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Electrical Resilience in Residential Microgrids Powered by Biogas Micro-Combined Heat and Power (Micro-CHP) Systems †

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Abstract: The authors of this paper analyze the use of biogas-powered micro-Combined Heat and Power (micro-CHP) systems for residential microgrids to enhance their resilience during blackouts. With the increasing frequency of natural disasters, ensuring power system reliability has become a critical concern. Microgrids can provide a solution to this problem by integrating distributed energy resources and operating them independently of the grid. The authors of this paper investigate the design and implementation of biogas-powered micro-CHP systems for residential microgrids. The paper concludes with a discussion of the potential of biogas-powered micro-CHP systems as a key component of resilient and sustainable energy systems in the future.

Keywords: resilience; microgrids; micro-CHP; residential buildings; biogas; blackouts; power outage; grid robustness; grid reliability

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1. Introduction

As natural disasters become more frequent, ensuring the reliability of power systems has become a critical concern [1]. Microgrids offer a solution to this problem by integrating distributed energy resources and operating autonomously from the main grid [2]. By generating and storing energy locally, microgrids can mitigate the impact of blackouts caused by extreme weather events or other disruptions to the grid [3]. This paper investigates the feasibility of using biogas-powered micro-Combined Heat and Power (micro-CHP) systems for residential microgrids to enhance their resilience during electric blackouts, addressing technical and economic aspects.

This study analyzes the implementation of a microgrid system based on biogas-powered micro-CHP systems in a specific residential building located in Spain. Apart from building a microgrid that can bear a blackout, the study also explores the implementation of micro-CHP systems to fulfill the thermal demand of the building. Hence, the designed system proposes a solution to cover the complete energy demand, while having a resilient microgrid.

2. Methods

2.1. Analyzed Building

The selected building for the microgrid design and implementation is a residential building that has 264 apartments. It was built between 1919 and 1921, and it is in Bilbao (Spain), which has an ambient temperature range between 9.5 °C and 21.6 °C, with an average temperature of 15.1 °C.

Regarding the heating system, there is no specific system designed for the whole building. There are different individual heating systems installed in the households, such as electric radiators or gas heaters.

2.1.1. Electrical Demand of the Building

The electrical demand of the building is presented in the following bar chart per month in Figure 1 below:

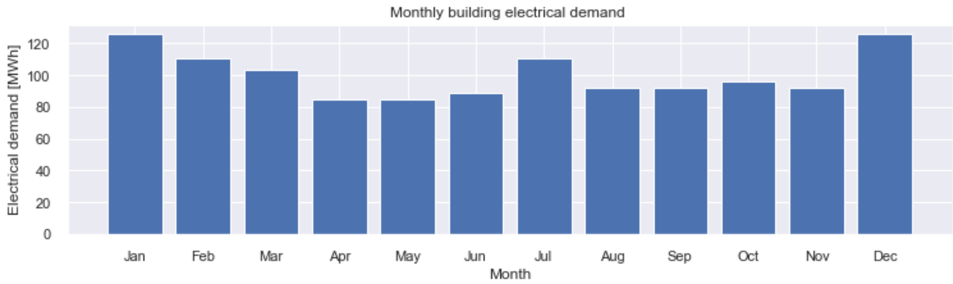

Figure 1. Monthly building electrical demand.

As reflected in Figure 1, the highest demand occurs during the winter months, as some apartments are heated with electric heaters. In July, there is a slight increase in the demand compared with that in the warmer months due to the use of the air conditioning devices that some households have.

2.1.2. Thermal Demand of the Building

The thermal demand, which is composed of hot water and space heating demands, is shown in the following bar plot for each month in Figure 2:

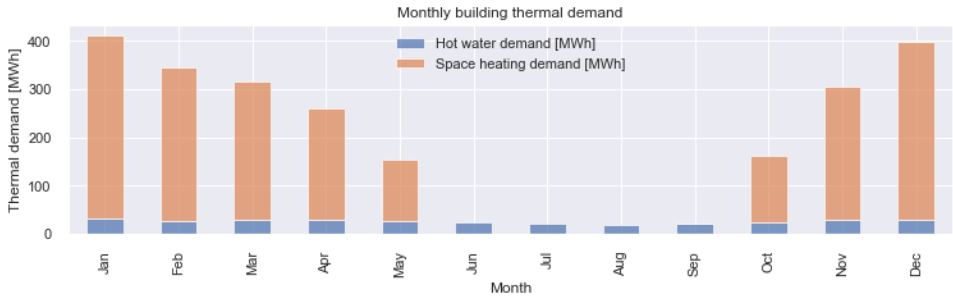

Figure 2. Monthly building thermal demand: hot water demand and space heating demand.

Figure 2 depicts the wide variability in the thermal demand due to the space heating load according to the season of the year. The hot water demand remains almost constant during the year.

2.1.3. Critical Electric Loads in Residential Buildings

Compared to commercial or industrial buildings, residential buildings do not have such critical electric loads. Nonetheless, the microgrid needs to provide enough energy for at least the refrigerators and freezers (7% and 1.6% of the total electrical load of a household [4]) to avoid food loss and other related costs.

2.2. Microgrid and Energy System Configuration

A microgrid system mainly based on micro-CHP systems was designed for the study. In addition, the microgrid system is supported by other elements to meet the thermal energy needs of the residential building. This is a complete list of the components of the proposed microgrid:

- Electrical grid: The microgrid is connected to the main grid to be able to import and export electricity.
- Micro-CHP system: It is the main electricity generation system of the microgrid. The thermal output of the micro-CHP system is used to heat the water of the water storage tank.

- Water storage tank system: The water heated with the micro-CHP system is discharged to meet the building's thermal demand. In case the thermal load is lower than the thermal energy stored in the water tank system, the tank system will store the remaining energy.
- Boiler system: This energy system is used when the thermal energy is not met by the water storage tank's thermal output. The boiler system is powered by natural gas.

2.2.1. Micro-CHP System

Considering that the maximum yearly electrical demand is around 170 kWh in the building and that the critical electric loads account for 8.6%, the minimum micro-CHP-rated electrical output should be around 15 kW.

As the thermal energy demand is high in the building, and electricity is set up to be sold to the grid during normal operation conditions, a system of two micro-CHP units is selected for the microgrid. This strategy is convenient for the Spanish market since the considered average export price is 0.19087 EUR/kWh [5], and the considered average import price is 0.13337 EUR/kWh [6]. Therefore, it is profitable to sell the electricity generated in the microgrid, while the microgrid buys the needed electricity from the grid.

To promote the use of renewable energies, biogas-powered commercial micro-CHP units are used, with a total thermal output of 77.4 kW, and a total electrical output of 50 kW. With this configuration, not only the electrical critical loads of the building are satisfied, but also the lighting load (10.3% of the total demand [4]) is partially met.

A minimum setpoint of 15 kW is configured for the micro-CHP system to avoid it having to start and stop working often. Both units work in parallel: they start working when the thermal demand is higher than the set point. Thermal demands lower than the minimum setpoint are met by the water storage tank. In case the micro-CHP system is not running and the energy stored in the water storage tank is not enough to cover the thermal demand, a system of boilers will supply the remaining thermal energy.

2.2.2. Water Storage Tank System

For thermal energy storage, a total capacity of 75 kW is needed. Two commercial tanks with 49.8 kW and 25.4 kW, respectively, are implemented in the system. The water storage tanks heat their water using the micro-CHP system's thermal energy and discharge enough heated water to the building. In case there is no need to discharge all the energy, the tank system will store it. Despite the chosen tanks being insulated, 3% thermal energy losses are considered for analysis.

2.2.3. Boiler System

The boiler system supplies the thermal energy demand that cannot be covered by the micro-CHP system or the stored thermal energy in the water storage tanks. Additionally, the boilers should be dimensioned to be able to fulfill the demand in case the water storage tank system also has no stored thermal energy.

The boiler system dimensions were set following the next yearly monotonic curve based on the total thermal demand of the analyzed building (Figure 3).

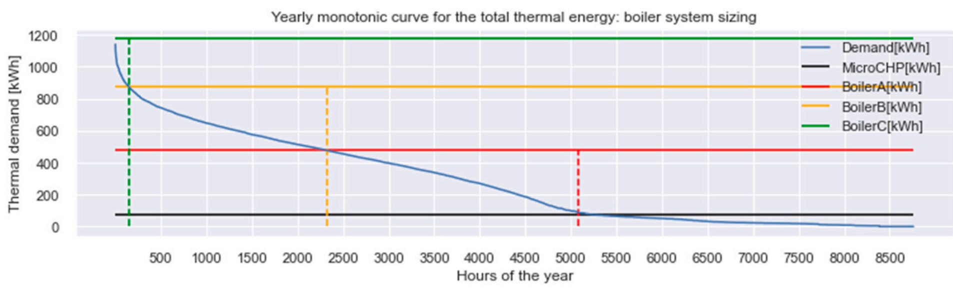

Figure 3. The yearly monotonic curve for the total thermal energy: boiler system sizing.

Considering Figure 3, two boilers of 400 kW (Boiler A and Boiler B) and one of 300 kW (Boiler C) powered by natural gas were chosen for the system. The selected setup avoids having a 1100 kW boiler running under its rated capacity most of the time, which will be oversized most of the time.

3. Results and Discussion

After performing the analysis of the microgrid system that also considers the thermal demand of the building it feeds, these are achieved results.

3.1. Electrical Energy

Considering that the maximum electrical load is 170 kWh and that the total electrical output of the micro-CHP units is 50 kW, which is equivalent to almost 30% of the electrical demand, the microgrid system is resilient enough to provide electricity to the critical units (refrigerators and separate freezers). Moreover, there is still 20% of the electricity coming from the micro-CHP units that can be used to fulfill other purposes in the microgrid: the lighting demand (10.3%), clothing driers (above 4%), cooking units (below 2%), microwaves (1.5%), clothing washers (below 1%), and others [6]. Consequently, the microgrid can withstand long-term grid blackouts without affecting the lifestyles of the building residents.

3.2. Thermal Energy

The following stacked chart displays the usage of each element of the energy system to fulfill the thermal demand per month (Figure 4).

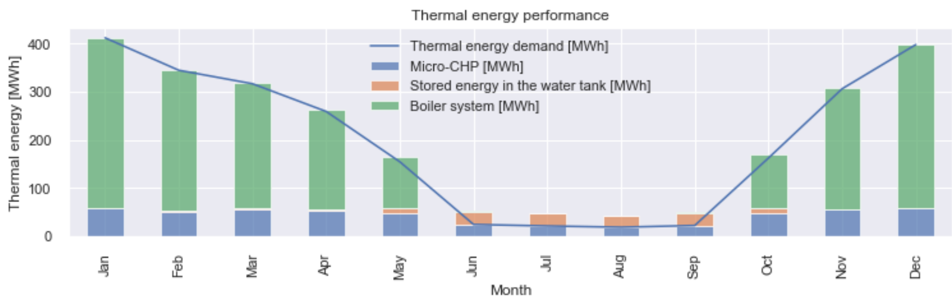

Figure 4. Thermal energy performance.

As shown in Figure 4, due to the variability in the thermal demand, the boilers need to support the micro-CHP units for 8 months of the year. During the warmer months, the micro-CHP system combined with the water storage tank is enough to meet the thermal demand as there are no heating needs in the building.

The following stacked bar plots show some more specific thermal energy performance cases for winter (15 February) and summer (1 August) in Figures 5 and 6, respectively.

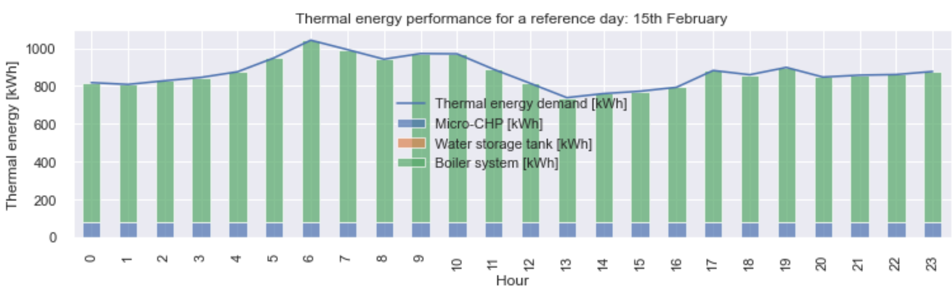

Figure 5. Thermal energy performance for a reference day: 15 February.

As shown in Figure 5, when greater thermal demands are needed due to the heating needs of the building, the boilers are the dominant generators in the system. Nevertheless, micro-CHP units run most of the time to provide a base load that is enough to meet the hot water demand. In Figure 6, the output of the micro-CHP is greater than the demand (usually during the summer months), and the excess is stored in the water storage tank system.

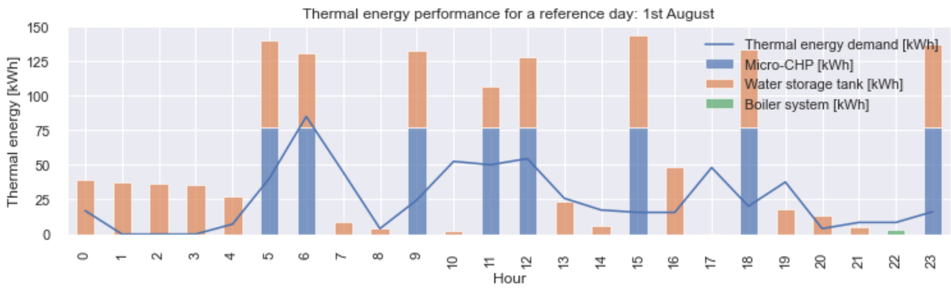

Figure 6. Thermal energy performance for a reference day: 1 August.

The micro-CHP power could indeed have been increased by adding more units or using other units with a greater thermal output, but this configuration is focused on having the units working at a good load level for many hours instead of having an oversized system. With this setup (start setpoint of 15 kW), the micro-CHP units run for 6655 h per year (almost 76% of the year), and there is no need to have a greater storage tank capacity, which translates to higher losses during the summer period due to the over-dimensioning of the system.

As for the water storage tank system, the maximum stored energy is just above 75 kW, which perfectly matches the selected storage capacity of the tanks. Figure 5 shows that the stored energy level during colder months is low, whereas in Figure 6, the water storage tanks store the remaining thermal energy as in the summer months when there is no space heating demand.

In the case of the boilers, the two 400 kW boilers and the 300 kW boiler work for 6400, 2174, and 146 h per year, respectively. More than 73% of the time, at least one boiler needs to complement the micro-CHP system to meet the thermal load. This occurs during the cold months (Figure 5) when the thermal demand is composed of both hot water and space heating loads.

3.3. Economic Results

With the designed setup, the micro-CHP units work for 6653 h for the entire year. This means the total electrical energy they produce is equivalent to 332.65 MWh per year, considering an average export price of 0.19087 EUR/kWh, which means that the revenue obtained by electricity generation (without considering the blackout period) is about EUR 63,493 per year.

Regarding the yearly electricity consumption, this building consumes around 1209 MWh per year. With an average electricity import price of 0.13337 EUR/kWh, the total cost for electricity will be around EUR 161,244 per year.

As a result, the yearly electrical cost for the building will be about EUR 97,751 per year, which provides an almost 40% economic saving. With this configuration, each dwelling can save up to EUR 240 per year.

4. Conclusions

This analysis shows that it is possible to have a resilient microgrid system based on biogas-powered micro-CHP generation that can meet the critical loads, while not affecting the lifestyles of the building residents during a blackout. Furthermore, the designed microgrid system can fulfill the hot water and heating demands of the building with the support of other equipment, such as water storage tanks and boilers. Water storage tanks are used to store the surplus of thermal energy provided by the micro-CHP system, and the boilers are turned on to meet the remaining thermal demand. As for the economic aspect of the microgrid, the current configuration provides up to 40% savings per year due to the sale of micro-CHP-generated electricity on the Spanish electricity market. The microgrid purchases electricity from the grid to meet the demand of the residential building. Despite the thermal economic results not being considered in the scope of this study, it might be expected to also find savings, as currently, each apartment has its system to cover the thermal needs. The building most probably will benefit from the implemented biogas micro-CHP system mainly due to the economy of scales: it will reduce the cost per apartment, it will require less thermal equipment to maintain, there will be better prices for fuel, and other factors that can help to reduce the thermal energy bill. The proposed methodology can be used for similar buildings and scenarios and is a valuable system to enhance the resilience of buildings and microgrids.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ECP2023-14613/s1.

Author Contributions: Conceptualization, I.D.L.-O. and D.B.-D.; methodology, I.D.L.-O.; software, I.D.L.-O.; validation, D.B.-D.; formal analysis, I.D.L.-O.; investigation, I.D.L.-O. and D.B.-D.; resources, I.D.L.-O. and D.B.-D.; data curation, I.D.L.-O.; writing—original draft preparation, I.D.L.-O.; writing—review and editing, D.B.-D.; visualization, I.D.L.-O. and D.B.-D.; supervision, D.B.-D.; project administration, D.B.-D. All authors have read and agreed to the published version of the manuscript.

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Nomenclature and Formulae

CHP	Combined Heat and Power
Micro-CHP	Micro-Combined Heat and Power

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