MINISTERUL EDUCAȚIEI ȘI CERCETĂRII
UNIVERSITATEA TEHNICĂ
DIN CLUJ-NAPOCA

Inginerie Electronică, Telecomunicații și Tehnologii Informaționale

# PhD Thesis
## -ABSTRACT-

# Solar Resource Monitoring and Prediction Systems for Renewable Energy-Based Microgrids

| PhD Student: | Scientific Supervisor: |
|---|---|
| Eng. Ioan-Vladimir Voicu | Prof. Dr. Eng. Dorin PETREUȘ |

**– Cluj-Napoca –**
**2026**

## Introduction

Solar energy is one of the most promising sources of renewable energy. The Sun provides an inexhaustible resource capable of supporting the growing energy demands of modern society. In the current context, marked by pollution, climate change, and the need to reduce dependence on fossil fuels, interest in renewable energy has significantly increased, with solar energy taking a central role in the global energy transition.

The abundance of solar radiation, the scalability of photovoltaic (PV) technologies, and the potential for integration into smart grid-type electrical networks make solar energy a valuable resource. Modern photovoltaic systems, built from solar cells connected into modules and panels, can power everything from individual homes to industrial applications and national grids, integrated into microgrids, smart buildings, or distributed energy infrastructures.

However, the intermittent and variable nature of solar radiation, influenced by factors such as clouds, weather conditions, pollution, or the position of the Sun, requires precise monitoring and high forecasting capability for solar resources. Reliable measurement of global horizontal radiation (GHI) is essential for the proper sizing of PV systems, optimizing production, and enabling their efficient integration into distribution networks.

In this context, data acquisition systems (DAQ) play a central role. They allow the continuous collection, storage, and analysis of parameters such as solar radiation, temperature, current, voltage, and power, providing a detailed and real-time view of PV system performance. Thus, the thesis proposes the development of a scalable architecture for monitoring and forecasting solar resources, designed to support the integration of photovoltaic energy into microgrids and facilitate the multiplication of the system into a distributed network of terrestrial measurements. Both high-precision measurement methods (with a pyranometer) and low-cost solutions are explored to enable system expansion with reduced costs and wide coverage.

Study 1 (Chapter 4) describes the development of the initial data acquisition system for measuring solar radiation, starting from a Kipp & Zonen pyranometer connected to a Raspberry Pi microcomputer. This system transmits irradiance and temperature data to a server (VM) that hosts a time-series database (InfluxDB) and a web visualization solution (Grafana). Together, these components form an open-source, replicable system designed for continuous monitoring of solar resources.

Study 2 (Chapter 4) presents a software solution that uses measurements of global horizontal radiation (GHI) to determine the radiation on the panel plane (POA) and estimate photovoltaic energy production. The estimation is done using the open-source PVLib library, and the system allows real-time dynamic adjustment of parameters through the Grafana platform. In the second part, the analysis and forecasting of GHI are addressed by implementing a short-term ARIMA model in an interpretable and statistically validated framework.

Study 3 (Chapter 6) proposes an alternative method for measuring solar radiation (GHI) by using a small photovoltaic panel connected to a current sensor. The electrical current generated is used in relation to the values provided by a reference pyranometer, for calibration using an artificial neural network (ANN). This approach offers a replicable, low-cost solution for estimating GHI, contributing to expanding the possibilities for implementing sensor networks for GHI measurement.

Study 4 (Chapter 7) extends the previous system by integrating a fisheye lens camera, which extracts additional parameters from visual analysis of the sky. The information extracted from the captured images is used to train a Long Short-Term Memory (LSTM) model capable of predicting rapid variations in GHI radiation. This approach is important in the context of microgrids, where rapid adaptation to atmospheric changes is needed to maintain energy stability.

Study 5 (Chapter 8) focuses on securing the system by implementing the Keycloak solution, intended for authentication and authorization of access to the collected data set. This integration ensures interoperability with the Grafana visualization platform. Thus, the conditions are set for the system’s expansion into a distributed and secure network for monitoring solar resources.

The thesis aims to contribute to the field of renewable energy through an integrated approach that combines measurement tools, data processing technologies, and forecasting methods, aimed at improving the integration of solar energy into modern electrical grids. The use of low-cost solutions creates the foundation for the development of terrestrial networks for GHI measurements, supporting the management of smart microgrids..

# 4. Development and Implementation of a Solar Radiation and Temperature Data Acquisition System

## 4.1. Summary

This chapter details the design and deployment of a complete open-source hardware and software system for acquiring and processing solar radiation and temperature data. The primary goal is to support the monitoring of photovoltaic (PV) panel performance and analyze their impact on electrical networks, especially within microgrids.

The system is built around a Raspberry Pi connected to a Kipp & Zonen Class C pyranometer, installed near real PV panels at the experimental infrastructure of the Technical University of Cluj-Napoca. It continuously collects Global Horizontal Irradiance (GHI) and temperature data, which are stored in a time-series database (InfluxDB) and visualized in real time via the Grafana interface. This architecture provides flexible tools for both real-time and historical analysis, useful for operational management and research.

Starting in 2024, data collection was enhanced from 1-minute to 1-second resolution, enabling the detection of fast solar radiation fluctuations caused by cloud passage—critical events that impact PV system performance and grid stability.

Beyond direct measurements, the system includes a clear-sky solar radiation model based on Ineichen’s method, implemented through the PVLib Python library. Comparing measured GHI with clear-sky GHI (GHI_CS) helps quickly identify overcast conditions and assess panel performance under variable skies. This comparison forms the basis for deriving conversion coefficients linking solar radiation to electrical power output.

Historical data from 2018 to 2024 were analyzed to understand solar resource behavior across different weather conditions and seasons. Heatmaps visualized GHI and GHI_CS distributions throughout the year, highlighting seasonal trends, periods of high variability, and

critical times for renewable energy grid operations. These visual tools support both model validation and microgrid planning.

The conversion coefficient α, relating GHI to PV power output, was calculated using 2017 data and analyzed for seasonal variation. It ranged between 1.9 (summer) and 2.9 (winter), with an annual average of 2.36. This coefficient aids in preliminary PV production estimates and system sizing.

Spectral analysis of high-resolution data employed Fast Fourier Transform (FFT) and Kolmogorov 5/3 scaling to quantify the energy associated with rapid solar radiation fluctuations ("ramp" events). The spectral energy in the 0.1–0.5 Hz frequency band provides a measure of disturbance potential, useful for designing microgrid control strategies like load adjustment or storage activation.

The open-source system supports additional features such as exporting data in CSV format for further analysis and integration into external applications. It can also maintain high availability through database replication and automated backups. This robust, efficient, and accessible platform delivers high-quality solar radiation data essential for PV production estimation, with practical applications in research, development, and smart grid operation.

In conclusion, the chapter demonstrates that an accessible open-source system using affordable components can ensure precise real-time solar radiation monitoring. This provides critical data for PV performance analysis and smart microgrid management. The platform is scalable and easily replicable in other locations, contributing significantly to optimizing renewable energy integration in modern power systems.

# 5. Real-Time Estimation of Photovoltaic Energy Production Using GHI

## 5.1. Summary

Chapter 5 presents the development and validation of a low-cost, open-source solution for real-time estimation of photovoltaic (PV) energy production based on local measurements of global horizontal irradiance (GHI). The system is built around a Raspberry Pi 5 connected to a Kipp & Zonen pyranometer, capable of collecting high-frequency solar radiation data (1 Hz). Data is stored in an InfluxDB time-series database and visualized in real time using Grafana, with the ability to configure PV system parameters through a web interface.

The estimation method relies on converting GHI to plane-of-array irradiance (POA), using standard decomposition and transposition models such as ERBS and Hay-Davies. These models break GHI into its direct and diffuse components and project them onto the tilted surface of the PV modules, accounting for reflected radiation as well. Key PV system parameters tilt, azimuth, panel count, rated power, and temperature coefficient can be adjusted dynamically to reflect real installation conditions.

A major focus of the study is the importance of high-resolution measurements. By comparing 1-minute and 1-second (1 Hz) data, the study shows that rapid variations in solar radiation—known as ramp events, typically caused by passing clouds—are significantly underestimated or even missed at lower sampling rates. For example, in a selected cloudy day, 770 ramp events ($\geq 50$ W/m$^2$) were detected at 1 Hz resolution, while only 156 were captured at 1-minute resolution. This highlights the critical role of high-frequency data for accurate PV production estimation and real-time microgrid control.

To forecast short-term GHI, the study employs ARIMA (AutoRegressive Integrated Moving Average) models, tailored to capture rapid fluctuations in irradiance. These models were trained on real data and tested for multiple forecast horizons (5, 15, 30, and 60 minutes). The performance was evaluated using metrics such as MAE (Mean Absolute Error), RMSE (Root Mean Squared Error), and $R^2$ (coefficient of determination). Results showed strong predictive performance for short-term horizons (e.g., $R^2 = 0.92$ at 5 minutes), with accuracy decreasing gradually over longer horizons ($R^2 = 0.81$ at 60 minutes), due to the stochastic nature of solar variability.

Spectral analysis of the time series (via FFT and Power Spectral Density) confirmed that energy associated with ramp events is concentrated in the 0.1–0.5 Hz frequency band. This supports the use of 1 Hz data in monitoring and forecasting applications, especially in microgrids where sudden drops in PV output can destabilize the network. High-resolution data allows for better anticipation of these events and supports decision-making related to energy storage, load management, and inverter control.

In conclusion, this chapter demonstrates the feasibility of using a simple and replicable system—based on affordable hardware and open-source tools—for real-time estimation of PV production, without relying on commercial monitoring systems or cloud infrastructure. The proposed framework is suitable for research, education, and operational use in distributed energy systems. Furthermore, future work could enhance prediction accuracy by integrating additional meteorological variables or using machine learning models such as LSTM or XGBoost, especially in conditions with high solar variability.

# 6. Methods for Estimating Global Horizontal Irradiance (GHI) Using Miniature Photovoltaic Panels and Neural Networks

## 6.1. Summary

Chapter 6 presents the development of a low-cost IoT system designed to estimate Global Horizontal Irradiance (GHI) using miniaturized photovoltaic (PV) panels along with current and voltage sensors (INA219), combined with environmental sensors (BME280) measuring temperature, humidity, and pressure. The main goal is to provide an affordable alternative to professional pyranometers, which are expensive and challenging to scale for wide or distributed sensor network deployments.

The system collects real-time data at a 1-minute resolution, including the current generated by the PV panels and ambient conditions. These data are combined with open-source numerical models for clear-sky conditions (using the PVLib library and the Ineichen model) to estimate solar irradiance. The estimation relies on an Artificial Neural Network (ANN) model initially trained with data from Site A during the period September 2024 – April 2025.

The first model (ANN1) uses PV current and temperature as input features to estimate GHI under clear-sky conditions. To extend the model's applicability to other locations and variable weather conditions, a second model (ANN2) was developed. ANN2 takes the output of ANN1 and refines it based on real GHI measurements from Site B, including reference pyranometer data. This two-stage architecture allows local calibration and adjustment to factors such as microclimate and panel orientation deviations.

Initial laboratory tests confirmed the proper functioning of sensors and data acquisition systems, while outdoor deployment allowed for collection of comprehensive real-world datasets for training and validation. Statistical analyses, including Pearson correlation and SHAP (SHapley Additive exPlanations) interpretation, highlighted that PV current and ambient temperature are the most influential variables for GHI estimation. Other variables, such as the solar zenith angle (SZA), though significant, were excluded from later models to avoid overfitting and redundancy.

Model performance evaluation showed that ANN1 performs well under clear-sky conditions but exhibits larger errors during partially cloudy or rapidly changing weather. ANN2 significantly reduces these errors, achieving a mean absolute error (MAE) below 10% and near-zero bias, indicating accurate and balanced predictions.

Identified limitations include the low-cost system's reduced ability to capture rapid meteorological events and the need for periodic recalibration using reference instruments. Future improvements could involve integrating additional sensors (e.g., for diffuse and direct irradiance) and employing more advanced temporal models such as LSTM or Transformer networks to better capture the dynamics of solar irradiance.

In conclusion, the study validates the use of low-cost sensors and machine learning models for distributed solar irradiance monitoring. The proposed system offers an economical, scalable, and flexible solution deployable on embedded platforms for practical applications in microgrids, solar resource forecasting, and education.

# 7. Low-cost solution for short-term solar radiation forecasting

## 7.1. Summary

Integrating solar energy into smart energy systems requires accurate solar radiation forecasts to efficiently manage the natural fluctuations of photovoltaic (PV) power production. Modern solutions often rely on edge-based platforms that collect and process data locally at the source. This reduces reliance on cloud infrastructure and latency, making them ideal for remote or resource-limited locations.

A systematic literature review from 2011 to 2020 shows that most studies use classical statistical methods for solar radiation forecasting, but the trend is shifting towards machine learning approaches. Data typically comes from all-sky images (captured with fisheye cameras) and meteorological sensors. Image processing techniques, including computer vision methods for cloud tracking, are commonly employed.

Recent research proposes empirical models that correlate relative luminance extracted from whole-sky images with actual solar radiation measurements, outperforming traditional methods in capturing rapid variations. An open-source hybrid CNN-LSTM model trained with images and historical Global Horizontal Irradiance (GHI) data offers very short-term forecasts (up to 15 minutes) with significantly lower errors compared to classical approaches.

In this context, a low-cost platform was developed based on a Raspberry Pi 5 equipped with a high-quality fisheye camera and a miniature photovoltaic panel connected to an INA219 sensor for current measurement. The system also includes environmental sensors (temperature, humidity, pressure) and extracts simple image features like average luminance to approximate sky conditions.

Collected data are correlated and used to train an LSTM neural network capable of providing short-term GHI forecasts (5, 10, 15, and 30 minutes). Power over Ethernet (PoE) ensures continuous operation, and the Raspberry Pi's processing power enables real-time analysis and prediction.

The system is modular and scalable, using a central server with InfluxDB for data storage, accessible through Grafana for real-time parameter monitoring and analysis. Images are captured using a Sony IMX477 sensor with a fisheye lens, providing a hemispherical view of the sky.

Image analysis involves extracting spectral and luminance features (red/blue ratio, luminance, saturation). Thresholding and binary masking techniques isolate clear sky regions from cloudy or obstructed areas. These features are statistically correlated with actual radiation measurements and meteorological conditions using Pearson's correlation coefficient to identify the most relevant variables for GHI prediction.

The trained LSTM model uses these multimodal data inputs (weather parameters, PV panel measurements, image features) to forecast GHI over short intervals, capturing rapid changes caused by passing clouds. Model performance is evaluated using statistical metrics like RMSE and MAE, showing sufficient accuracy for practical application in smart grids or PV microgrids.

This approach offers an efficient, cost-effective, and scalable alternative to traditional methods, reducing infrastructure needs and enabling deployment on edge devices such as Raspberry Pi.

# 8. Secure Access in Grafana via Keycloak: Implementation and Discussions

## 8.1. Summary

This chapter presents the implementation and benefits of a Keycloak-based solution for Single Sign-On (SSO) and Identity and Access Management (IAM), with a strong focus on high availability and scalability. By leveraging HAProxy together with Keycloak and Infinispan clustering, it has been demonstrated that service continuity can be maintained even during failover scenarios, ensuring session affinity and user state replication. This approach minimizes disruption and provides a seamless experience for end-users.

Integration with the eduGAIN federation opens opportunities for European collaboration, allowing users from other institutions secure and controlled access to local services. However, this integration requires careful configuration of attributes and ongoing monitoring of authentication flows to maintain compliance with eduGAIN standards. Attribute release and interfederation tests confirm that the solution meets standardized requirements, although expanding to other federations will require additional verification and configuration.

The chapter also highlights Keycloak's flexibility through integration with external applications using OpenID Connect (OIDC), exemplified by Grafana and GitLab. These applications can use Keycloak for authentication and authorization without locally storing user credentials, centralizing access management and enhancing security.

Looking forward, the solution can be extended by implementing OAuth2 with JSON Web Tokens (JWT), enabling applications to validate standardized tokens directly. This would reduce the load on Keycloak servers and decrease authentication latency, improving overall efficiency and scalability while facilitating rapid integration of new applications.

Practical experience underscores the importance of proactive administration of the Keycloak infrastructure, including continuous performance monitoring, regular updates, and failover testing. Proper management of clustering and HAProxy components is essential to prevent scalability issues and maintain a smooth user experience.

In conclusion, the presented architecture demonstrates that Keycloak provides a robust, flexible, and scalable framework for authentication and authorization. It combines advanced features such as SSO, conditional post-login flows, eduGAIN integration, and OIDC support, with future extensibility through JWT and rapid integration of external services. This ensures fine-grained access control and enhanced data security.

Additionally, future developments are expected to extend authentication mechanisms to IoT devices, such as sensors, enabling them to transmit signed and authenticated data via JWT, thus expanding authentication security beyond traditional users.

# 9. General discussions

The results obtained in this thesis demonstrate the feasibility and utility of an integrated approach based on open-source hardware and software solutions for monitoring and forecasting solar resources. The proposed system, built on the Raspberry Pi platform and equipped with low-cost sensors, has proven capable of providing relevant data for estimating global horizontal irradiance (GHI) as well as for short-term forecasting of photovoltaic energy production.

Compared to established commercial solutions, the developed system presents several clear advantages: low costs, high flexibility in configuration, and the possibility for expansion or adaptation to various microgrid scenarios and research applications. The use of open-source software components (InfluxDB, Grafana, PVLib, Keycloak) allowed both a reduction in licensing costs and the creation of a transparent and reproducible framework, which represents a significant benefit for the academic community and initiatives in resource-limited environments.

The integration of a small photovoltaic panel as an alternative solar sensor, calibrated through artificial neural networks, demonstrated that indirect measurements can partially substitute dedicated instruments without significantly compromising the accuracy of results. This approach opens interesting research directions for developing distributed networks of micro solar sensors, useful in applications such as local forecasting, microgrid management, or the study of radiation variability.

Regarding forecasting, the use of ARIMA models provided a solid baseline, while advanced LSTM models, trained on multimodal datasets (meteorological data, PV currents, all-sky images), highlighted the potential of artificial intelligence algorithms to anticipate ramp events. These results emphasize the importance of hybrid approaches that combine the simplicity of statistical methods with the predictive power of deep learning models.

However, the developed system is not without limitations. Variability in atmospheric conditions and the presence of missing data during certain periods influenced the accuracy of estimates. Additionally, the hardware resources of the Raspberry Pi platform, although sufficient for real-time data collection and processing, may represent a constraint for complex models or intensive analysis scenarios.

Nevertheless, the obtained results confirm the working hypothesis and support the idea that low-cost, open-source solutions can significantly contribute to democratizing access to advanced solar monitoring and forecasting technologies. In a global context marked by the transition to renewable sources and the need for integrated energy resource management, such systems can serve as valuable tools for both research and practical applications in microgrids and isolated communities.

# 10. Final conclussions

## 10.1. General conclussions

The main objective of this work was the development and validation of a complete, integrated, and low-cost framework for the acquisition, analysis, and forecasting of solar resources and implicitly photovoltaic energy production for microgrid networks. By using Raspberry Pi microcomputers, accessible sensors (pyranometer, INA219, BME280, fisheye camera), and open-source software tools (InfluxDB, Grafana, PVLib, Keycloak), the possibility of creating a robust, scalable, and efficient platform capable of meeting the current demands of the energy transition was demonstrated.

The main conclusions can be summarized as follows:

The low-cost hardware–software integration is viable and performant.

Experiments showed that a Raspberry Pi-based system, configured with radiation and meteorological sensors, can provide data of sufficient quality for monitoring and forecasting solar energy. Comparison with reference equipment demonstrated that the proposed solution can achieve comparable performance with a significantly better cost/benefit ratio.

Solar resource measurement and estimation can be performed through hybrid methods. This work demonstrated that global horizontal irradiance (GHI) can also be estimated using alternative methods with a pyranometer, a 0.3 W PV panel, and the INA219 sensor. This type of virtual sensor, calibrated via artificial neural networks, can offer an economical solution for distributed applications or physical deployment where infrastructure is lacking.

Solar forecasting requires a combination of traditional and advanced methods. Statistical models (ARIMA) proved useful for short-term prediction under relatively stable conditions but cannot adequately capture sudden events. The integration of recurrent neural network algorithms (LSTM), fed with multimodal data (PV current, meteorological conditions), showed substantial improvement in forecasting radiation ramp events.

The time-series database and interactive visualization add value to the system. Using InfluxDB for data storage and Grafana for visualization allows real-time analysis and parameter adjustment during simulations and experiments, turning the platform into a tool both for research and operational use.

Security and scalability are essential for practical implementation. The integration of Keycloak for authentication and access control confirms the possibility of expanding the system toward distributed and collaborative networks, an important step for large-scale adoption in microgrids or energy communities.

The work proposes a fully integrated, open-source architecture. Its originality lies in bringing together all hardware, software, and methodological components into a single framework, creating an accessible and replicable solution suitable for educational, research, or industrial purposes.

Overall, the results confirm the basic hypothesis: low-cost systems, if properly designed and calibrated, can support both real-time monitoring and advanced forecasting of solar resources. Furthermore, they can significantly assist the development of smart microgrids by optimizing the integration of renewable energy using modern data acquisition and analysis technologies.

## 10.2. Originality and Contributions of the Thesis

The thesis proposes and validates an integrated framework for monitoring and forecasting photovoltaic (PV) energy production using low-cost hardware and software solutions, with an emphasis on replicability and flexibility. Although numerous studies address solar radiation measurement and PV production forecasting, the combination presented here — miniaturized photovoltaic sensors, edge processing on Raspberry Pi, statistical and artificial intelligence models, as well as open-source visualization and security — represents a distinct contribution to the specialized literature.

The main elements defining the originality of the thesis include:

Implementation of a complete, low-cost, and replicable system that integrates:

- Data acquisition from a reference pyranometer and a small PV panel with INA219 sensor;
- Preprocessing and storage of data in an open-source time-series database;
- Visualization and interaction with the data through Grafana, with the capability to adjust PV parameters in real time.

Real-time estimation and forecasting of PV production by combining GHI measurements with the PVLib library for plane-of-array (POA) irradiance calculation and using ARIMA algorithms for short-term predictions adapted to ramp events.

Development of a low-cost method for estimating GHI using a 0.3 W PV panel and an artificial neural network (ANN) model calibrated with pyranometer data, providing an economical and flexible alternative for solar radiation monitoring.

Integration of a multimodal system for irradiance forecasting that combines data from the PV panel, INA219 sensor, BME280, and fisheye camera for all-sky images, used to train an LSTM network aimed at forecasting rapid radiation variations.

Ensuring data security and access by integrating Keycloak, leveraging existing users, which enables system extension towards a distributed architecture for collecting and visualizing GHI data under secure conditions.

In conclusion, the innovative contributions of the thesis do not lie solely in the implementation of each individual component but in combining them into a coherent, complete, and accessible framework that can be used in both research and practical applications for microgrids or distributed systems with limited resources. This approach enables scalable and adaptable collection, processing, and forecasting of solar data, demonstrating the potential of low-cost technologies for renewable energy monitoring.