Manglar Living Lab: Energy Management Through a Smart Microgrid with Artificial Intelligence

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Abstract: Latin America, and Colombia in particular, are making strides in their energy transition by implementing innovative projects that prioritize sustainability and efficiency. This article presents a conceptual framework of the Manglar Living Lab pilot plant, detailing the microgrid architecture with the goal of overcoming energy challenges and focusing on efficient energy management. Central to this initiative is the development of a smart metering device, driven by artificial intelligence (AI), with a technological platform and real-time monitoring capabilities. This Living Lab not only bolsters Colombia's energy transition strategy but also illustrates the potential of localized AI-powered solutions to enhance energy efficiency and grid reliability in the region.

1 INTRODUCTION

Living Labs have emerged as innovative platforms that facilitate co-creation and experimentation in real-world environments, promoting energy efficiency and sustainability. These are collaborative spaces where end-users, researchers, and companies co-design and test innovative solutions in practical settings. In the field of energy efficiency, Living Labs enables the implementation and evaluation of sustainable technologies and practices in communities and buildings by Almirall et al. (2012). Various studies have explored how AI can enhance the efficiency and stability of microgrids.

The integration of smart technologies, such as energy management systems and IoT devices, is essential in energy efficiency-oriented Living Labs. Ballon et al. (2018) and Mohamed et al. (2016) analyze how these technologies facilitate real-time monitoring and optimization of energy consumption in urban environments, thereby enhancing sustainability and reducing costs.

Active participation of end-users is crucial in Living Labs. Leminen et al. (2012) explore how co-creation and community involvement in the design and testing of energy solutions lead to greater acceptance and effectiveness of implemented initiatives.

Several university institutions have implemented Living Labs to promote energy efficiency:

- The Smart City Málaga project is designed to transform university campuses into smart cities, facilitating the efficient management of resources while fostering innovative research and educational activities. These factors are crucial to the development of future smart cities. The project's emphasis on energy efficiency measures and active demand management strategies led to a significant reduction in energy consumption (Forte at all. 2019).
- The University of Genoa has established the "Living Lab Smart City" to test cutting-edge, sustainable technologies for energy production, distribution, and management. The goal is to transform the Savona Campus, which resembles a small urban district with approximately 2,500 residents, into a model of an innovative and sustainable city by implementing demonstrative infrastructure that can be replicated at the city district level (Laiolo et al.2021).

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- Akpolat et al. (2024) proposes the planning, modeling, implementation, and operation of a laboratory-scale distributed energy resource (DER) and a living laboratory structure with a hybrid energy system. This system utilizes photovoltaics, a small-scale wind turbine, a proton exchange membrane fuel cell, and a lead acid battery energy storage system. The objective of this system is to enhance the standards of education and research within the electrical and electronic engineering fields. Specifically, this system structure has facilitated opportunities for researchers and students to engage in diverse areas such as renewable energy, control systems, power electronics, energy management systems, and software development.
- The Sorocaba Institute of Science and Technology (ICTS) of Unesp intends to initiate its transition into a smart campus. The first step in this endeavor is to adopt measures related to the measurement of consumption and control of electric energy and water, thereby establishing a solid foundation for the implementation of TIC (Zarpellon, B. O. 2024).

Despite the benefits, the implementation of Living Labs faces challenges such as management of the data generated and long-term sustainability. Schuurman et al. (2016) address these challenges and propose strategies to overcome them, emphasizing the importance of proper planning and continuous adaptation to community needs.

1.1 Integration of Artificial Intelligence (AI)

The implementation of smart grids, which combine traditional electrical grids with modern information and communications technologies, as well as distributed generation systems and microgrids, is no longer a futuristic concept but a reality in many developed nations. The emergence of AI in managing the energy use of smart microgrids has presented an auspicious solution for optimizing energy distribution and consumption. This is particularly relevant given the increasing integration of renewable energy sources.

Bernstein et al. (2015) and Mastelic et al. (2017) proposed a composable method for real-time control of active distribution networks by utilizing explicit power setpoints. This approach effectively coordinates distributed resources, enhancing both grid stability and efficiency. Similarly, Simões and Farret (2014) emphasized the application of artificial intelligence (AI) techniques, such as neural networks and fuzzy logic, in renewable energy systems and microgrids. Their research demonstrates how these methods can optimize microgrid operation and control, adapting dynamically to fluctuations in energy generation and demand. In Le, T. T. H., & Kim, H. (2018) the research consisted of detecting home appliance events using low frequency active power signals. Decision Tree and Long Short-Time Memory (LSTM) were used to detect ON/OFF events with high accuracy reaching accuracies of 92.64% and 96.85% respectively.

Lazzarett et al. (2020) propose load monitoring modules that detect power changes, identify loads, and report data to an operations center. The detection method is based on half-cycle apparent power and signature analysis using power envelopes.

Da Silva Nolasco. (2021) proposes a new architecture based on "Convolutional Neural Network" CNN that integrates detection, feature extraction and classification of high frequency NILM signals. Their approach uses a grid to divide the input signal into segments and a series of convolutional layers to extract features from the signal. Demonstrating greater feasibility to be used in the real world.

Mohseni et al. (2022) introduced a capacity planning model for off-grid microgrids, utilizing metaheuristic-based optimization algorithms. This model proved to be effective in planning and managing microgrid operations in remote areas, significantly improving energy efficiency and reducing costs.

The implementation of the Living Lab with the integration of non-intrusive load monitoring (NILM) can become an emerging approach with cost-effective energy management solutions. This is achieved by utilizing the aggregate load obtained from a single smart meter within the power grid. Furthermore, by integrating machine learning (ML), NILM can efficiently utilize electrical energy and lessen the load for the energy monitoring process (Silva, M. D., & Liu, Q. (2024)).

These studies highlight the potential of AI to revolutionize energy management in smart microgrids, providing more efficient and adaptive solutions to the current challenges in the energy sector.

1.2 Our Contribution

Latin America, and particularly Colombia, is actively pursuing projects to address the global energy transition challenge by integrating innovative technologies and sustainable practices. This article introduces a groundbreaking Living Lab developed in Colombia as part of these efforts, focusing on energy efficiency and intelligent energy management. The Living Lab, named MANGLAR, serves as a collaborative space for the co-creation and real-world testing of advanced energy solutions.

The centrepiece of this initiative is a novel technological platform and smart measuring device, designed to optimize the operation of a microgrid. Leveraging artificial intelligence (AI), the platform enables real-time monitoring, demand-response optimization, and predictive analytics, ensuring efficient energy use and improved grid reliability. This integration of AI into the microgrid management framework represents a significant advancement in addressing the region's energy challenges, particularly in decentralized and renewable-based power systems.

The article presents the conceptual framework of the Living Lab, details the architecture of the smart microgrid, and highlights the results from pilot implementations. By contextualizing this innovation within Colombia's broader energy transition strategy, the work underscores the importance of localized solutions and technological innovation in achieving sustainable energy goals in Latin America.

Next, section 2 then provides a detailed description of the generation system available in the Living Lab. It also focuses on the equipment and tools that enable real-world experimentation. Finally, Section 3 presents the design of a smart metering device that employs edge AI to efficiently manage the microgrid. This work highlights the importance of localized solutions and technological advancements as key enablers of Colombia's energy.

2 SUSTAINABLE ENERGIES: ADVANCING SOLAR GENERATION

In Colombia, the electricity service is stratified according to family income and work activities. The regulated electricity market comprises sectors 1 to 3, which include low-income households; sector 4 belongs to middle-income households. Sectors 5 and 6 are made up of higher-income households and the commercial sector. On the other hand, the industrial sector belongs to the unregulated market, where they can choose the marketer and freely agree on the price of electricity (Salazar G. (2013)). In Guerrero Hernández et al. (2022) a mixed integer optimization model is proposed for energy management in the Manglar Lab under the conditions of the tariff system in Colombia.

The name Manglar had its origin in a coastal ecosystem where unique trees and shrubs thrive, swampy where solar radiation and winds are excellent for the generation of electricity. These unique trees, through the process of photosynthesis, capture solar energy and become a support and food habitat for many marine and terrestrial species. Manglar Living Lab was created in the Energy 2030 project, financed by the World Bank. This electronic engineering research laboratory at the University of Sucre becomes a fundamental pillar in the energy transition of the university campus and a place for the generation of knowledge in the areas of power electronics, artificial intelligence and device design.

The Manglar Living Lab has a capacity of 20 kWp in the solar generation system, subdivided into three sections, each composed of 8 JKM400 reference photovoltaic panels. In addition, it has three CPS SCA6KTL-SM type inverters and a BESS storage system with an energy capacity of 12.6 kWh, which provides electrical energy to the laboratory in case of absence of the conventional electrical supply (see figure 1).

Figure 1: Microgrid Manglar.

The building has four floors with an elevator and solar panels installed on the roof. This building houses physics, chemistry, agribusiness and electronics laboratories. It has an average daily consumption of 5903kWh. Figure 2 shows the data of the power generated by the group of 8 solar panels connected to an inverter in a measurement period of 48 hours.

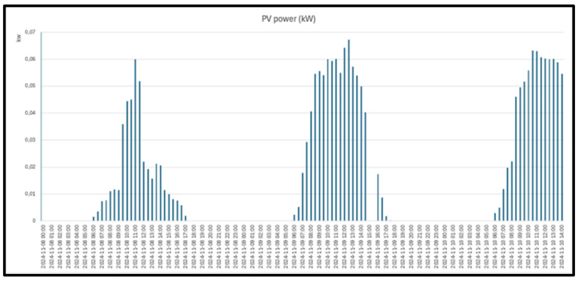

Figure 2: Data obtained from the solar inverter.

The laboratory is equipped with a lithium battery bank that provides up to 2 hours of electrical autonomy. The importance of a **battery bank** in a microgrid is pivotal to achieving efficient energy management and cost optimization, particularly in scenarios where the aim is to minimize operational costs Mazidi el al (2023). This physical space houses equipment such as 5 personal computers, a modem, a 3D printer, a video wall, an LED lamp, a water dispenser, and an electric coffee maker (see Table 1).

Table 1: Electronic devices in the laboratory.

Quantity	Apparatus	Power (W)
1	Water Dispenser	80
1	Electric Coffee Maker	900
1	3D Printer	350
1	Router	30
4	Led Lamp	12
4	Video wall	250
5	PC	340
1	CNC	200

2.1 Smart Microgrid

Figure 3 illustrates an energy management system for "Manglar Living Lab". The building icon with solar panel and battery represents a solar energy system with energy storage. The thick black vertical line symbolises the main source of energy that powers the laboratory, and the surplus is distributed throughout the building. The enclosure designated as "NILM" serves as a non-intrusive load monitoring system. This advanced technology facilitates the identification of energy consumption associated with individual devices without the necessity of installing separate meters for each one. It operates by analysing fluctuations within the total electrical current, thereby disaggregating the consumption of each appliance.

An Emporia® Gen 3 energy meter is used to record laboratory consumption. The average daily consumption is 33.5 kWh and figure 4 shows the average daily load profile.

3 SMART MEASURING DEVICE

This section describes the prototype for monitoring and managing electric energy using artificial intelligence (AI). This system, composed of various interconnected components, collects real-time data on the electric flow and then analyses it to make decisions that improve the efficiency and stability of the network.

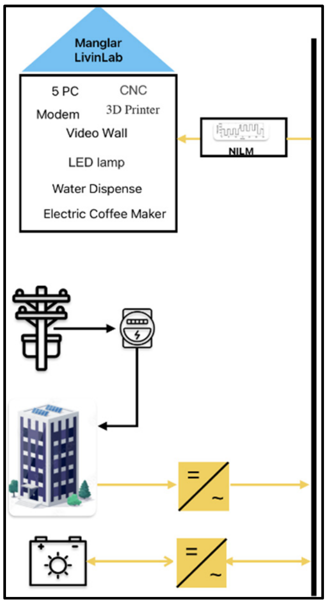

Figure 3: Energy management system for "Manglar Living Lab".

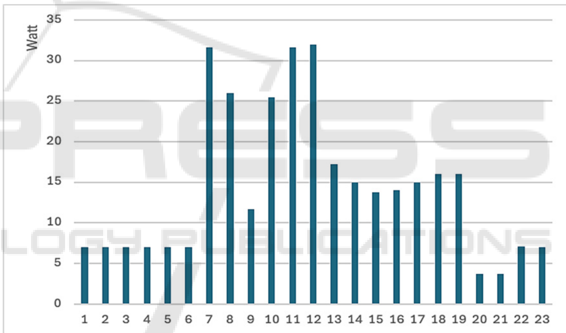

Figure 4: Average daily laboratory consumption.

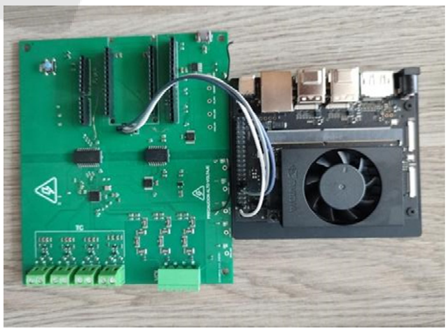

Figure 5: Integration of ADE9000 and jetson Orin.

Firstly, current and voltage sensors, located at strategic points in the electrical network, capture crucial information about the magnitude of the electrical flow. This data is transmitted to the ADE9000, an integrated circuit specializing in the measurement of energy variables such as RMS voltage, RMS current, active power, and power factor, among others. This device acts as a collection and preprocessing center, and in turn, sends the processed information to the Jetson Orin, a powerful NVIDIA computing platform with 8GB of RAM and an Arm® Cortex-A78AE v8.2 6-core processor, via the SPI communication protocol (see figure 5).

The Jetson Orin is the brain of the system, where the AI algorithms responsible for analysing the received data reside. These algorithms, trained to recognize patterns and anomalies, can detect fluctuations in demand, identify possible network failures, and even predict future energy needs in real time. This analytical capability allows the system to make intelligent decisions to optimize energy distribution, balance the network load, and ensure a stable supply.

Finally, the Jetson Orin, through a Wi-Fi connection, communicates with a cloud-based management system. This connection allows remote monitoring of the network, storage of historical data for long-term analysis, and updating of AI algorithms with new information (see figure 6). Data is visualized and stored in InfluxDB.

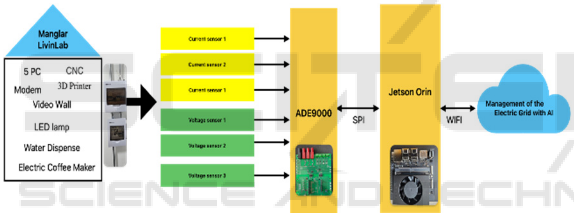

Figure 6: Average daily laboratory consumption.

Figure 7 depicts the fluctuation of voltage, current, and power within the Manglar living lab's electrical system over time. There is a clear correlation between the three variables: an increase in current corresponds with an increase in power, and a slight decrease in voltage. This suggests that the system is subjected to a variable load, and that voltage can be affected when energy demand is high. Also, in 8 displays the fluctuation of frequency and power factor in an electrical system over time. The frequency, although it remains close to 59.95 Hz, presents variations that, although they appear small, can indicate instabilities in the generation or distribution of electrical energy. A fluctuating power factor such as the one observed in the second chart, with values ranging between 0.6 and 0.9, suggests that electrical energy is not being used efficiently. It is important to monitor these fluctuations, since they can affect the performance and useful life of the equipment, as well as increase energy consumption and associated costs.

Therefore the Artificial intelligence (AI) presents a range of possibilities to optimize instabilities in electrical loads and the identification of laboratory equipment. Potential strategies include:

- Optimizing energy use: AI can identify consumption patterns and recommend strategies to optimize energy use, such as scheduling the operation of high-consumption equipment during periods of low demand or implementing automatic shutdown systems.
- Responding to unforeseen events: AI can detect anomalies in consumption and react autonomously to unforeseen events, such as demand peaks or supply failures, by activating mitigation measures to minimize the impact on loads.
- Machine learning platforms: These platforms allow for the development and training of AI models for prediction and control purposes.

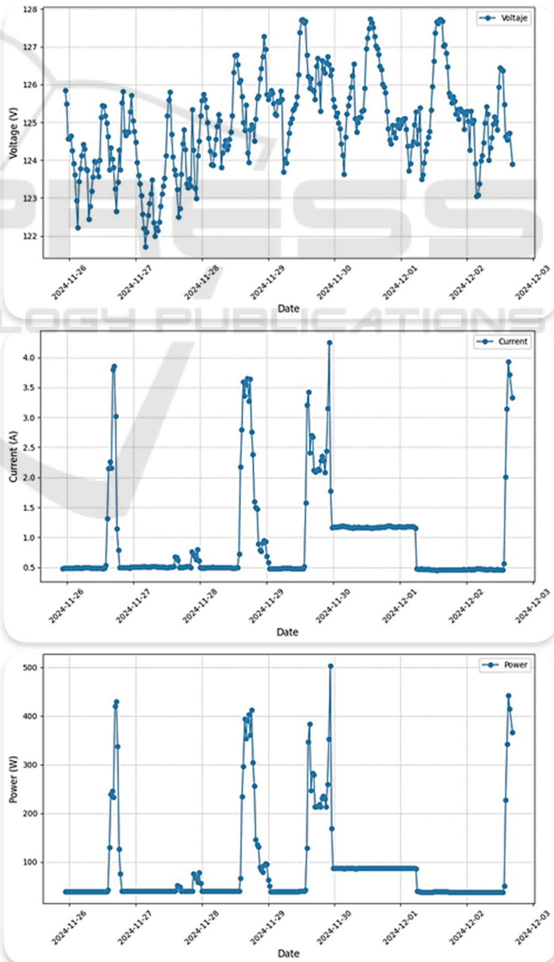

Figure 7: Average voltage, current and power variables with the prototype.

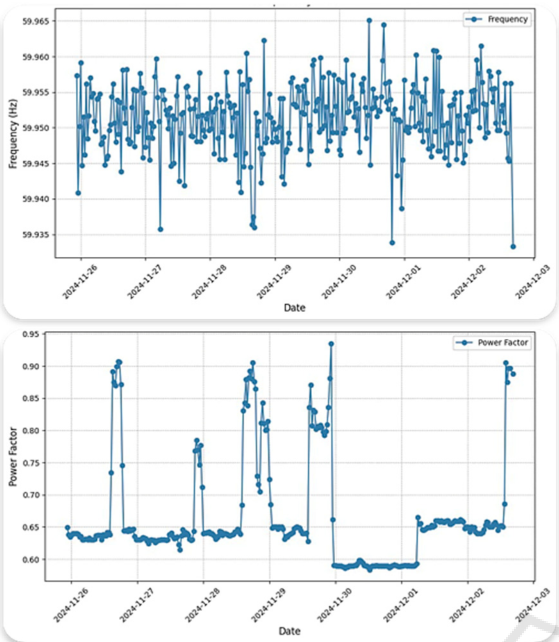

Figure 8: Frequency and power factor measurement with prototype.

4 CONCLUSIONS

The MANGLAR Living Lab, equipped with a smart microgrid prototype and AI technology, is being tested as a tool for managing electrical energy in laboratory environments. The results obtained so far are visualized and stored in InfluxDB. Storing this data will allow us to understand the behavior of the load profile and perform AI training for energy management. It also helps us predict future energy needs, which facilitates decision-making and resource optimization.

Despite the progress made, the MANGLAR project is in its initial phase and presents opportunities for future research. A more comprehensive evaluation of the long-term impact of the intelligent energy management system is required, including cost-benefit analysis and scalability assessments. Furthermore, the integration of new renewable energy sources, such as wind or biomass, and the development of more sophisticated AI algorithms could further improve the efficiency and resilience of the microgrid.

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