

INNOVATIVE TEACHING OF RENEWABLE ENERGY TECHNOLOGIES THROUGH REAL-TIME DATA MONITORING OF MICROGRIDS

Antonio Escámez¹, Daniel Sánchez-Lozano¹, Roque Aguado²,
David Vera¹, Marcos Tostado-Véliz¹, & Manuel Gómez-González¹

¹*Department of Electrical Engineering, University of Jaén (Spain)*

²*Institute of Carbon Science and Technology, CSIC (Spain)*

Abstract

This paper presents a virtual laboratory designed to support remote instruction on renewable energy-based microgrids within undergraduate Electrical Engineering programs. The system comprises four 100 Wp photovoltaic panels and a 400 W wind turbine generator. Microgrid data are collected through dedicated acquisition devices and stored in a time-series-optimized database. A Telegram application programming interface (API) enables access to microgrid and weather station data. Student feedback, gathered through a questionnaire, indicates high satisfaction with the virtual laboratory, with an average rating of approximately 4.5 out of 5. Participants strongly agreed that the platform enhanced academic skills and supported the achievement of program learning objectives. Overall, the virtual laboratory significantly improved students' understanding of renewable energy microgrids and constitutes an effective complement to traditional in-person laboratory instruction.

Keywords: *Interactive learning, remote access, telegram bot, graphical user interface, virtual laboratory.*

1. Introduction

The impacts of climate change are increasingly evident, leading governments worldwide to promote ambitious strategies to achieve carbon neutrality (IEA, 2022). A representative example is the European Green Deal, which aims to reach climate neutrality by 2050 (European Commission, 2023). Achieving this goal requires the large-scale integration of renewable energy sources, particularly solar and wind, together with the electrification of sectors such as transportation.

The high penetration of renewable generation introduces significant challenges to power system operation due to its variability and uncertainty. To address these issues, advanced solutions such as energy storage, demand response, and coordinated energy management are required. In this context, microgrids have emerged as a promising framework, enabling the efficient integration of distributed energy resources while improving system reliability and flexibility (NREL, 2023).

In parallel, the growing relevance of sustainability has increased the importance of renewable energy education within engineering programs. Laboratory-based learning remains essential, but access to conventional laboratories is often constrained. Recent advances in digital technologies have therefore promoted the adoption of virtual and remote laboratories, which allow students to perform practical experiments through Internet-based platforms, improving accessibility, safety, and resource efficiency (Sapriati et al., 2023).

Despite their widespread use in electrical engineering education, the application of virtual laboratories to renewable-energy-based microgrids remains limited. Accordingly, this paper presents an educational experience based on a real-time monitored microgrid for the remote teaching of renewable energy technologies in undergraduate electrical engineering programs, highlighting its structure, implementation, and educational benefits.

2. Microgrid description

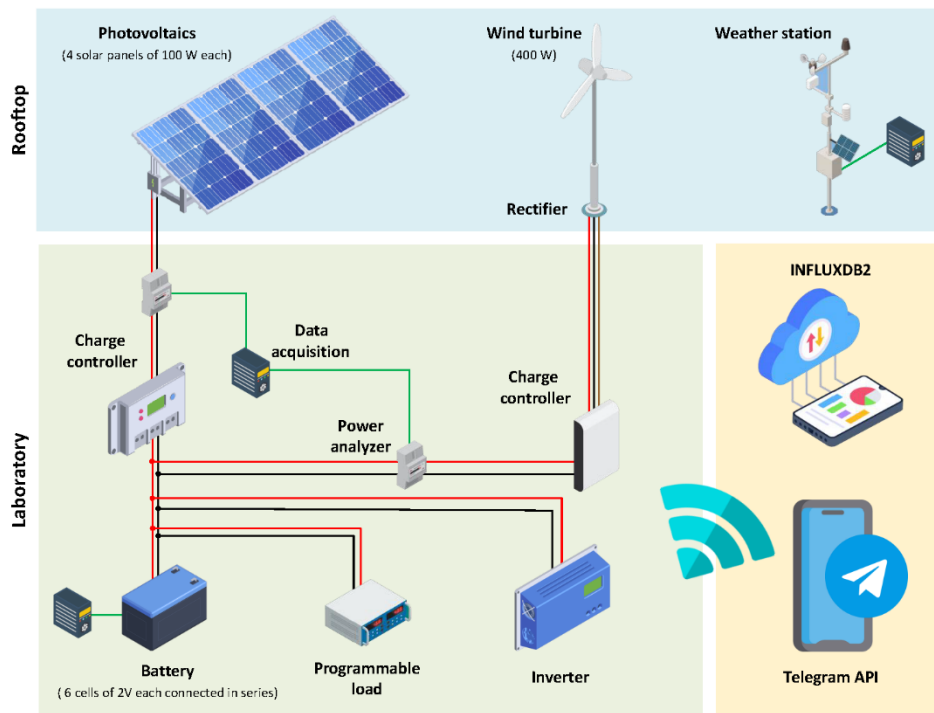
As shown in Figure 1, the microgrid integrates photovoltaic and wind energy sources with battery storage. The photovoltaic (PV) system consists of four 100 Wp panels, while the wind subsystem includes a turbine coupled to a 400 W generator. Energy storage is provided by a lead-acid battery bank with a rated

capacity of 431 Ah (C_{100h}). A nearby weather station measures key environmental variables, including temperature, solar irradiance, wind speed and direction, humidity, pressure, and precipitation.

Most of the remaining equipment is installed in the laboratory. The PV panels are connected to a charge controller linked to a series-connected battery bank. The wind generator feeds a rectifier and a dedicated charge controller, enabling safe conversion and regulation of the generated power prior to storage. Both controllers regulate voltage and current to prevent battery overcharging. The stored DC energy can be converted to AC through an inverter, while a programmable DC load allows controlled battery discharge, enabling the emulation of realistic consumption profiles.

Microgrid data acquisition is carried out through multiple devices: the charge controllers provide PV production data, power sensors monitor wind generation, battery communication interfaces supply state-of-charge information, and a datalogger records weather data. All measurements are stored in a time-series database (InfluxDB2), and the collected data can be remotely accessed through a Telegram-based interface.

Figure 1. Schematic diagram of the microgrid.



3. Methodology

The proposed methodology focuses on real-time data acquisition, processing, visualization, and remote interaction with a renewable-energy-based microgrid to support a virtual laboratory environment. Measurements from the wind turbine, photovoltaic system, battery storage, and weather station are collected using a unified data acquisition architecture based on a microcontroller, which aggregates and transmits the information to a personal computer at fixed time intervals.

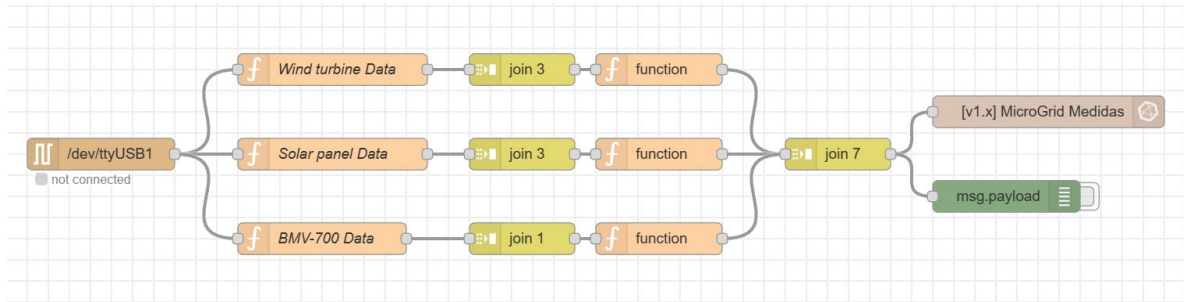
Data processing and storage are carried out using Node-RED and InfluxDB, respectively. Node-RED manages data reception, validation, and formatting, while InfluxDB serves as a time-series database optimized for high-frequency sensor data. As illustrated in Figure 2, the incoming data streams are parsed, combined, and stored in a structured manner, enabling efficient querying and long-term analysis.

For real-time visualization, a graphical user interface is implemented using Grafana. This dashboard allows users to monitor power generation from wind and photovoltaic sources, as well as the battery state of charge, over customizable time ranges. Visual indicators such as time-series plots, bar graphs, and gauges provide an intuitive understanding of system behavior and performance.

To enhance the educational experience, the monitoring platform is complemented by a virtual laboratory composed of a programmable DC electronic load and a messaging-based user interface. The programmable load enables students to emulate realistic consumption profiles and analyze battery response under varying demand conditions. In parallel, a Telegram-based interface allows users to remotely query real-time information on power generation, energy production, battery status, and weather conditions.

Together, these tools provide continuous remote access to the microgrid, fostering interactive, experiment-driven learning in renewable energy education.

Figure 2. Data processing using Node-RED and InfluxDB.

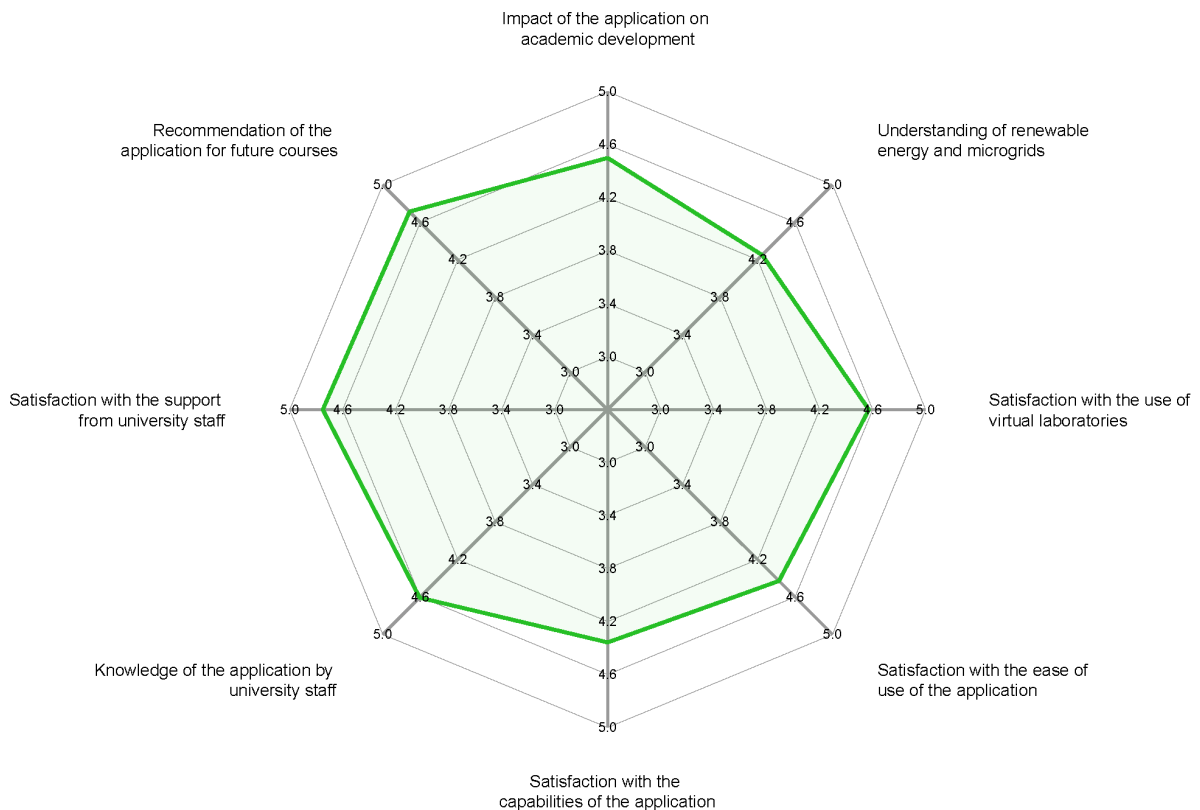


4. Educational benefits and educator's perspective

This section analyzes the educational benefits of the developed virtual laboratory and presents educators' perspectives on its impact on student engagement and skill development in undergraduate electrical engineering programs. Remote laboratories are expected to enhance traditional learning environments by providing additional educational value and practical relevance (Grout, 2017).

To evaluate the educational experience, a questionnaire based on a five-point Likert scale was administered to 28 participants. The survey assessed perceived skill development, alignment with degree objectives, usability, and overall satisfaction. The aggregated results are presented in Figure 3 using a radar plot.

Figure 3. Radar plot of the participant feedback on the questionnaire aimed at assessing various aspects about the educational experience of the developed virtual laboratory.



As shown in Figure 3, the feedback was highly positive, with an overall average score of 4.50 out of 5. Participants strongly agreed that the virtual laboratory effectively supports the development of academic skills, contributes to achieving undergraduate learning objectives, and should be more widely

integrated into engineering curricula. High satisfaction was also reported regarding the system's usability, functionality, and visual design, as well as the preparedness of academic staff to manage such tools.

The virtual laboratory enables students to actively interact with a real microgrid, promoting a deeper understanding of solar and wind energy systems through hands-on experimentation rather than purely theoretical instruction (Grout, 2017). This experiential learning approach enhances knowledge retention and practical competence. From an instructional perspective, the platform allows educators to deliver more engaging content and supports self-regulated learning by providing continuous remote access to real system data (Sapriati et al., 2023). Overall, the virtual laboratory improves accessibility, flexibility, and educational quality, aligning with modern trends in engineering education (Almarshoud, 2011).

5. Conclusions

This paper has investigated the role of virtual laboratories as an effective approach for supporting the remote teaching of microgrids based on renewable energy technologies, with particular emphasis on their design, implementation, and deployment within undergraduate electrical engineering programs. The proposed virtual laboratory represents a flexible and scalable educational resource that complements conventional laboratory-based instruction and addresses several limitations associated with exclusively face-to-face experimental activities.

Unlike traditional laboratory models that depend heavily on physical presence and direct supervision, the developed platform enables continuous remote access to a real microgrid, allowing students to observe, analyze, and interact with renewable energy systems under realistic operating conditions. This approach not only enhances accessibility and inclusiveness but also promotes active and experiential learning, thereby strengthening students' understanding of key concepts related to solar and wind energy integration, energy storage, and system management. As a result, the microgrid-based virtual laboratory contributes to a more comprehensive and practice-oriented educational experience.

Furthermore, the remotely accessible nature of the laboratory supports self-regulated learning and facilitates the adaptation of teaching methodologies to diverse student needs and learning paces. By integrating real-time data monitoring and interactive tools, the platform bridges the gap between theoretical instruction and practical application, fostering higher levels of engagement and motivation. Consequently, the virtual laboratory serves as a valuable pedagogical instrument for modern engineering education, particularly in the context of sustainability-driven curricula.

Future developments of the proposed system may include the integration of additional sensors to expand monitoring capabilities, enhancements to data storage and processing infrastructures, and further refinement of the remote user interface to improve usability and interactivity. Moreover, the incorporation of artificial intelligence and data-driven models for forecasting energy production and system behavior represents a promising direction. Such advancements would not only deepen students' technical understanding but also enable the acquisition of cross-disciplinary competencies in data analytics, predictive modeling, and intelligent energy management, thereby further enriching the educational value of the virtual laboratory.

Acknowledgments

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