23rd International Conference on Renewable Energies and Power Quality (ICREPQ'25)
Tenerife (Spain), 25th to 27th June 20245
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.23, September 2025

Empowering Rural Communities through Microgrids: The CEL-RURAL Project Approach

L. Vargas[1], R.Vidal[1] and J.R.D. Frejo [2]

[1] Instituto Nacional de Técnica Aeroespacial (National Institute of Aerospace Technology)

Ctra. San Juan del Puerto – Matalascañas km.34, 21130 Mazagón (Huelva), Spain

[2] Departament of Ingeniería de Sistemas y Automática, Universidad de Sevilla.

C/ Camino de los Descubrimientos s/n., Sevilla 41092, Spain)

e-mail: vargasvl@inta.es, rvidana@inta.es, jdominguez3@us.es

Abstract.

The CEL RURAL project has been conceived with the objective of promoting the implementation of renewable energy solutions in rural areas, with a view to enhancing the development of sustainable energy systems. The project has three overarching aims: first, to create energy self-sufficient Local Energy Communities (LECs); secondly, to optimise energy efficiency; and thirdly, to monitor energy systems for improved operation. In addition, the project focuses on community engagement, fostering innovation, and ensuring compliance with local and international regulations. The project is currently testing microgrid solutions and energy storage technologies, including the use of lithium-ion (Li-ion) batteries in one of the pilot plants, specifically LiFePO4. This is being done through four pilot plants across Portugal and Spain.

Keywords.
Energy communities, local energy communities (LECs), energy storage, microgrids.

1. Introduction

The energy sector is currently facing a significant challenge, primarily due to the limited availability of reliable and cost-effective energy sources, as well as the urgent need to mitigate the environmental impacts caused by the use of polluting fossil fuels such as coal. Achieving the expected emission reductions requires a radical transformation of the energy sector. In response to the Paris Agreement, the European Green Pact sets as its main objective to make Europe the first carbon neutral continent by 2050 and includes a set of policy initiatives driven by the European Commission.

By 2030, the EU aims to reduce greenhouse gas emissions by at least 55% compared to 1990 levels. To meet this challenge, many countries are adopting a variety of renewable energy sources (RES) as part of a transformative approach towards a more sustainable energy model [1].

In this context, rural local energy communities emerge as voluntary groupings of individuals, companies, public entities, or other organizations that collaborate to develop energy projects, activities, and services aimed at generating environmental, economic, and social benefits. These initiatives not only promote environmental sustainability but also improve energy security and generate local economic development.

LECs play a key role in the energy transition by addressing economic, environmental, and social aspects of sustainability [2]. From an economic perspective, they enable their members to reduce energy costs and contribute to the fight against energy poverty. Technically, these communities bring energy generation closer to the points of consumption, which minimises losses in the electricity system and fosters greater competition.

Despite their potential, rural local energy communities face challenges, including regulatory barriers, investment costs, and technical complexity. However, advancements in decentralized energy technologies, digital monitoring tools, and innovative business models are facilitating their implementation. By leveraging these opportunities, local energy communities can not only achieve greater energy autonomy but also serve as a model for sustainable energy solutions in both rural and urban environments.

This project is composed of a group of partners who will contribute their expertise and capabilities. FEGAMP, DipÁvila, CIM Cávado, and AREAL are well-acquainted with the specific needs of their regions and serve as key liaisons with local authorities in the areas where the four pilot projects will be implemented. ITG, INTA, US, and UAlg will contribute their knowledge in the design and management of energy systems for these types of communities.

2. Description of the project

The CEL RURAL project was born out of these needs, with the aim of promoting the implementation of renewable energy in rural areas, thus strengthening the development of a sustainable energy system.

2.1 Project objectives

The Project aims to do the following:

- Promoting energy sustainability through the utilization of energy sources. This not only encompasses the installation of efficient energy infrastructures but also the promotion of practices that reduce environmental impact and optimize the use of natural resources. The long-term goal is to create an energy self-sufficient Local Energy Community (LEC), reducing dependence on non-renewable sources and minimizing the carbon footprint.

- Monitoring all energy systems to ensure their proper daily operation. This involves the use of advanced monitoring systems to track the performance of installations in real-time, proactively detect and resolve issues, and adjust operational parameters as necessary to maximize efficiency and energy generation. Furthermore, agile and effective procedures for incident and failure management will be implemented to minimize downtime and service interruptions.

- Optimizing energy efficiency in the management of the LEC. This includes the application of advanced technologies and management strategies to ensure that the generated energy is used as efficiently as possible. The objective is to develop an energy system where production and consumption are balanced, reducing losses and maximizing the use of resources.

- Efficiently managing financial resources, ensuring transparency in the distribution of costs and benefits, and seeking new funding sources. Fairly managing the revenues from the sale of energy surpluses and creating reserves for future investments and maintenance.

- Establishing mechanisms that facilitate participation and information exchange among community members. Specific objectives include launching educational and awareness programs on energy and sustainability and creating effective communication channels.

- Fostering innovation and continuous development. This involves integrating technological innovations and best practices into the LEC's operations to optimize performance and sustainability. Additionally, collaboration with academic and research institutions will be promoted to support the development of new energy solutions and improve existing practices.

- Complying with all local, national, and international regulations to ensure the legitimacy and continuous operation of the LEC. This includes not only legal aspects but also quality and safety standards.

3. Pilot Plants in the CEL-RURAL Project

The CEL-RURAL project involves the implementation of four pilot plants in different locations, each with specific technical characteristics and objectives. These pilot plants serve as testbeds for the development and validation of microgrid control strategies, enabling the integration of renewable energy sources and the implementation of advanced control techniques.

Additionally, they aim to identify and address practical challenges associated with the deployment of energy communities, including regulatory, economic, and operational barriers. By evaluating these real-world obstacles, the project seeks to facilitate the widespread adoption of renewable-based microgrids while promoting local engagement and participation in sustainable energy solutions. Below is a detailed description of each pilot plant.

These four pilot plants represent diverse applications of microgrid technology in rural and community settings. By integrating renewable energy sources, energy storage, and advanced control strategies, the CEL-RURAL project aims to create scalable and replicable solutions for sustainable energy development.

3.1 Culatra Island Renewable Energy Pilot

The Culatra Island pilot plant is located in the Algarve region of Portugal and aims to transform the local community into a model of sustainability through the efficient use of renewable energy. This initiative seeks to create a resilient, self-sufficient energy model tailored to the island's specific needs, with active involvement from the local population.

The installation consists of five photovoltaic generation units with a total installed capacity of 85.8 kWp and an estimated annual production of 156.4 MWh. The system also includes a battery storage capacity of 46.08 kWh, allowing for improved energy management and reliability. The energy produced is distributed among residential users, small businesses, and community facilities such as schools and health centers. Additionally, an advanced monitoring system records real-time data on energy generation and consumption, facilitating optimal load balancing and efficiency improvements.

3.2 Fontiveros Pilot

Located in the municipality of Fontiveros, Ávila, Spain, this pilot plant is based on a rooftop photovoltaic installation at the San Juan de la Cruz Cultural Center. The site was chosen due to the availability of a publicly owned building suitable for solar panel installation.

The facility includes 70 bifacial photovoltaic panels with a total peak power of 30.8 kWp and an inverter capacity of 25 kW. To enhance energy management, the system is complemented by a 20 kWh battery storage unit. The energy generated is used to supply nine local consumption points, including municipal buildings owned by the City Council and the Provincial Council of Ávila. The integration of this microgrid supports the creation of a broader local energy community, aiming to expand its reach in the future.

3.3 Xermade Pilot (CEL XERando)

The Xermade pilot plant, located in Galicia, Spain, was selected through a competitive process initiated by FEGAMP to develop a rural energy community. The project involves 42 members, including households, small businesses, and municipal facilities.

The installation consists of 80 photovoltaic modules with a total peak power of 40 kWp. Energy conversion is handled by two inverters with a combined capacity of 35 kW. The system also includes a 10 kWh battery storage unit, optimizing self-consumption and energy distribution. The plant is expected to generate approximately 68 MWh per year, and different energy distribution scenarios will be tested using project-developed algorithms to maximize environmental, social, and economic benefits.

3.4 Vila Verde Cultural Center Pilot

Installed in the historic building Adega Cultural de Vila Verde in Portugal, this pilot plant integrates renewable energy with cultural and community functions. The site, originally a cooperative winery, has been repurposed into a multipurpose center hosting exhibitions, events, and educational activities.

The microgrid installation features a photovoltaic system mounted on the building's roof, covering an area of 3,000 m². This system supplies energy to multiple community facilities within a 2 km radius, including schools, libraries, and public administration buildings. The initiative aims to demonstrate how historical sites can be adapted for modern sustainable energy solutions, reinforcing the connection between heritage conservation and technological innovation.

4 Energy storage technology tested in CEL-RURAL project

The Laboratory of the Renewable Energy Area of INTA in El Arenosillo (Huelva) is equipped with various test benches for the evaluation and demonstration of electrochemical technologies for the storage and generation of electrical energy (batteries, supercapacitors, and fuel cells) at the cell and module scale, for both stationary and mobile applications.

The INTA will provide support and participate in the evaluation of the technical solutions implemented in the pilot projects, as well as in the technical aspects of the guidelines for the deployment of communities, tender models, collaboration agreements, and training activities.

Additionally, it will be responsible for investigating storage systems complementary to the LEC that optimize the use of the generated energy. Regarding the various energy storage technologies, INTA will focus on Lithium-Ion (Li-ion) batteries, which are a viable option for energy backup in energy communities due to their high energy density and fast charging times. Specifically, characterizations and profiles will be carried out on LiFePO4 batteries, which can withstand higher temperatures and have a lower cost compared to other lithium batteries.

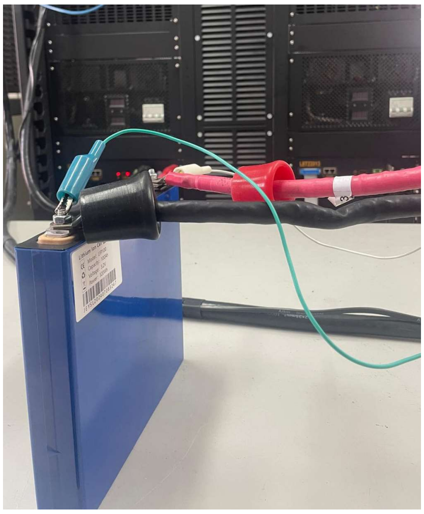

Figure 1: Experimental testing of the LiFePO4 battery

The following figure provides a detailed schematic representation of the operational principles of LiFePO4 (Lithium Iron Phosphate) batteries, illustrating the key involved in their functioning.

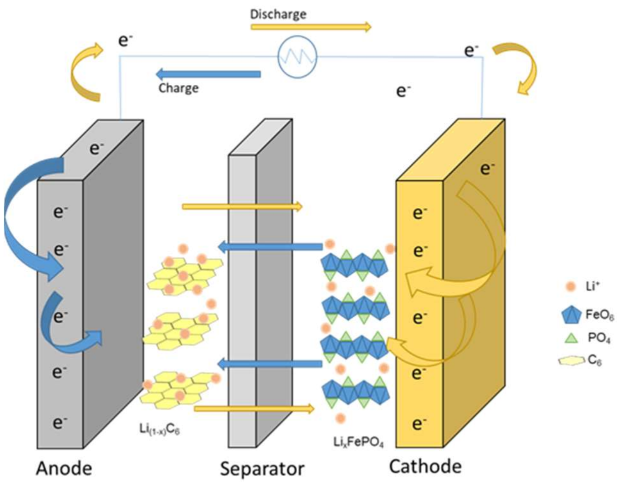

Figure 2: LiFePO4 battery operating mechanism

5 Modeling and Control of Microgrids in the Context of the CEL-RURAL Project

The CEL-RURAL project aims to develop and optimize microgrid systems for rural applications. To study and control a microgrid, the first necessary step is to develop a model of the system. In the context of the CEL-RURAL project, a mathematical model of the four pilot plants will be developed using Simµgrid. Simµgrid is a Matlab/Simulink library that includes mathematical models of key microgrid components such as batteries, fuel cells, electrolyzers, and renewable energy sources (RES). The models provided by Simµgrid are simple, configurable, and nonlinear, allowing for the simulation and testing of energy management system (EMS) controllers. This tool facilitates the design of microgrids by enabling the evaluation of different control strategies in a simulation environment.

For example, the pilot plant on the island of Culatra has been modeled using Simµgrid (see Figure 1). These models will allow for simulations and the design of controllers to test their performance before implementation in the real system. Through these simulations, we can evaluate fault tolerance mechanisms, optimize energy dispatch strategies, and improve the overall resilience of the microgrid to disturbances.

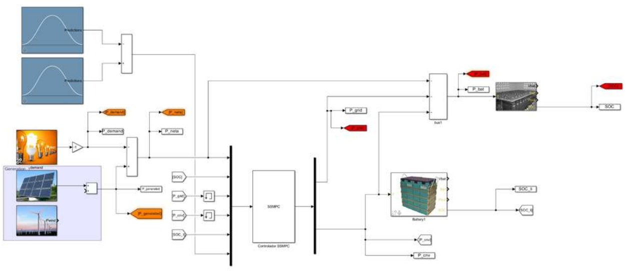

Figure 3: Simulink model of the Culatra pilot plant using Simµgrid for microgrid simulation and control design

To validate the behavior of the Culatra microgrid model and assess the effectiveness of the control strategies, a set of simulation experiments was conducted using realistic operational parameters. The photovoltaic system has a capacity of 85.8 kWp, with an estimated annual production of 156.4 MWh. The battery system includes a storage capacity of 46.08 kWh, with charge and discharge power limited to ±4.6 kW (10% of capacity), and a state-of-charge (SOC) operating window between 10% and 90%. The system is also constrained by a grid exchange limit of ±500 kWh. These constraints reflect the technical and regulatory boundaries of the pilot installation.

To improve the operational performance of the pilot microgrids, we will implement Model Predictive Control (MPC) algorithms [3]. Also referred to as receding horizon control, MPC sets itself apart from traditional control methods by employing optimization techniques to compute control actions based on predefined cost functions and constraints. This approach has been extensively utilized in distributed generation (DG) systems with power converters and in microgrids featuring multiple renewable energy sources (RES).

MPC provides several key benefits: (1) it facilitates the explicit incorporation of multiple constraints from both control and physical perspectives; (2) it allows for optimal system operation enhancing dynamic performance; (3) it directly generates control signals, simplifying implementation; and (4) it allows seamless integration with various solving algorithms, making complex optimization problems more manageable. Furthermore, MPC enables predictive scheduling, allowing for proactive adjustments in response to forecasted energy production and demand variations, which is relevant for microgrids integrating high shares of renewables.

Despite its advantages, implementing MPC in microgrids presents several challenges. The intermittent nature of RES, the need for precise load sharing, the mitigation of circulating currents, and ensuring grid stability are critical issues that must be addressed. Therefore, the CEL-RURAL project will explore the hierarchical control of microgrids using MPC to tackle these challenges effectively.

By leveraging Simµgrid for modeling and MPC for control, the project aims to develop robust, efficient, and sustainable microgrid solutions for rural energy applications. In particular, emphasis will be placed on designing adaptive control mechanisms that can dynamically adjust to evolving grid conditions, thereby enhancing operational reliability and efficiency.

6. Conclusion

This document provides an overview of the CEL RURAL project, describing its objectives and a brief summary of one of the technical activities carried out to contribute to solving the energy poverty problem in Spain and Portugal.

The objective of the testing and modelling activities described in this paper is to simulate and demonstrate the operation, in controlled environments, of pilot installations and different commercial or pre-commercial technologies that can be used in rural LECs and to simulate their interrelationship with other systems and between consumers in the community.

The partners' experimental facilities will allow the development of digital energy twins of the pilot facilities and simulate and test their behaviour under different scenarios, considering extensions of the facilities with new technology and the application of new business models in the community.

Future work will focus on several key areas: validating Model Predictive Control (MPC) strategies using real-world operational data; comparing MPC with alternative microgrid optimization techniques such as rule-based control and heuristic algorithms; and assessing the economic feasibility of scaling LECs beyond the current pilot locations.

Acknowledgement

The project CEL RURAL (Ref. 0081_CEL_RURAL_6_E) is co-financed by the European Regional Development Fund (ERDF), within the INTERREG VA Spain-Portugal cooperation programme (POCTEP).

References

[1] Tracker, C. A. (2021). Warming projections global update. *Climate Analytics and New Climate Institute: Berlin, Germany*.
[2] Lowitzsch, J., Hoicka, C. E., & van Tulder, F. J. (2020). Renewable energy communities under the 2019 European Clean Energy Package–Governance model for the energy clusters of the future. *Renewable and Sustainable Energy Reviews*, *122*, 109489.
[3] Bordons, C. Garcia-Torres, F. & Ridao, M.A., *Model Predictive Control of Microgrids*, Springer, 2020