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Environmental Monitoring System to Optimize the Performance of Solar Panels in University Environments

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Abstract

A temperature and radiation monitoring system were developed to optimize the performance of solar panels at the Faculty of Engineering and Applied Sciences (FICA) of the Technical University of Manabí. The objective was to implement IoT technologies and high precision sensors for data capture, the waterfall development methodology was applied that facilitated a structured approach, ensuring that each phase, from requirements analysis to maintenance, was executed effectively. The result was the collection of critical data that allows a detailed analysis of the performance of the solar panels. These results demonstrated that the system not only improves the monitoring of solar panels, but also contributes to the more efficient use of renewable energy sources. In addition, the integration of a Dashboard with the Geoportal digital platform allowed a clear and accessible visualization of the data, facilitating informed decision making to optimize the performance of the panels. In conclusion, this system represents a viable solution to improve energy efficiency and offers a solid foundation for future expansions, including the incorporation of more sensors and integration with other IoT platforms, which will further strengthen the sustainability and impact of the project.

Contents

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1 Introduction

In recent decades, photovoltaic solar energy has experienced significant growth, establishing itself as an essential source for sustainable development and reducing dependence on non-renewable energy (Dörenkämper et al., 2021). However, the efficiency of photovoltaic systems can be compromised by the lack of precise monitoring of critical variables such as temperature and solar radiation, factors that directly affect the performance of solar panels (Enaganti et al., 2020).

This study focuses on the implementation of an environmental monitoring system designed to optimize solar energy generation at the Faculty of Engineering and Applied Sciences (FICA) of the Technical University of Manabí. The main objective is to address the lack of accurate information on the performance of solar panels, providing a practical solution through the waterfall development methodology.

The research is classified as applied, integrating data collection techniques that include documentary research and interviews, complemented by the use of advanced technological tools to develop an efficient and effective monitoring system (Farhan & Hasan, 2021). This project not only has local relevance, by improving energy efficiency at the Technical University of Manabí, but also aligns with global trends towards the adoption of clean energy.

In this context, the implementation of the proposed monitoring system aims to contribute to the knowledge and application of modern technologies in the generation and monitoring of solar energy, with significant implications for the optimization of the performance of solar panels in university environments and beyond.

2 Materials and Methods

For the development of the temperature and radiation monitoring system in solar panels, several advanced technologies and sensors were used:

- ESP32 Wifi Arduino Module: This versatile 30-pin module supports both analog and digital inputs and outputs, making it an ideal choice for projects that require low power consumption and the ability to drive multiple sensors. The ESP32 is widely used in IoT applications due to its Wi-Fi and Bluetooth connectivity capability, allowing real-time data transmission from sensors installed on solar panels (Santos, 2022).
- Type K thermocouple: Used to measure temperature over a range of 0 to 1023 degrees Celsius, this sensor is renowned for its high accuracy and is suitable for environments requiring high temperature measurements, such as photovoltaic systems. This sensor is integrated with a MAX6675 amplifier that facilitates data reading through the ESP32, allowing continuous monitoring of the temperature of the solar panels (Random Nerd Tutorials, 2021).
- Sensor UV CJMCU-GUVA-S12SD: This sensor measures the intensity of ultraviolet radiation in a range of 240 to 370 nm. Its low energy consumption and high sensitivity make it suitable for the detection of solar radiation, providing critical data for optimizing the performance of solar panels. This sensor is easy to connect to microcontrollers such as the ESP32, making it easy to integrate into the monitoring system (ESP32 Learning, 2017).
- DTH22 Temperature and Humidity Sensor: This digital device measures ambient temperature and humidity over a range of -40 to 80 degrees Celsius with an accuracy of ±0.5°C, making it ideal for applications requiring reliable measurement of environmental conditions. It is compatible with most modules available on the market, and its low margin of error ensures that the data is accurate and useful for analysis (ESP32 Tutorial, 2024).

These sensors were connected directly to the solar panels at one end and to the control circuit at the other, allowing the capture and transmission of data on temperature, humidity and radiation to a central database. This information is essential to detect hot spots on solar panels, which are generally caused by dirt accumulation, negatively affecting energy performance.

Dashboard development methodology

The waterfall development methodology was used to implement the Dashboard in a web application for monitoring. This methodology, widely used in software development projects, follows a linear and sequential approach, where each phase of the project must be completed before moving on to the next. This model is particularly useful in projects with well-defined and stable requirements, allowing detailed planning and controlled execution of development (AppMaster, 2024; ProjectManager, 2024).

The process began with a thorough analysis of system requirements, ensuring a clear understanding of solar radiation and temperature monitoring needs. This analysis included the compilation of requirements from the different stakeholders involved, which allowed defining the functionalities and characteristics that the Dashboard should have (AppMaster, 2024).

Next, we proceeded with the design phase, where both the logical and physical design of the system were established. The logical design included structuring how data would be displayed and user interactions with the system, while the physical design focused on the technical architecture necessary to support these functionalities, such as the selection of IoT technologies and the structure of the foundation. of data.

After design, the system was implemented according to the established specifications. During this phase, the sensors were integrated with the ESP32 module and the user interface for data visualization was developed. This process included code development and integration of the different components of the system to ensure that they all worked cohesively.

In the testing phase, rigorous tests were carried out to verify the functionality of the system under various environmental and usage conditions. These tests were essential to identify and correct possible problems before the final launch of the system, ensuring that the system met the requirements and expectations defined in the initial phase (AppMaster, 2024).

Finally, an ongoing maintenance plan was established to ensure that the monitoring system remains efficient and adaptable to future updates. This maintenance includes regular calibration of sensors and updating software and hardware as necessary.

Software validation

Validation of the monitoring system developed for solar panels was carried out using the System Usability Scale (SUS), a widely recognized and standardized questionnaire that evaluates the perceived usability of products and systems. The SUS consists of 10 items answered on a five-point Likert scale, ranging from “Strongly Disagree” to “Strongly Agree” (Brooke, 1996).

This evaluation method is highly effective in obtaining a quick and reliable measure of usability, allowing developers to identify areas of improvement in the user interface and overall system functionality. In the case of the monitoring system, the SUS results are expected to reflect high user satisfaction, given that the design focused on clarity, accessibility, and ease of use (Lewis, 2018).

The application of SUS not only helps evaluate perceived usability, but also provides valuable data that can be used for future comparisons, ensuring that system improvements maintain or exceed previously established usability levels (McLellan et al., 2012). Although usability testing has not yet been completed, the system is expected to achieve positive scores based on preliminary feedback.

3 Results and Discussions

Identification of requirements and design of use cases

At the Faculty of Engineering and Applied Sciences (FICA) of the Technical University of Manabí, the need to optimize the performance of solar panels through a temperature and radiation monitoring system was identified. This system aims to provide accurate and real-time information on the operating conditions of the panels, which directly affect their efficiency.

Functional and non-functional requirements

Among the functional requirements, the collection of data in real time, the graphical visualization of this data, the ability to download information in formats such as CSV, and the functionality of filtering data by various criteria such as date and location stand out. These requirements ensure that the system provides accurate, real-time information, facilitating detailed analysis of solar panel efficiency. On the other hand, non-functional requirements focused on key aspects such as interface design, system performance, security, and scalability. The need for a responsive graphical interface that represents the institutional colors of the university was established, ensuring a consistent user experience. Additionally, it was ensured that the system could handle large volumes of data without compromising performance, and was hosted on a secure server with SSL protection. These requirements were essential to ensure the reliability, security and adaptability of the system to future needs.

Use Case Design

The main actors identified included the Geo-Portal administrator, teachers and students. The Geo-Portal administrator has full access to the website infrastructure, with capabilities to manage users, maps and data quality, ensuring comprehensive control of the system. Teachers and students, for their part, can access the information generated in real time, allowing them to monitor and analyze the performance of the solar panels from any location, as shown in Figure 1.

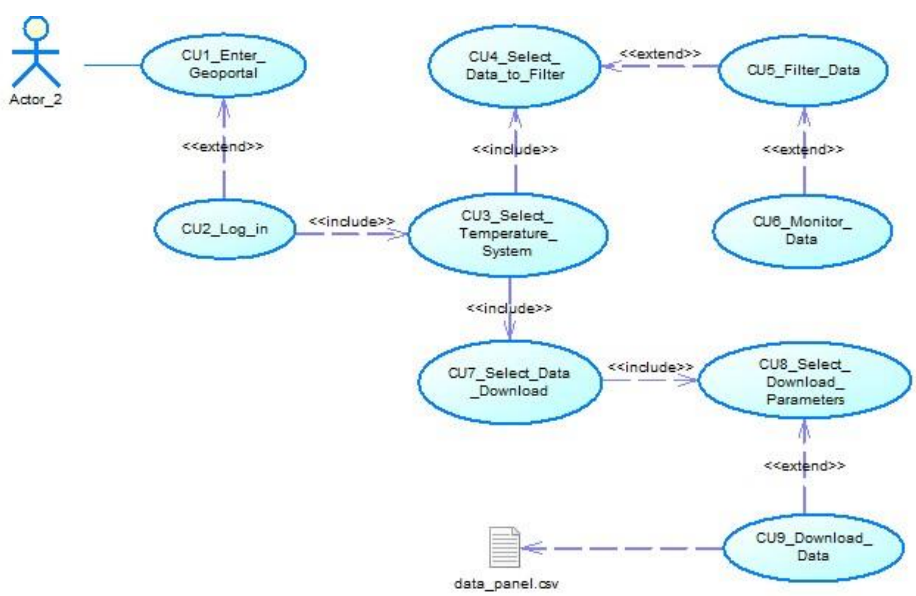

Figure 1. Use case diagram

Each actor has specific roles designed to facilitate their interaction with the system, guaranteeing efficient and secure access to information. This focus on use case design ensures that all users can interact effectively with the system, maximizing its functionality and usefulness within the academic context of the university (Ludin et al., 2018; Khare et al., 2016).

Software logic design

The design of the software logic is structured around a workflow that allows users to interact with the Web application. The process begins with the user entering the institutional Geoportal, where the user is required to log in to guarantee security and controlled access to the system's functionalities. Once authenticated, the user can select the temperature monitoring system they wish to view. This selection is crucial as it defines the specific data that the user will be able to monitor. After selecting the system, the user proceeds to choose the data they wish to view. The system allows filters to be applied, giving the user the flexibility to focus the display on specific aspects such as the date range or locations of interest. Selected information is presented in graphical format, allowing the user to monitor how temperature and radiation parameters vary over time. In addition, the system offers the option to customize the graphs, giving the possibility of selecting different types of visualization according to the user's needs. This functionality is essential to tailor the user experience and provide greater clarity in data interpretation (López-Lapeña & Pallas-Areny, 2018; Rich et al., 1993).

In parallel, the system includes a functionality that allows the user to open a modal window to configure the data download parameters. This option is particularly useful for users who need to export data for further analysis or documentation. The system verifies the completeness of the selected data before allowing the download, thus ensuring the integrity of the exported information. Finally, the process culminates when the user decides to log out or continue with other activities within the Geoportal, guaranteeing a safe and orderly closure of the workflow. The software logic is clearly illustrated in the flowchart presented in Figure 2, which details each step of the process and the key interactions between the user and the system.

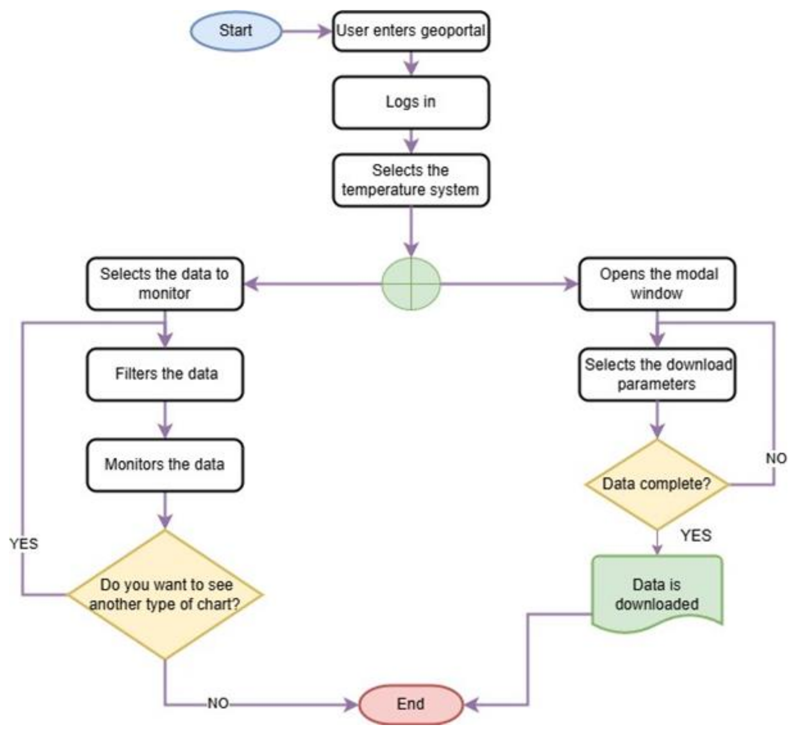

Figure 2. Software Logic Design Flowchart

This structured approach ensures that system users can interact with the monitoring functionalities intuitively and effectively, allowing quick and secure access to data relevant to optimizing solar panel performance

Deployment design

The deployment design of the temperature and radiation monitoring system is based on a distributed architecture that consists of three main nodes: the solar panels, the web server, and the users, as shown in Figure 3.

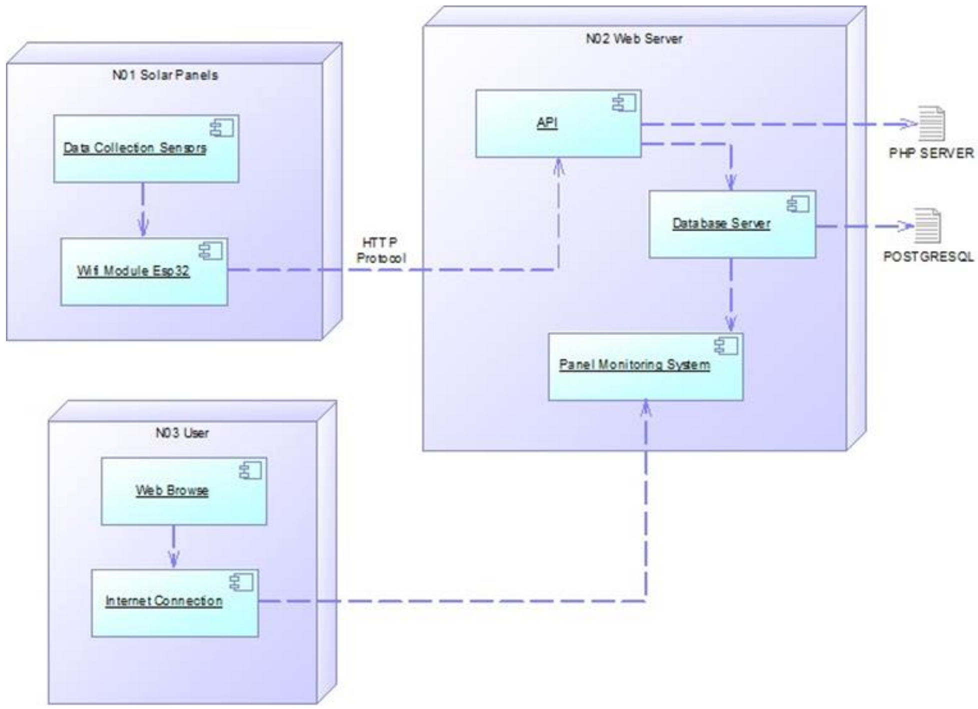

Figure 3. Diagram of the monitoring system deployment design

In the first node, the solar panels are equipped with sensors that measure temperature and radiation. These sensors send the data to the ESP32 WiFi module, which is responsible for transmitting the information to the web server through the HTTP protocol. The second node, the web server, hosts the API that handles data requests and the PostgreSQL database server, which stores all the collected information (Sox et al., 1999; Winands et al., 2011). This server also houses the monitoring system that allows the visualization of data in real time through a Dashboard accessible from any web browser. The third node includes users, who access the system through a web browser, interacting with the interface to monitor and analyze the data, apply filters and download the information. On the other hand, the solar panel temperature and radiation monitoring system has a Dashboard, an intuitive and functional graphical interface that allows users to view and manage the collected data efficiently Figure 4.

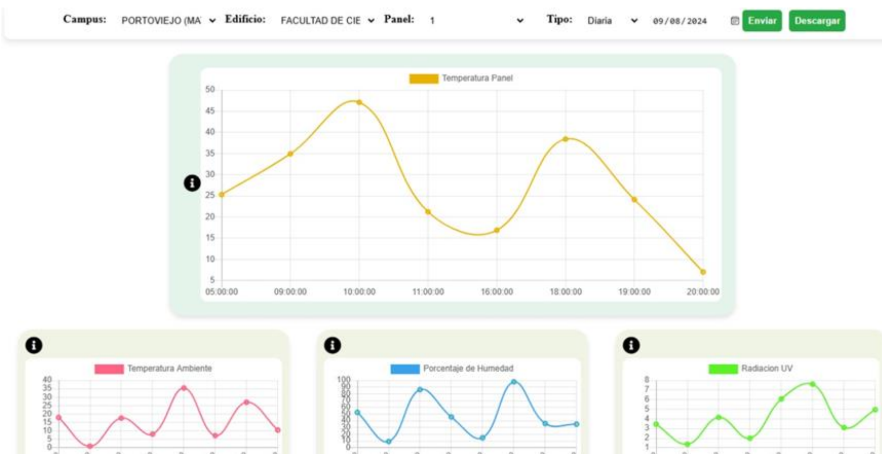

Figure 4. Dashboard of the monitoring system

Figure 4 shows the main work area of the Dashboard. In this section, users can select the campus, building, and specific dashboard they want to monitor. The option to choose the type of display (daily, weekly, monthly) and the corresponding date is also offered. A main graph is displayed in the center of the screen showing the panel temperature over time. Below this graph are other graphs that display ambient temperature, humidity percentage, and UV radiation. These graphs are updated in real time, allowing constant monitoring of critical parameters that affect the performance of the solar panels (Cajape et al., 2024).

Figure 5 illustrates the process of downloading data in CSV format. Users can access this feature through a button at the top of the Dashboard (Sauro & Lewis, 2016). Clicking "Download" opens a modal window that allows users to specify the date range for the information they want to export. This functionality is essential for those who need to perform more detailed analysis outside the system, allowing easy integration with other data analysis tools.

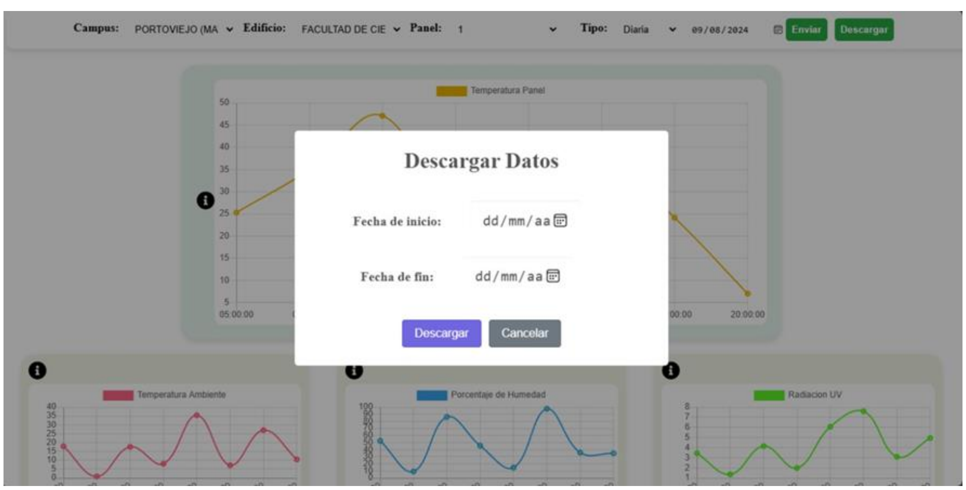

Figure 5. Data download process in CSV format file

This Dashboard design facilitates access and visualization of data in real time, and also offers additional tools for customizing and exporting information, ensuring that users can work with data flexibly and according to their specific needs. The system developed has addressed the lack of monitoring on FICA's solar panels and has also contributed significantly to the advancement in the efficient use of renewable energy sources. This achievement has important implications both locally and globally, supporting efforts to adopt more sustainable and efficient technologies in energy generation (Abdallah et al., 2023; Meribout et al., 2023).

In future perspective, it is recommended to continue training the personnel who operate the system and perform regular maintenance to ensure its optimal operation. Likewise, additional research is suggested on new technologies and techniques in solar energy monitoring, which will allow the system to be kept updated and aligned with technological advances. This project represents a significant technical advance, opening the door to new research and development opportunities in the field of renewable energy, ensuring a lasting impact on optimizing solar panel performance and energy sustainability (Kodama, 2003; Abdenacer & Nafila, 2007).

4 Conclusion

The development of the temperature and radiation monitoring system for solar panels at the Faculty of Engineering and Applied Sciences (FICA) of the Technical University of Manabí has achieved the objectives set, offering an effective solution to optimize solar energy generation. Through the integration of IoT technologies and high-precision sensors, the system has enabled the capture and detailed analysis of key data that influences the performance of solar panels. The waterfall development methodology applied in this project has proven to be effective, ensuring a structured and sequential approach from requirements identification to system maintenance. Each phase of the project was meticulously planned and executed, ensuring that specific objectives were met, such as the implementation of a reliable monitoring platform and the integration of data into the institutional Geoportal. The system provides a solid foundation for future expansion and improvements, such as the inclusion of more sensors and modules for more comprehensive monitoring. In addition, the possibility of integrating the system with other IoT platforms is proposed for greater automation and efficiency in data management.

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