beneath the green roof and one beneath the asphalt roof), while the remaining two sensors were placed on exposed roof areas under direct sunlight.
- Small PT1000 thermocouples with a narrow diameter were used as sensors, fixed in place with heat-resistant reflective aluminum tape. This approach reduced direct solar heating of the sensors and maintained strong attachment even at high roof temperatures.

a) b)

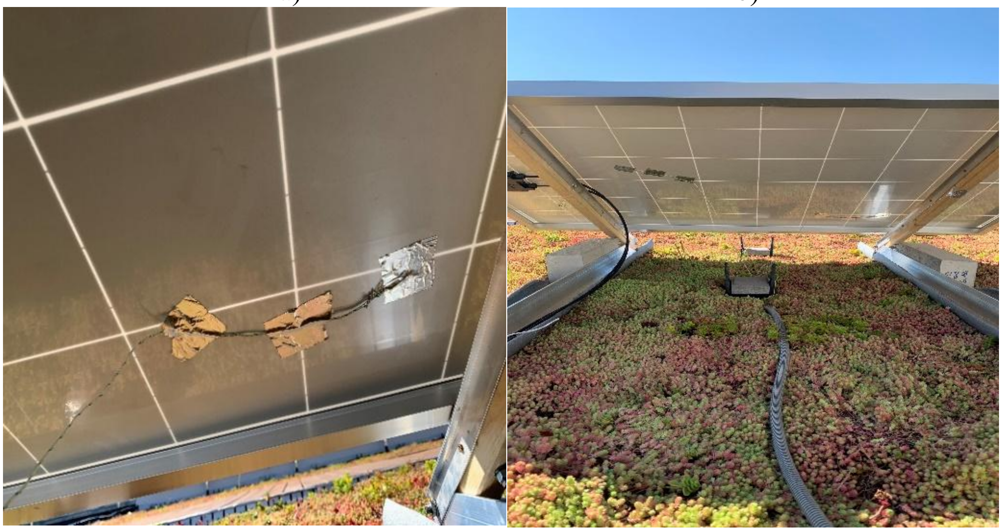

Figure 3 a): Close-up of the temperature sensors mounted on the back of the PV panel
Figure 4 b): Rear view of the PV panel illustrating the positions of the temperature sensors and the underlying roof surface

The temperature monitoring setup employed an ALMEMO 500 data acquisition system (Ahlborn), illustrated in Figure 5, which enables simultaneous recording from multiple channels with high precision. The unit is prepared for continuous operation throughout the measurement and set to log values every five minutes. Captured data can be transmitted wirelessly to a tablet interface or exported in CSV format for further analysis. Routine calibration and inspections are planned to guarantee accurate sensor performance over time.

Figure 5: ALMEMO 500 device employed for recording temperature data

2.4 Assessment of photovoltaic module electrical output

To evaluate the electrical characteristics of the PV modules, a portable I-V tracing instrument, the EKO MP-11 Checker (Figure 6), will be used. This device records the full current-voltage response of each panel and determines essential electrical metrics, such as:

- Isc – the current under short-circuit conditions,
- Voc – the voltage when the circuit is open,
- Imp and Vmp – the current and voltage at the point of maximum power,
- Pmax – the highest power the module can deliver.

Due to the availability of only one measuring instrument, data collection will alternate between the two panels, with connections manually switched by the operator. The transitions are planned to be very brief (typically 1–2 minutes) to reduce the influence of varying sunlight on the measurements. All recorded datasets are stored internally within the tracer and can later be transferred via USB to a computer. Analysis will be performed using the MP-11 software, which allows plotting of I-V curves, extraction of key parameters, and exporting data in text or CSV formats for further evaluation.

Figure 6: EKO MP-11 device employed to measure the electrical performance of photovoltaic modules

The I-V characteristics will be recorded multiple times daily - during morning, noon, and afternoon - under varying sunlight levels to evaluate how solar radiation and temperature influence the efficiency of the panels.

2.5 Meteorological data

The local rooftop meteorological station at TUKE will be used to continuously track environmental conditions. The parameters measured include:

- Total solar irradiance [W/m²],
- Air temperature [°C],
- Relative humidity [%],
- Wind speed and direction [m/s, °].

Recorded data will be stored on the station's internal memory and periodically retrieved using software AMR WinControl. Time alignment between the meteorological readings and temperature sensor data will be verified to ensure precise correlation between environmental factors and PV performance measurements. These atmospheric variables are crucial for assessing how solar radiation and ambient conditions affect both the temperature of the PV modules and their energy output.

2.6 Data analysis and integration

All collected datasets—including temperature, I–V, and meteorological measurements—will be analyzed using Excel. The analysis aims to uncover relationships among:

- PV module surface temperature,
- Ambient air temperature,
- Solar irradiance,
- Electrical outputs (Isc, Pmax, Voc).

The analyzed datasets will be employed to produce time-series charts, diagrams highlighting temperature variations, and correlation tables for each measurement interval. In addition, the data will serve as input for simulation software such as DesignBuilder, supporting the development of a BIM-compatible model. This modeling framework allows forecasting the behavior of the biosolar roof under different environmental conditions and design scenarios. The approach is designed to be transparent and reproducible, enabling other researchers to replicate the experiments and verify simulation outcomes with actual measurement data.

2.7 Overview of measurement equipment

Table 1 shows a comprehensive overview of all equipment utilized in this research, detailing their key capabilities and technical specifications. The instruments together form an organized system designed to capture thermal, electrical, and meteorological parameters associated with the PV modules under study. Devices were carefully chosen to ensure full compatibility and synchronized recording of measurements. The ALMEMO 500 functions as the main hub for collecting temperature data, whereas the EKO MP-11 I-V Checker measures the electrical performance of the panels. Meanwhile, the rooftop weather station adds real-time environmental context by providing data on solar irradiance, ambient temperature, relative humidity, and wind conditions. This summary illustrates the interconnected arrangement of the measurement setup, ensuring precise, reliable, and continuous data acquisition throughout the observation period.

Table 1: Summary of measurement equipment

Device	**Function**	**Measurement rate**	**Recorded parameters**
Photovoltaic panels	Power output	–	Voltage and current metrics
ALMEMO 500	Thermal data record	5 min intervals	Surface temperatures

EKO MP-11	I-V characteristic	3x per day	Voc, Isc, Imp, Pmax, Vmp
Meteorological Station	Meteo. data	recorded (1–5 min) intervals	Temp. Irradiance, Wind
Software	Data processing	–	DesignBuilder, Excel
Device	Function	Measurement Rate	Recorded Parameters

3 Measurement workflow overview

For clarity, Figure 7 summarizes the overall workflow of the measurement. The methodology follows five sequential steps:

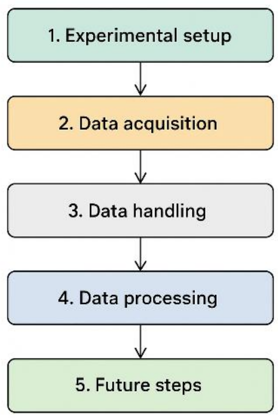

Figure 7: Simplified flowchart of the study's measurement process

1. Experimental setup.
The physical configuration of sensors and measurement points will be established as described in the previous sections.

2. Data acquisition.
Temperature data will be continuously recorded at a fixed logging interval, together with meteorological data from the nearby station.

3. Data handling.
Collected datasets will be transferred, organized, and checked for completeness and timestamp consistency. Incorrect or missing values will be removed.

4. Data processing.
Validated data will be aggregated and analyzed to identify thermal patterns and differences between the monitored roof systems.

5. Future steps.

Long-term monitoring and integration of electrical performance measurements will follow to enable a more comprehensive evaluation of the tested configurations.

4 Results and discussion

The experimental setup described in this work provides a robust framework for conducting an in-depth comparison of the thermal response and electrical performance of photovoltaic modules installed over two distinctly different roof surfaces, while ensuring that both panels operate under identical external conditions. The measurement system - comprising data logger ALMEMO 500, the EKO MP-11 device for I–V curve acquisition, and the nearby rooftop meteorological station - has already been installed and is fully prepared for data collection. Temperature sensors were strategically positioned to capture detailed surface temperature profiles and to clearly distinguish the thermal behavior of the two monitored modules. It is anticipated that the green roof with Sedum vegetation will moderate temperature fluctuations more effectively than the traditional asphalt roof. The most pronounced cooling influence is expected on the rear side of the photovoltaic module, where direct convective heat exchange with the roof substrate occurs. Previous research indicates that vegetated roof systems can reduce operating temperatures and improve panel efficiency; however, the extent of this benefit is influenced by several variables, including solar radiation intensity, wind speed, moisture content within the substrate, and the thermal inertia of the green roof layers. Electrical measurements will be performed using the I–V checker, with stable operating curves expected for both panels. Any differences in performance are likely to become visible during periods of high irradiance. The planned statistical evaluation will aim to quantify the cooling effect provided by the green roof under varying meteorological conditions and to explore the relationships between module temperature and key performance indicators such as Voc, Isc and Pmax.

Beyond the on-site measurements, the recorded dataset will later be incorporated into dynamic energy simulations performed in DesignBuilder. Using real monitoring data as input for numerical models and BIM-based workflows will allow the development of more reliable digital representations of biosolar roof behavior under Central European climate conditions. Such calibrated models will make it possible to estimate long-term energy production, evaluate thermal effects at the roof level, and assess the potential for reducing carbon emissions in urban environments.

The combination of continuous field monitoring with simulation tools therefore provides a comprehensive method for analyzing and refining biosolar roof systems. Future stages of the research will concentrate on extended data collection, verification of simulation accuracy, and sensitivity testing of critical design variables - including the distance between panels, depth of the green roof substrate, and the specific vegetation composition. This stepwise approach is expected to support the optimization of biosolar configurations for practical implementation.

5 Conclusion

This study introduces a practical framework for examining how biosolar roof systems perform when exposed to real outdoor conditions. By integrating measurements of temperature,

electrical output, and local weather variables, the approach allows for a clearer understanding of how green roof vegetation affects the operating temperatures and overall efficiency of photovoltaic modules.
Although detailed data evaluation will follow, the full measurement system has already been installed (Figure 8), tested, and confirmed to operate reliably. This ensures that the ongoing monitoring will generate high-quality information suitable for future simulation tasks and performance optimization. The experimental configuration presented here may also serve as a reference model for other researchers investigating energy-efficient and environmentally oriented roof solutions.

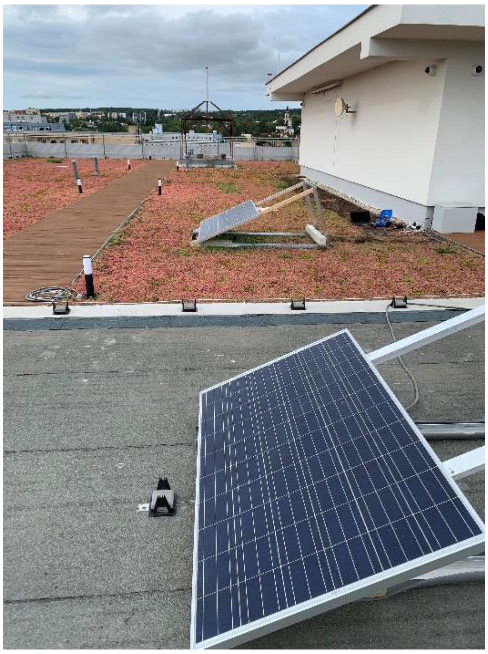

Figure 8: General view of the TUKE rooftop with the two photovoltaic panels installed over the green and asphalt roof sections

Furthermore, the project highlights the growing role of interdisciplinary collaboration at the Faculty of Civil Engineering of the Technical University of Košice—bringing together expertise from building design, renewable energy systems, and digital simulation tools. Continued measurements and upcoming analyses are expected to support practical applications of biosolar roofs in Slovak urban environments and contribute to broader discussions on sustainable building technologies.

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