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Different electrochemical energy storage systems in a smart microgrid

Análisis de rendimiento de sistemas de almacenamiento de energía electroquímica de la microrred inteligente CEDER-CIEMAT

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KEYWORDS
Batteries, energy management, microgrid.
Baterías, gestión de energía, microrred.

ABSTRACT: As the utilization of renewable energy continues to grow, microgrids have played a vital role in their generation. Batteries have emerged as the most commonly utilized storage system to effectively store this energy. This paper proposes a novel approach to manage energy consumption at the Centre for the Development of Renewable Energy (CEDER) by leveraging both lithium-ion and lead-acid batteries. This computer-based management system controls the flow of energy that can be charged or discharged in 15-minute intervals. By optimizing the use of both battery types, the energy consumption of CEDER has been reduced by an estimated 90 to 200 kWh, depending on the specific case study.

RESUMEN: A medida que la utilización de energías renovables continúa creciendo, las microrredes han desempeñado un papel vital en su generación. Para almacenar eficazmente esa energía, las baterías han surgido como el sistema de almacenamiento más utilizado. Este artículo propone un enfoque novedoso para gestionar el consumo de energía en el Centro de Desarrollo de Energías Renovables (CEDER) aprovechando tanto las baterías de iones de litio como las de plomo ácido. Este sistema de gestión informático controla el flujo de energía que puede cargarse o descargarse en intervalos de 15 minutos. Al optimizar el uso de ambos tipos de baterías, el consumo de energía del CEDER se ha reducido en aproximadamente 90 a 200 kWh, dependiendo del caso de estudio específico.

1. Introduction

A microgrid is a collection of interconnected loads and distributed energy resources (generation sources and storage systems) within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. These microgrids can function while connected to the main grid, or operate independently (islanded mode). They are gaining popularity as an alternative energy solution for supplying power to various locations such as large areas, small communities, buildings, or individual households[1]. Renewable energy resources can be used to generate power in different ways, with photovoltaic (PV) and wind energy being the most frequently utilised methods.

Microgrids provide economic benefits and a more reliable power supply compared to traditional grids, despite relying on intermittent power sources such as solar PV and wind energy. These microgrids are unique or customized power networks that can be designed using various control and topology methods, depending on the specific objectives and requirements.

Recently, there has been a growing effort to reduce greenhouse gas emissions by utilising renewable energy sources. This has created a new landscape where sustainable energy systems have become critical. Microgrids have emerged as a viable alternative to carbon-emitting energy systems, playing a significant role in this new paradigm. Additionally, microgrids are capable of managing frequency regulation, peak shaving, and energy arbitrage, which has helped reduce carbon dioxide (COx) emissions[3].Most microgrids operate on alternating current (AC) as it is the most commonly used supply for load networks. AC can be efficiently transformed up or down by using a transformer. Nevertheless, direct current (DC) microgrids have gained traction recently due to their higher power conversion efficiency. The efficiency of DC systems depends on the technology of the primary source and the balance between AC and DC loads. Advanced primary source technologies and an optimal ratio of AC to DC loads are key factors in enhancing system performance.[4].

Microgrids have become increasingly popular to prevent network destabilisation caused by renewable generation facilities. These fluctuations in load are managed with advanced control and information technology [5]. An Energy Management System (EMS) is necessary to ensure efficient and secure utilisation of distributed energy resources, which includes both, supply and demand side management while meeting system constraints. The EMS of a microgrid is essential to achieve an economical, sustainable, and reliable operation[6]. Distributed control allows the system to accommodate an information event, so that in case of any failure in a generation unit, the distribution system does not shut down, thus preventing cascade failure[7]. T hree main types of EMS optimisation methods can be found: computational intelligence, mathematical programming, and hybrid techniques[8]. These methods help improve the EMS' energy efficiency using techniques such as Artificial Intelligence (AI), conventional approaches, and metaheuristic-based methods [9]. A proposed optimal EMS can also help schedule resources and improve the performance of PV, wind, or tidal microgrid utilisation [10].

Storage technologies are crucial to supporting intermittent power generation. Energy demand fluctuates throughout the day and year, leading to peak and valley demands that are influenced by climatic conditions and other factors[11]. Therefore, storage systems play a key role in buffering energy variations, compensating for renewable intermittency, and mitigating load uncertainties to improve the stability of the entire microgrid. By managing the energy flow and reducing the operating losses, the presence of energy storage in the microgrid also enhances its efficiency[12].

The key technical and economic characteristics of renewable technologies that need to be managed include their rated power, efficiency, energy density, lifespan, cycle times, and capital costs, which are particularly important when establishing microgrids [13]. Although the cost of storage devices remains high, existing methods for sizing storage and renewable resources rely on hourly solar insolation, wind speed, and load data [14]. In [15], an improved approach is proposed to address the battery energy storage system (BESS) planning, which considers the BESS's useful life and capacity degradation. To account for these factors, the Mixed Integer Linear Programming (MILP) method is used to determine the optimal size, technology, depth of discharge (DOD), and replacement year for the BESS.

Nowadays, the progress of electrochemical energy storage has significantly accelerated due to its cost-effective performance, independence from natural conditions, easy installation, and adaptable utilisation [16].

Storing energy in the form of electrochemical reactions has become a crucial aspect of developing renewable energy solutions in microgrids. This involves using various types of batteries that convert the energy stored in their active materials into electrical energy through a process of oxidation-reduction. Electrochemical technologies have emerged as a competitive and readily available option in the market, offering a high degree of cost-effectiveness, as well as good power and energy densities. Moreover, the choice of battery technology is typically based on the economic capacity of the donor or investor [3], [17]. Battery systems offer a range of useful services, including frequency and voltage regulation, demand response, and congestion management[18].

Lead-acid and lithium-ion batteries are the top choices for electrochemical energy storage in microgrids. Lead-acid batteries have been widely used due to their reliability and cost-effectiveness[19]. However, the operating conditions of microgrids can lead to battery stress, reducing their lifespan and requiring frequent replacements[20]. To counteract this, periodic equalisation charges are necessary[21]. Despite their lower energy density and weight ratio, lead-acid batteries are still capable of providing microgrids with significant currents while maintaining a relatively high-power density[22].

The lithium-ion battery is a well-established energy storage solution in the electric market, with high energy density and efficiency. The cathode and anode materials determine battery capacity. Although the power variation frequency of the battery is low and charging and discharging times are long, its higher energy density and volumetric power make it a suitable option for producing small units with a small size [23]. Lithium-ion batteries are widely used in renewable energy grids and microgrids due to their long life, safety, and lower environmental impact compared to other batteries, such as lead-acid batteries, making them an ideal solution for energy storage[24], [25].

Lithium iron phosphate (LFP) batteries are currently one of the most popular types of lithium-ion batteries due to their low cost of raw materials, minimal toxicity, environmental friendliness, excellent safety features, strong cyclic performance, and long lifespan. These qualities make them a highly desirable option for use in microgrids[26].

The main objective of this research was to investigate the impact of lead-acid and lithium-ion batteries on energy consumption patterns and peak demand reduction in CEDER microgrid. The study involved discharging both types of batteries simultaneously while adjusting their power setpoint to optimise their efficiency. Furthermore, the lead-acid batteries were charged during periods of energy surplus, utilising the microgrid's energy generation systems.

The paper is structured into three main sections. Section 2 provides an overview of CEDER, including its energy generation sources, loads, and storage systems. Section 3 presents the practical case study where batteries were used, and the results were analysed. Finally, the paper concludes with Section 4, which summarises the key findings and implications of the study.

2. Overview of CEDER microgrid

CEDER depends on CIEMAT (Centre for Energy, Environmental and Technical Research), and it has a smart microgrid that is operated and administrated in real time.

2.1. Microgrid

CEDER's microgrid is connected to a 45 kV power line and serves a 45/15 kV (1000 kW) substation.

From this substation, medium-voltage power is distributed via an underground network of eight transformer substations, which adjust the power to low-voltage, three-phased supply delivering 400 V. The contracted power is 135 kW.

The network can operate as a ring, enabling a medium-voltage perimeter some 4200 metres long, and as a radial network (see Figure 1). All of the components that comprise the systems for distributed generation, distributed electricity storage and loads are connected at low voltage.

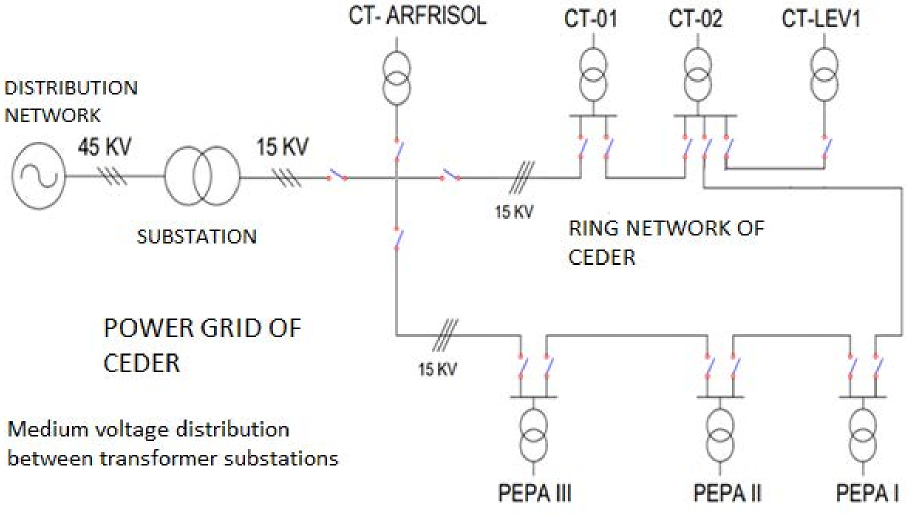

Figure 1 Medium-voltage distribution between transformation centres.

2.1.1 Generation systems

The following elements of distributed generation constitute the grid at CEDER:

- Wind-energy systems: Ceder has 19 sites available for installing wind turbines. Currently, 8 of them are occupied and 5 of them are connected to the microgrid:
    - Atlantic AOC: 50 kw (diameter 15 m downwind).
    - Ennera: 3.5 kw (Ø 4.36 m upwind).
    - Ennera Windera S: 4.2 kw (Ø 4.36 m upwind).
    - Ryse E5: 3.5 kw (Ø 4.3 m upwind).
    - Norvento NED100: 100 kw (Ø 22 m upwind)
- PV systems: There are 11 PV systems (see Table 1) connected to the microgrid. All these systems are south-orientated due to the northern hemisphere location of CEDER.

Table 1 PV Systems at CEDER.

Name	Power (kW)	Technology
Arfrisol	10	monocrystalline
Building 3	10	monocrystalline
Building 9	20	Thin film
LECA1	20	polycrystalline
LECA2	20	polycrystalline
PEPA III	5	polycrystalline
Energysis	10	monocrystalline
Turbine	15	monocrystalline
PEPA II	20	monocrystalline
Building 2	5	monocrystalline
Rios	30	Bifacial monocrystalline

- Micro-hydropower plant: with a Pelton turbine and asynchronous three-phase generator directly coupled to the turbine impeller, with a maximum power of 60 kW. The turbine head is approximately 62 m and consists of three water tanks.
- Generator set: 100 kVA. It functions as a generation element synchronising with the grid.

2.1.2 Storage systems

The CEDER microgrid integrates different storage technologies, which make the centre a flexible environment for demand management.

- Mechanical storage: The pumped hydro-storage system associated with the micro-hydro power plant consists of a pumping system with the following components:
- 4 centrifugal pumps of 7.5 kW each.
  - 3 water-storage tanks:
    - Primary tank ~ 500 m^3 located in LEVI.
    - Upper tank ~ 1500 m^3 placed 16 m below the primary tank.
    - Bottom tank ~ 1900 m^3 placed 70 m below the upper tank.
- Electrochemical storage: There are 3 storage systems connected to the microgrid, we will see in the next chapter.

2.1.3 Loads

A microgrid must be completed with loads that will request energy to perform their functions (motors, lighting, boilers, laboratories, etc.). Ensuring the supply of these loads, or at least the priority ones, will be the responsibility of the microgrid manager.

In the CEDER, these loads are the ones that allow its daily operation; that is, the different buildings that make up the centre are the ones that demand energy for their operation. These loads have different consumption patterns:

- Installations that behave like an industrial environment.
- Installations that behave like a domestic environment.
- Installations that behave like a service sector.

In this way, the microgrid has different consumption profiles, which will allow for different adjustments to generation and storage, based on the varied behaviour of existing demand.

2.1.4 Management system

The control system of the CEDER microgrid is made up of three blocks [27] (see Figure 2):

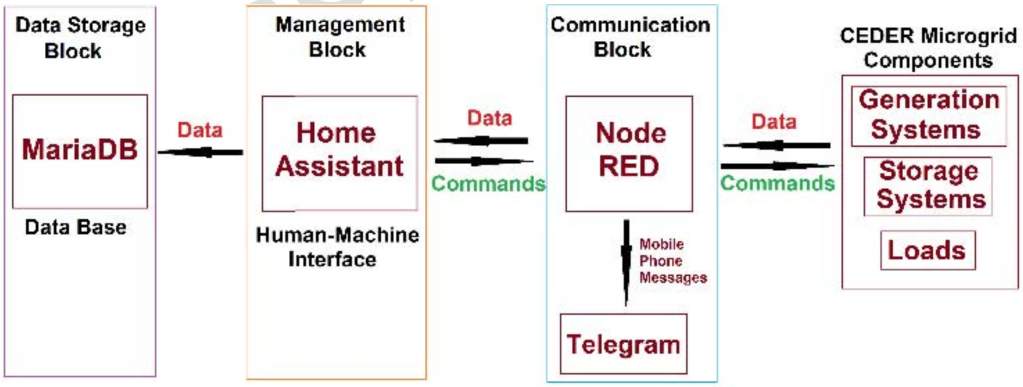

Figure 2 Elements of CEDER microgrid control system [28]

- Communication block: It is based on two open-source software programmes, NodeRED [29] and Telegram. NodeRED integrates different communication protocols (Modbus, MQTT, HTTP, etc.) that allow the control system to connect with the different generation, storage, and consumption systems that make up the CEDER microgrid. This way, information can be collected from each of them, and operating instructions can be sent to them as established. Telegram allows the management system to communicate with the microgrid operators through their mobile phones, for sending alarms and notices regarding the operation of the microgrid.
- Management block (EMS): It is based on an open-source software that functions as a user interface (HMI): HomeAssistant [30]. It allows real-time monitoring of the elements (generation, storage, and consumption) that make up the microgrid, giving operating instructions to each of them and programming the energy strategies defined by the network operators. Additionally, it is accessible from any point with an internet connection.
- Data storage block (Database): It is based on an open-source software program, MariaDB [31]. It is a relational database that allows for the storage of information from all the generation, storage, and consumption elements of the microgrid for analysis and processing. It allows the storage for instant values, i.e., real-time data per second, thanks to programmed events and calculations (minute or 15-minute averages, such as those used by the energy distribution company that supplies to CEDER), all this through SQL programmes.

This is important because, in addition to real-time monitoring for immediate decision-making, it is essential to store and analyse the data to establish medium and long-term management strategies.

2.2 Electrochemical storage systems

This section presents the different battery-based ESS connected to the CEDER microgrid [32].

- **Lead-acid battery system I:** comprised of 120 cells of 2 V each (total 240 V) Tudor 7EAN100T (Classic OPzS 1080) lead-acid batteries, with a capacity of 1,080 Ah (260 kWh).
  It is connected to the microgrid via a 50 kW DC/AC inverter with an isolation transformer and an inductance.
- **Lead-acid battery system II**: comprised of 120 sets of 2 V (240 V) Tudor 5EAN70T (Classic OPzS 765), lead-acid with a capacity of 765 Ah (180 kWh).
  It is connected to the microgrid via a 20 kW DC/AC inverter with an isolation transformer and an inductance.
- **Lithium Iron Phosphate Batteries (LFP)**: The system comprises two racks of 14 modules, with 196 cells per module, each of 3.2 V and 50 Ah (30 kWh). This is connected to the microgrid via a 30 kW inverter.

3. Results and analysis

The carried-out study examined three different scenarios for reducing energy consumption in a centre. Lead-acid batteries and lithium-ion batteries will be used in order to achieve this. The study analyses three different time periods to determine how energy expenditure can be reduced. First, it assesses the impact if battery discharge during a two-hour peak energy consumption period. Next, it examines an eight-hour period on a day with high energy consumption throughout the day. Finally, it studies the effect of battery use during a five-hour morning period, where nearly 80 kW was consumed. Table 2 provides information on the maximum power output of lead-acid batteries and LFPs during each of these periods. The three approaches to energy reduction differ based on the power and timing of battery discharge.

Table 2 Battery capacity discharge at different power settings.

Time	PEPA I (kW)	PEPA II (kW)	LFP (kW)
2 h	31	15	12
5 h	18	11	4
8 h	15	8.2	2.8

Next, Figures (3-7) display data gathered every 15 min, providing us with a fairly accurate depiction of energy production and consumption during the day. The red line represents consumption without the use of batteries, whereas the blue line represents consumption with the use of batteries.

In the first scenario, we examined the reduction in high-energy consumption spikes for a total of two hours and forty-five minutes, as shown in Figure 3. We selected February 28 as our target date, which experienced two instances of peak consumption of approximately 110 kW for 15 min interval, if batteries were not employed.

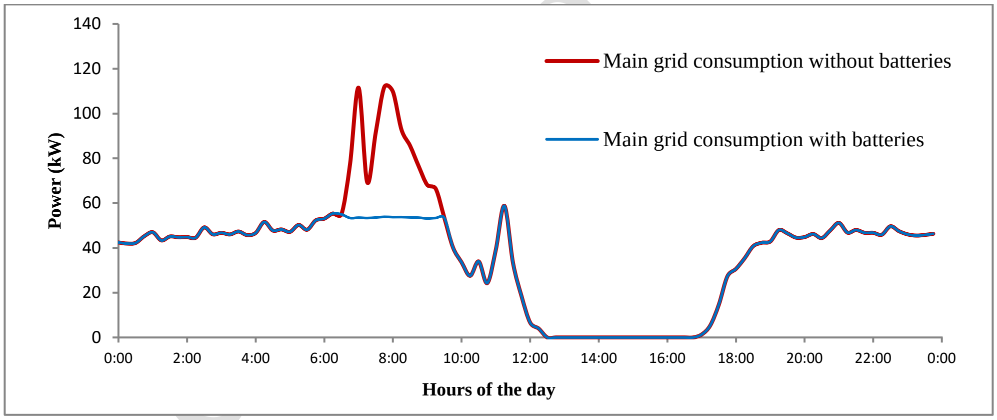

Figure 3 Consumption reduction of 2 h.

To reduce this high-energy use, the batteries were discharged simultaneously, varying the discharge power of each one of them every 15 minutes. In this way, using the batteries, consumption peaks are eliminated and CEDER's consumption pattern is uniform. The batteries have been discharged for 165 minutes, and they delivered 58 kW in some periods of 15 minutes since together, they can supply 58 kW for 2 hours constantly. With this discharge of the three batteries simultaneously, it has been possible to maintain an electrical network consumption of approximately 53 kW, mitigating such high peaks in energy consumption. It means savings of 159.5 kWh on electricity bills.

The next scenario (as illustrated in Figure 4) aims to minimise the consumption of electricity from the grid for an extended period of 8 consecutive hours. The specific day selected for analysis is February 14, which exhibited a higher average consumption rate of over 40 kW from 4:00 a.m. until 12.00 noon, with a peak of 125 kW occurring for one 15-minute interval.

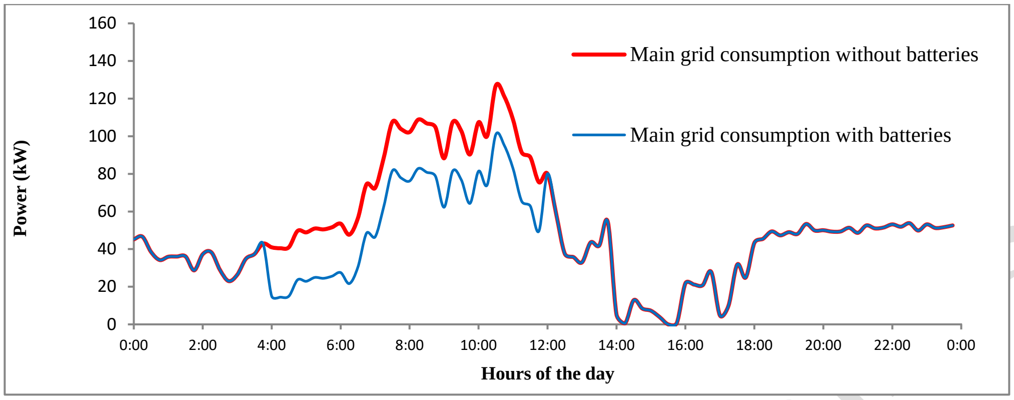

Figure 4 Consumption reduction of 8 h.

During the 8-hour period, the same batteries were employed as in the previous scenario, which could deliver a total power output of 26 kW for 8 hours of power drops. By utilizing the batteries effectively, a total of 208 kWh of consumption from the grid was reduced. Moreover, half of the time during which the batteries were discharged occurred during the high-cost electricity consumption periods.

The final study focuses on reducing energy usage for 5 hours and 15 minutes by combining previous cases (refer to Figure 5). In this study, the batteries were used for 315 minutes and requested a maximum of 36 kW, with discharge values adjusted to maintain a consistent energy consumption rate. As a result, 150 kWh of energy was saved during peak energy cost periods.

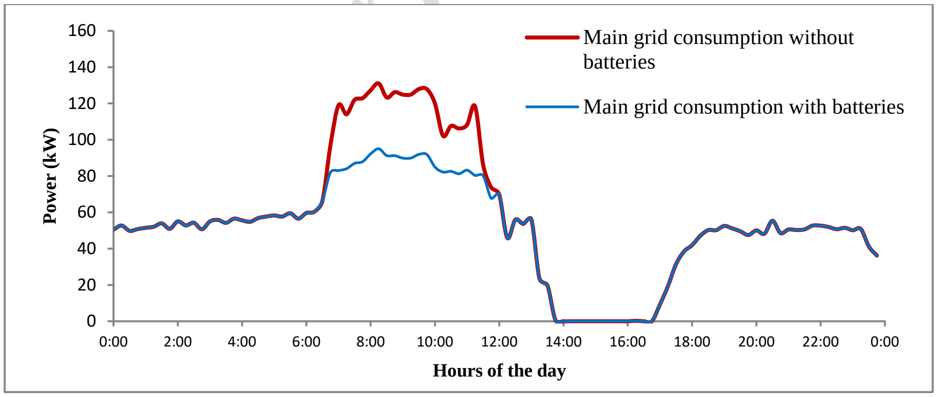

Figure 5 Consumption reduction of 5 h.

In each of the three cases studied, energy generation, including battery contributions, never exceeded the total energy consumption of the facility. Therefore, excess energy was not discharged into the distribution network. Battery discharge occurred each morning, around the start of the workday, and was completed before 2:00 p.m. in all cases, making it easier to manage through the computer during working hours. However, discharging the batteries during periods of higher energy costs, between 6:00 p.m. and 9:00 p.m. when prices peak, would be more cost-effective and beneficial in reducing electricity bills.

To reduce energy consumption at CEDER, batteries are discharged, but before that, they must be charged. This study focused on how to charge the batteries using surplus energy from CEDER's microgrid. Days with high solar radiation levels were selected to ensure high energy production from the PV modules, resulting in surplus energy. The objective is to charge the batteries at different power levels during these periods of excess energy. Computer control is used to vary these settings and has different ways of charging the batteries based on the needs of the centre.

The power setpoints used to charge Lead-acid battery system I are 10 kW and 30 kW. The impact of battery charging on 10 kW is evaluated first. In Figure 6, the blue line represents the energy that CEDER microgrid would have injected into the distribution grid if the batteries had not been charged, while the red line represents the injection into the distribution grid when the batteries are charged. The total time during which energy is discharged into the network is approximately 8 hours. The yellow line represents the charge of the batteries, which can receive a constant 10 kW charge for approximately 8 hours. By charging the batteries at 10 kW, it was possible to stop discharging energy into the network and utilize a total of 78 kWh of energy.

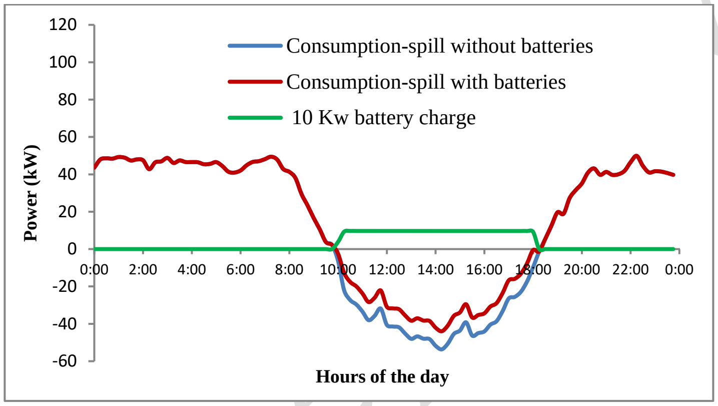

Figure 6 Load study at 10 kW.

Figure 7 illustrates how battery charging impacts a 30 kW power load on the CEDER microgrid. The batteries are charged for 3 hours and 30 minutes and can store up to 100 kWh of energy during that period. The red and blue lines represent energy consumption with and without battery use, respectively, while the yellow line shows the energy charged by the batteries. The battery charge is programmed to regulate the charge setpoint to avoid drawing power from the electrical network and minimise costs.

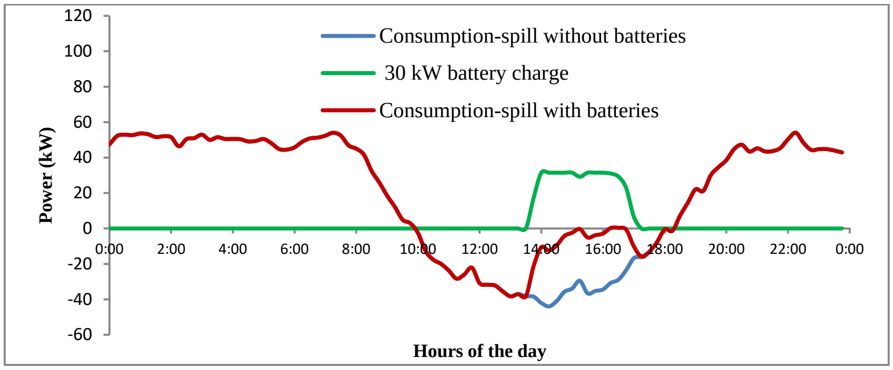

Figure 7 Load study at 30 kW.

4. Conclusions

The aim of this study was to examine the impact of using lead-acid and lithium-ion batteries concurrently to decrease the electricity consumption of CEDER. The analysis involved investigating the performance of both types of batteries during discharge and charge.

Due to the fluctuations in energy generation and consumption in the microgrid, it is necessary to control the energy produced and consumed by means of a computerized system. The computerized system manages the charging and discharging of the batteries, with the overall goal of reducing consumption peaks and minimizing energy consumption over extended periods of time. By optimizing battery usage and maintaining them properly, energy can be used more intelligently, resulting in reduced electricity bills and less energy being sent back to the main grid. In all three scenarios analysed, the use of batteries resulted in significant reductions in energy consumption, 93 kWh, 150 kWh, and 208 kWh for 2-hour, 5-hour, and 8-hour periods, respectively. While the computer system controlled the discharge of the batteries, further energy savings could have been achieved if both batteries were discharged simultaneously to their maximum capacity during each period studied.

The optimal scenario depends on the tariff periods of the distribution company. Ideally, batteries should be used to eliminate the power peaks that can cause a significant increase in the electricity bill if the contracted power is exceeded and, if there is sufficient energy, to reduce consumption in those periods when the tariff is higher.

5. Declaration of competing interest

We declare that we have no significant competing interests, including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

6. Funding

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7. Author contributions

Conceptualization, O.I-M.; Methodology, O.I-M., P.P-C. and M.M.G.; Software, O.I-M. and A.H.J.; writing—original draft preparation O.I-M., A.Z.L., M.M.G and P.P-C.; writing, M.M.G. and O.I-M.

9. Data availability statement:

Data were collected at CEDER-CIEMAT from during year 2022.

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