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STUDY ON THE USE OF DIGITAL TWIN IN ANALYSIS OF PHOTOVOLTAIC SYSTEM

BY

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Abstract. Photovoltaic systems are an efficient and environmentally friendly solution for meeting energy needs in both the industrial and domestic sectors. Implementing a system that monitors early defects and predicts failure based on weather conditions could significantly improve the performance and reliability. This paper indicates the importance of monitoring and parameter simulation (electrical and thermal) that influence the operation mode of photovoltaic (PV) system. It also highlights the benefits of a practical approach to failure management and anticipation events by simulated setup. By integrating the concept of Digital Twin (DT), which consists in creating a digital replica of the PV system in real time, an intelligent decision system could be developed, being capable of identifying and correcting potential problems before they appear.

The analysis of collected data and the integration of weather forecasts allow simulation and testing of different scenarios, thus providing the possibility to make decisions and optimize (PV) system operations. Information retrieved via the Application Programming Interface (API) interface was processed through Python scripts, while data from PV system was collected using specialized sensors.

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Subsequently, all relevant data has been stocked within automated scripts, which then facilitated the creation of a database for integration output parameters from data block of PV created in Simulink. This approach could be a viable solution for optimizing the use of solar energy, helping to reduce costs and environmental impact in both industrial and domestic applications.

The system contains a PV panel, battery management system (BMS), sensors monitoring temperature, pressure, and relative humidity. The data obtained from the practical work have been entered into the simulation, confirming, and validating the experimental stand. Many research on PV systems develop algorithms to monitor and make the system capable of tracking the sun for maximum efficiency. Thus, a comprehensive approach combining monitoring of parameters of PV with external weather data can significantly improve the efficiency, reliability, and durability of a PV system.

Keywords: weather API, thermal degradation, corrosive layout, weather anticipation, prototype stand.

1. Introduction

In Romania, awareness of the importance of renewable energy has increased significantly in recent years.

In recent years, the depletion of non-renewable natural resources has raised alarm bells among the global population. Energy needs continue to increase year on year, so the question of using other renewable natural resources to meet energy demand has been raised. Renewable energy recovers naturally and comes in various forms from nature such as sunlight, wind, tides, geothermal heat, and rain. These energy sources are inexhaustible, unlike fossil fuels. Besides the fact that fossil fuels are exhaustible, they pose another big problem among the population, but also among nature, namely a high degree of pollution. Pollution is the process by which environmental contamination occurs and has consequences on human health, quality of life but also on ecosystems. As a solution to fossil fuel use, researchers have been looking for ways to capture and convert energy from renewable energy sources into electricity (Anamika and Sambit Sahu. 2015).

One of these ways is the PV module for capturing sunlight. Solar energy can be used in two main ways: captured energy can be used as thermal energy, and the second way is to convert solar energy into electricity. The latter way is the most used in industry. The development of solar cell technologies has resulted in the prices for obtaining electricity from solar energy to be competitive with prices for obtaining electricity from fossil fuels (Hullon, 2019; Finan, 2013).

The concept of real-time monitoring and anomaly prediction, whether caused by weather conditions or inefficient installation, enhances operational understanding and minimizes risks, ensuring optimal performance of a PV system.

DT is a concept that is used in different fields. The concept is validated based on hardware and software (Huang *et al*., 2021). The hardware component includes a PV panel with sensors to monitor output parameters. The software component focuses on detecting issues such as aging or defects that may arise over multiple operating cycles.

The software mainly includes the physical module, data algorithm module, DT based module, DT based platform and DT based interaction module (Huang *et al*., 2021).

Calculating data and building models are the basic tasks of DT technology (Xiong *et al*., 2022). This article aims to develop a model for querying weather data and analysing variations that may affect the operation of a PV prototype system.

There are studies that monitor the horizon as a function of time so that the energy coming from PVs is defined as the period between the actual operating time and the forecasted operating time. PV energy generation is strongly influenced by the weather situation. From the perspective of modelling approaches, PV power forecasting techniques can be broadly classified into physical methods, static methods, and artificial neural network (ANN) methods (Zhang *et al*., 2023).

The physical approach aims to build a mathematical model based on the principles of PV energy production. Input variables typically include external weather factors such as solar radiation, temperature, wind speed, cloud cover, humidity, supplied air pressure, and internal parameters of the PV installation, such as installation angle, conversion efficiency, panel release temperature during an operating cycle.

2. Power prediction model topology with Digital Twin

Lei et al. (2023), addresses the fact that DT is a transformative technology, being one of the most studied topics in the field of power electronics and focuses mainly on condition and health monitoring.

Yonce et al. (2023) highlight in their article that DT have gained momentum in both academic research and industrial applications due to their modelling capabilities. DTs are defined as having a physical component, virtual component, and an interconnection between the two components.

The reason for integrating a digital perspective into a PV system depends on the electrical and thermal parameters of the PV system and the climatic zone (Dwivedi *et al*., 2020). An analysis is being performed to help understand the technical requirements. The main datasheet of the PV panel systematically presents the overall degradation. Each panel has an electrical characteristic diagram with measurements showing different energy production levels, providing insights into electrical output parameters. Although the thermal environment might need to be analysed, it should be done from an electrical perspective. The main applications monitor only electrical parameters, lacking environmental data and predictive analysis.

In the paper published by the authors Zhang et al. (2023), an overview of short-term PV power forecasting is presented, along with a systematic prediction for electrical power distribution. The fact that there is an early forecast of the energy that can be generated from PV for a system that is about to be implemented provides an overview of the production and/or implementation costs. The existence of systematic learning programs on solar efficiency from an energy perspective helps developers and consumers understand the basic information needed when electricity produced from renewable sources is to be used.

In the absence of a full-scale PV stand with an entire environmental setup, in this article, a mini-stand setup was developed for configuration and simulation. Therefore, obtaining comprehensive results for a PV system requires a more adapted methodology to accurately analyse its behaviours. Thus, advanced models can be used to simulate the efficiency of the system in different thermal conditions.

This paper proposes the development of a miniature PV system, and the implementation of an analytical model based on real-time measurements.

The model considers various factors that influence the proper functioning of the system, including climatic conditions and system disturbances.

To cover multiple operating cycles at different temperatures, thermal simulations can be performed to evaluate system performance under vast conditions using models in Simulink. By analysing the simulated results, potential problems can be identified and solutions for improvement can be proposed, as well as the development of new concepts in the field of renewable energy.

3. Experimental setup

In Fig. 1, various views of the BoxV1 prototype are presented. Fig. 1 (a) provides a close-up of the main electronics enclosure, which contains multiple printed circuit boards (PCBs) integrated with sensors. Fig. 1 (b) shows a front view of the complete setup, highlighting the deployed solar panels mounted on a supporting frame. In Fig. 1 (c), several red and black wires are visible, connecting the 12V battery to the BMS. The last two images in Fig. 1 (d) and Fig. 1 (e), capture the rear and internal views of the photovoltaic panels, where thermocouple sensors are installed. These views also reveal the internal wiring connecting the ESP32 microcontroller to environmental (temperature, relative humidity, smoke particle, UV index, rain) and electrical sensors (voltage and current).

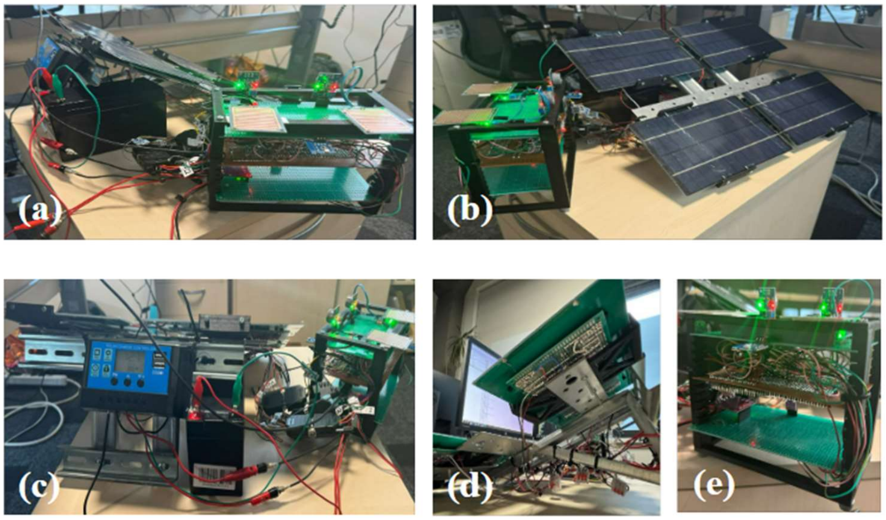

Fig. 1 – Stand prototype with BoxV1. a) Close loop of the main electronics enclosure; b) Front view of PV Setup; c) BMS and battery setup; d) Thermocouple under PV panel; e) Connection between sensors and ESP32.

The experimental bench is equipped with different sensors as described in Table 1.

Table 1
Sensor's utility

Sensor	Environment Monitoring	PV Monitoring	Electrical Monitoring
DS18B20	-	Cels Temperature	-
UV Sensor	UV Index	-	-
Rain sensor	Percentage of rain	-	-
MQ7	CO2 – smoke particle	-	-
MS5611	Temperature & Pressure	-	-
SHT35	-	-	Temperature & Relative Humidity
INA3221	-	-	Battery / PV setup Voltage / Current

The setup consists of four identical PV panels mounted on a fixed metal structure. The parameters of the PV panels are given in Table 2.

Table 2

Specification of the solar panels

Specification	*Value*
Open circuit voltage (V)	*14*
Short circuit current (A)	*0.35*
Maximum power voltage (V)	*17.8*
Maximum power current (A)	*1.2*
Maximum power (W)	*16.8*
Efficiency (%)	*14*
Pmax temperature coefficient (% / °C)	*− 0.24*

In the case of the PV system, data is collected from API every 24 hours, with readings taken four times per hour, resulting in 1,500 data points per day. To meet our requirements, the collected weather data needs to be filtered and organized.

The critical data for the PV system are those collected during periods with direct or indirect solar radiation, amounting to around 800 data points. This data is managed using a Python script and organized into Panda Data Frames, which are two-dimensional, labelled data structures like spreadsheets.

Table 3 presents the parameters that can be gathered via API obtain from Open-Meteo free open-source weather service. The most relevant for our application are: radiation level (G), temperature and relative humidity, which have a direct influence on production estimation.

Table 3

Weather parameters gathered via API

Parameter
Time (min)
Temperature (°C)
Relative Humidity (%)
Apparent Temperature (°C)
G^1 (W/m²)
UV Index

Sensor management is handled by the ESP32 microcontroller, renowned for its low power consumption, which makes it an excellent choice for integration into PV systems. Its versatility and efficiency make the ESP32 especially suitable for embedded applications.

4. Data correlation

Raw sensor values are recorded in a text file every 10 seconds, with approximately 104 values read from the sensors during each interval, resulting in about 37,440 values collected per hour. To comply with the parameter reading interval required by the API, the physically measured data is grouped into 15-minute intervals, each containing approximately 9,360 values.

Under each cell, a group of thermocouples denoted as Matrix 1 (M1) shows the highest temperature fluctuation, compared with M2, M3 and M4. This suggests uneven heating of the PV panels or potential production errors.

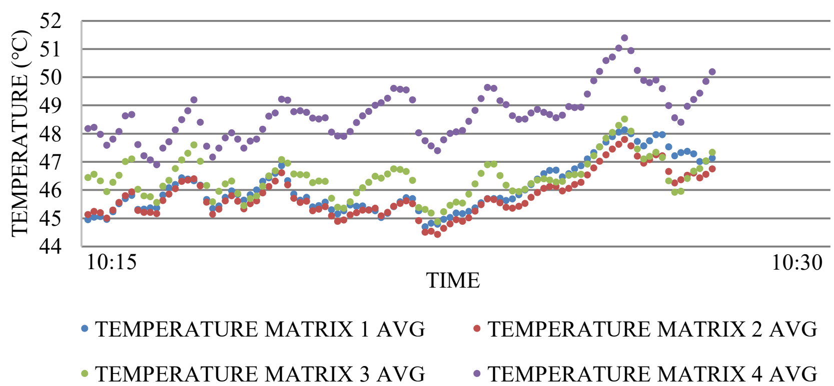

Fig. 2 – Average temperature evolution under each photovoltaic cell.

In order to validate the values obtained from the experimental setup, an alternative method is used — analysing meteorological data collected through the API. It is necessary to verify that this data corresponds to the measurements taken directly from the PV system.

Fig. 3 shows the progression of temperature gathered from the API sources alongside data obtained from the testing bench.

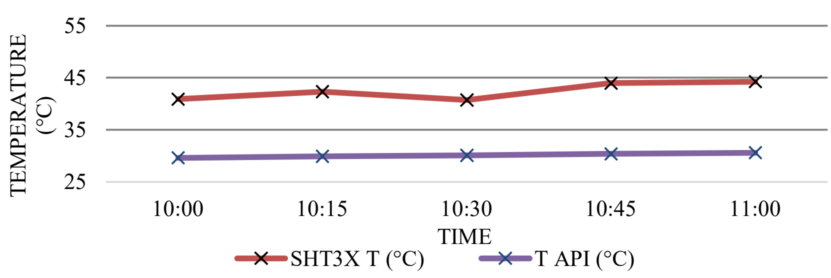

Fig. 3 – Evolution of environmental temperature.

The selection of a weather API in this article is justified by continuous capability to collect real-time data. The optimization of electricity production is heavily impacted by the "quality" of weather conditions, and real-time data collection provides an overall picture of the system's functionality. Mass data collection and filtering generate forecasts regarding energy production potential and provide real-time alerts regarding the amount of electricity produced on less favourable solar radiation days.

5. Digital Twin approach

DT concept allows performing test situations and interpreting output values in digital format. Thus, for the physical system in the practical work a DT is defined, a model realized in Simulink to simulate a perspective of output parameters in function of specific test situations.

Data from physical stand and weather API was filtrated and integrated into Simulink model (Validation block – Fig. 4) to develop a digital replica of PV panels.

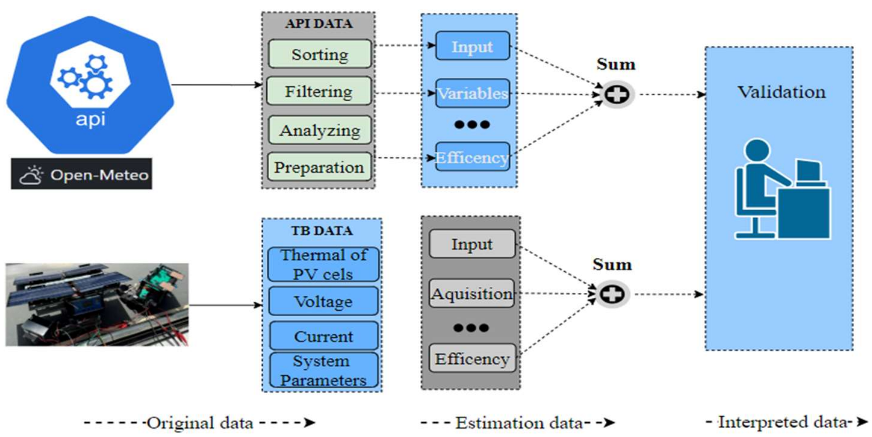

Fig. 4 – PV system electrical output parameters.

After all data is structured and integrated into model, the first simulation setup is ready to run. The model has a low start because it's necessary to configure each parameter from buck block (RLC) and PV block (Ersuel *et al*., 2012).

The calculations were performed systematically to obtain behaviours as close as possible to that of physical implementation. Thus, the values of the simulated output parameters coincided largely with those measured in the practical work.

Figs. 5 and 6 illustrate the voltage and current measurements for each radiation level and temperature impact.

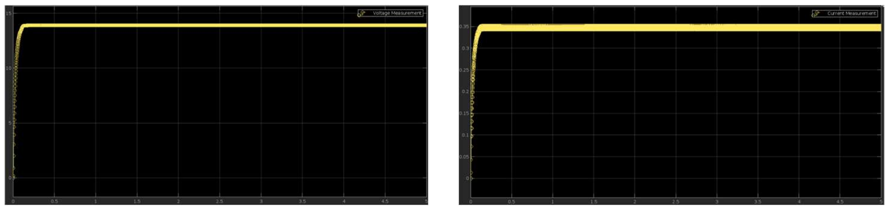

Fig. 5 – Ideal_Radiation level: 1000; Ideal_Temperature: 25°C.

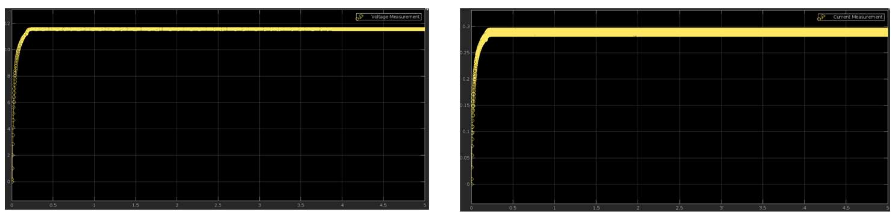

Fig. 6 – Radiation level: 725; Temperature: 52°C.

With this information obtained from the Simulink simulation environment, a prediction of the electrical parameters is performed. The voltage and current estimation can be performed to predict the electricity production of the system.

Other perturbations in the PV system were analysed through current and voltage measurements. Deviations in some cases caused the measurements to return incorrect values. With the simulation setup realized in Simulink, there exists a continuous method to monitor and correct these deviations.

6. Temperature impact on PV panel output

The INA3221 sensor is used to monitor current and voltage, offering a fast and cost-effective solution with I2C communication capability. Fig. 7 illustrates the measured output voltage and current over a one-hour period.

Normal fluctuations caused by variations in solar radiation intensity, temperature, shading, and other atmospheric conditions are evident. Additionally, a transient event is observed, resulting from the intentional disconnection of the battery from the system – highlighted in areas (1) and (2) of Fig. 8 – to test the sensor's sensitivity. Such transient events may be caused by:

- rapid changes in weather conditions;
- technical problems;
- charge/discharge cycles.

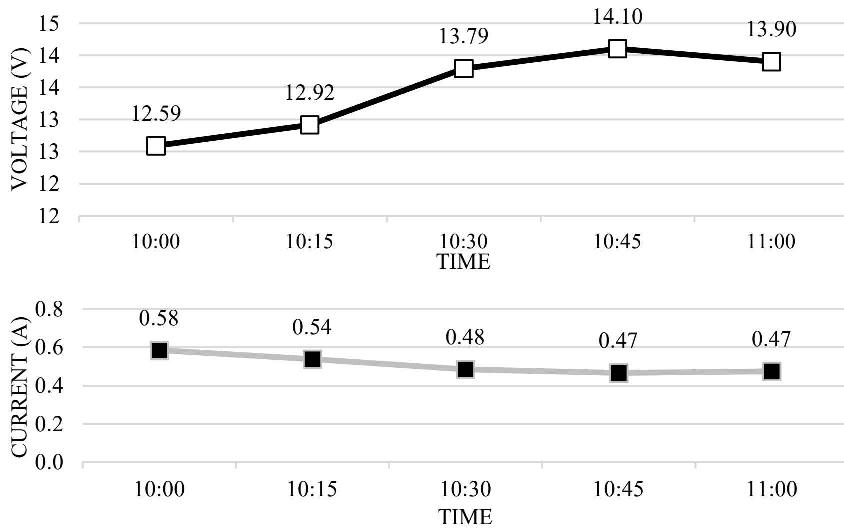

Fig. 7 – Voltage and current monitoring over 1h period.

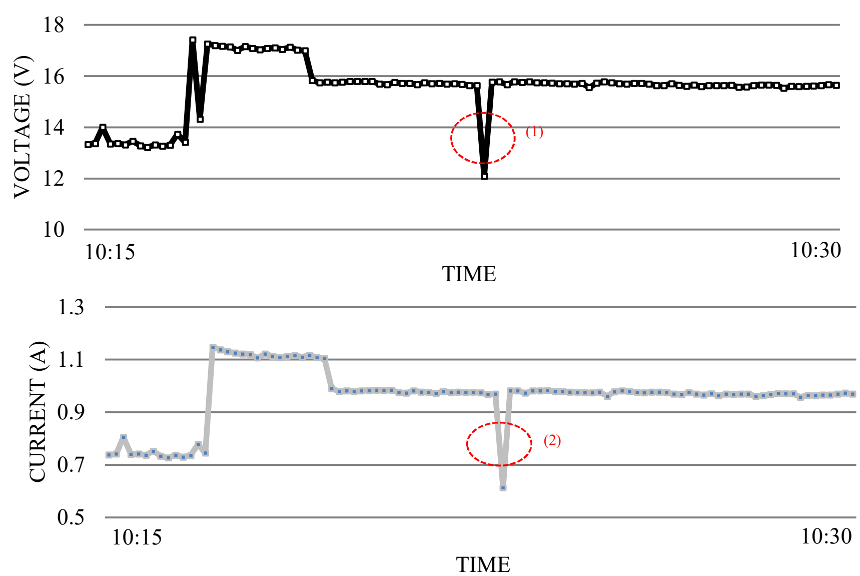

Fig. 8 – Fluctuations in voltage and current during the measurement.

Estimated energy production is highly dependent on weather conditions (Petrovic *et al*., 2014). As shown in Fig. 9, the system generates 105.96 Wh on a sunny day, representing the highest energy output. Under overcast conditions, production decreases to 52.98 Wh or less—approximately half the output of a sunny day. On rainy days, energy generation drops significantly, reaching only 15.89 Wh. These values were obtained using the Simulink environment and represent theoretical estimates. In a real-world scenario, actual energy production may vary due to additional influencing factors. This simulation serves as an initial attempt to approximate energy consumption under different weather condition.

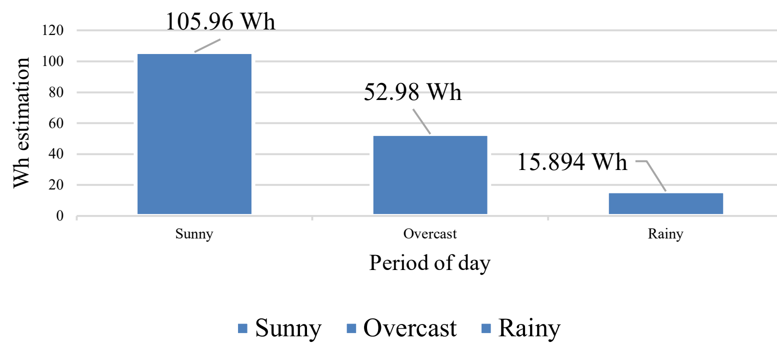

Fig. 9 – Estimate energy production.

7. Conclusion and Future Work

The study focuses on monitoring data and presenting a validate method which integrates into model in Simulink. Predictions about the electricity production can be made by tracking the parameters that contribute to aging and observing disturbances in a system realized in miniature.

The state of the art in this paper refers to the interconnected relationship between the Simulink model, the API weather-model and continuous learning using simulated scenarios. This model in the paper performs the role of a DT, realized to validate a prototype stand of PV panels. In complement, it provides an energy efficiency forecast and realizes a real-time database that can be accessed at any time to validate study concepts.

Thus, depending on the weather conditions and operating parameters of the PV system, having access to the database a dynamic monitoring of the performance is performed.

Although the method showed promise, it remains experimental, as it introduces several variables (solar angles, radiation, temperature) that could introduce uncertainties. Additional validation and refinement of the correction factors are needed to improve accuracy further.

Using meteorological data from multiple sources, such as satellite observations or alternative solar APIs, can significantly improve the accuracy of solar radiation estimates by reducing errors caused by local environmental variability. This multi-source approach ensures a more robust input for power prediction models.

Furthermore, applying the methodology to different types of photovoltaic systems across various geographic locations would provide a broader validation and demonstrate its adaptability. Incorporating a real-time adaptive correction mechanism that continuously updates the power estimates in response to environmental fluctuations would further enhance the system's precision and responsiveness under dynamic weather conditions

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STUDIU PRIVIND UTILIZAREA GEMENILOR DIGITALI ÎN ANALIZA SISTEMULUI FOTOVOLTAIC

(Rezumat)

Sistemele fotovoltaice reprezintă o soluție eficientă și ecologică pentru satisfacerea nevoilor energetice atât în sectorul industrial, cât și în cel casnic. Implementarea unui sistem care monitorizează defectele timpurii și prezice defecțiunile pe baza condițiilor meteorologice ar putea îmbunătăți semnificativ performanța și fiabilitatea. Această lucrare indică importanța monitorizării și simulării parametrilor (electrici și termici) care influențează modul de funcționare a sistemului fotovoltaic. De asemenea, subliniază beneficiile unei abordări practice a gestionării defecțiunilor și a evenimentelor de anticipare prin configurare simulată. Prin integrarea conceptului de DT, care constă în crearea unei replici digitale a sistemului fotovoltaic în timp real, ar putea fi dezvoltat un sistem inteligent de decizie, capabil să identifice și să corecteze potențialele probleme înainte ca acestea să apară.

Analiza datelor colectate și integrarea prognozelor meteo permit simularea și testarea diferitelor scenarii, oferind astfel posibilitatea de a lua decizii și de a optimiza operațiunile sistemului fotovoltaic. Informațiile preluate prin interfața API au fost procesate prin scripturi Python, în timp ce datele din sistemul fotovoltaic au fost colectate folosind senzori specializați. Ulterior, toate datele relevante au fost stocate în scripturi automate, ceea ce a facilitat apoi crearea unei baze de date pentru integrarea parametrilor de ieșire din blocul de date al PV creat în Simulink. Această abordare ar putea fi o soluție viabilă pentru optimizarea utilizării energiei solare, contribuind la reducerea costurilor și a impactului asupra mediului atât în aplicațiile industriale, cât și în cele casnice.

Sistemul conține un panou fotovoltaic, BMS, senzori care monitorizează temperatura, presiunea și umiditatea relativă. Datele obținute în urma lucrării practice au fost introduse în simulare, confirmând și validând standul experimental. Multe cercetări privind sistemele fotovoltaice dezvoltă algoritmi pentru a monitoriza și a face sistemul capabil să urmărească soarele pentru o eficiență maximă. Astfel, o abordare cuprinzătoare care combină monitorizarea parametrilor PV cu datele meteorologice externe poate îmbunătăți semnificativ eficiența, fiabilitatea și durabilitatea unui sistem fotovoltaic.