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Sizing of a fuel cell-battery backup system for a university building based on the probability of the power outages length

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Abstract

Hydrogen is a bright energy vector that could be crucial to decarbonise and combat climate change. This energy evolution involves several sectors, including power backup systems, to supply priority facility loads during power outages. As buildings now integrate complex automation, domotics, and security systems, energy backup systems cause interest. A hydrogen-based backup system could supply loads in a multi-day blackout; however, the backup system should be sized appropriately to ensure the survival of essential loads and low cost. In this sense, this work proposes a sizing of fuel cell (FC) backup systems for low voltage (LV) buildings using the history of power outages. Historical data allows fitting a probability function to determine the appropriate survival of loads. The proposed sizing is applied to a university building with a photovoltaic generation system as a case study. Results show that the sizing of an FC-battery backup system for the installation is 7.6% cheaper than a battery-only system under a usual 330-minutes outage scenario. And 59.3% cheaper in the case of an unusual 48-hours outage scenario. It ensures a 99% probability of supplying essential load during power outages. It evidences the pertinence of an FC backup system to attend to outages of long-duration and the integration of batteries to support the abrupt load variations. This research is highlighted by using historical data from actual outages to define the survival of essential loads with total service probability. It also makes it possible to determine adequate survival for non-priority loads. The proposed sizing is generalisable and scalable for other buildings and allows quantifying the reliability of the backup system tending to the resilience of electrical systems.

Keywords: Backup system; power outages; low voltage; fuel cell; hydrogen; photovoltaic system.

1. Introduction

Using hydrogen (H_2) as an energy vector represents an opportunity to decarbonise the environment and reach the goal of carbon neutrality by 2050 (IRENA, 2021). H_2 is a versatile energy vector that could be used in transportation, electric power generation, heating, and energy storage. It is anticipated that by 2030 H_2 could be explicitly integrated into daily life (IRENA, 2020).

The integration of H_2 is occurs primarily in the industrial sector, heavy and passenger transport, and large-scale power systems until reaching the commercial and residential sectors of low power, personal mobility, and energising

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of communities. The latter is in medium voltage (MV) and low voltage (LV) electrical networks (Lin et al., 2020; Yue et al., 2021). The integration in the low power sector is currently related to the consumption of H_2 through fuel cells (FC) as backup sources, FC electric vehicles, and a mixture of methane and H_2 for heat (Ahmed et al., 2020).

FCs stand out in generation systems due to their ability to supply for long periods. They could be used in hybrid generation systems and microgrids that feed isolated loads. It also highlights the application as an energy storage system (ESS) by integrating an electrolyser and a reservoir tank to generate and store hydrogen (Ma et al., 2021).

Some researchers have analysed the integration of H_2-ESS in hybrid generation and microgrids and have compared it with other ESSs such as batteries (Bat). For example, Xu *et al.* (2021) propose a techno-economic study for a photovoltaic (PV) and FC hybrid generation system. The proposal includes an electrolyser (EL), and an H_2 tank, guaranteeing the lowest overall net present cost (NPC). The system is intended to supply electricity to a remote area in China.

Similarly, Guo *et al.* (2021) present a techno-economic analysis for hybrid off-grid renewable generation systems integrating a PV system and a Proton Exchange Membrane FC (PEMFC). The results provide the optimal sizing of a PV, an FC, an EL and an H_2 reservoir tank considering the total NPC and loss of power supply probability (LPSP). The proposal is applied to a rural building in China with an annual demand of 240 MWh achieving 2.49% LPSP.

Evenly Mubaarak *et al.* (2021) and Eren (2022) have studied the integration of PV systems with H_2-ESS to supply isolated loads. In general, these works show that H_2-ESS is more suitable than Bat-ESS when storing large amounts of energy and for a backup supply of more than 30 hours (Jansen et al., 2021).

On the other hand, the use of FC as a backup system in on-grid networks is studied to a lesser extent. Since interconnected networks tend to be more reliable than isolated ones (Cigolotti et al., 2021). However, for low-reliability networks, the integration of FC systems may be helpful; likewise, it could increase the resilience of the electrical networks (Rahman et al., 2021). For example, Samy *et al.* (2021) address the problem of extensive power outages in a tourist resort in Egypt by taking advantage of renewable energies, including a H_2-ESS. The FC is used as a backup system when grid supply is unavailable. Results show that the levelized electricity cost of the proposed hybrid generation system is 37% lower than the local commercial power tariff for the case study.

In the same way, some researchers address the integration of diesel generators with FC for a backup system. For instance, Elavarasan *et al*. (2021) studied the PV-Diesel-FC configuration for a university building in India and applied demand-side management strategies to reduce peak power and obtain a smaller size of the sources. The analysis uses HOMER to simulate various scenarios and combinations between the sources.

Jahangir *et al*. (2021) describe an optimal design of H_2-diesel backup system for the Kargaran Cultural and Sports Complex in Iran. It has an average daily consumption of 5.2 MWh, and the highest load concentration is in the late hours of the day. The results show that the diesel-only backup system has the minimum NPC but the highest emission. The H_2-only backup system minimises pollutant emissions but has a higher NPC. However, the H_2-diesel backup system has both economic and environmental advantages.

In general, it is shown that integrating FC backup in interconnected networks is more environmentally profitable than generator sets and could be cheaper than batteries under certain conditions. The main conditions are the low reliability of the supply grid and high energy storage (Samy et al., 2021). Similarly, the facility's road interconnection plays an important role. Buying H_2 could be more profitable than producing it if it is feasible to transport H_2 to the facility. In this sense, the acquisition of the electrolyser is avoided (Cigolotti et al., 2021).

Survivability and the energy demand are critical parameters for the backup systems' sizing. That's why some research focuses on defining them. For example, Masrur *et al.* (2021) assess the technical-economic performance of a grid-connected microgrid in the event of a grid outage. A MILP-based optimisation model integrates the duration and date of outages to minimise the life cycle cost of the installation and increase electrical resilience due to extending survivability.

In the same line, Barik and Das (2021) analyse the location of the energy sources of an MG with distributed generation. They use a demand response support system to guarantee 0% LPSP in the simulated test. Likewise, Marqusee *et al.* (2021) investigate using an MG as an alternative energy backup system. They present a quantitative methodology to compare the reliability that an MG would provide. That uses the duration of the outages to define three metrics: *i)* probability of 100%-supplying critical load; *ii)* expected percentage of the unserved load, and *iii)* probability of meeting the most priority critical loads.

Against this background, this paper proposes a sizing strategy for an FC backup system for interconnected buildings. The proposal considers the power peaks to integrate a suitable battery bank and the cost of purchasing green H_2 to define the suitability of an electrolyser and reservoir tank. It uses actual historical data from power outages to fit a total supply probability (TSP) function according to the survivability provided by the backup system.

It uses NPC and the TSP as optimisation criteria. It also prioritises building loads and assigns a TSP to meet for each load group. The multi-criteria optimisation problem is solved with the PSO algorithm. The proposed sizing is applied to a university building as a case study. The case study corresponds to the Electrical Engineering building at the Industrial University of Santander, Colombia. This building has a 10 kWp interconnected PV system.

This research stands out for the proposal of a methodology for sizing an FC backup system based on the total supply probability (TSP). The simulated test uses actual demand and solar irradiation, and temperature profiles. Likewise, TSP uses actual historical data to calculate survivability. It also proposes grouping loads into three categories according to priority, and a TSP is assigned to each load category.

This paper is organised as follows: Section 2 presents the methodology and concepts of the research. Section 3 describes the case study and reveals validation results. Then, Section 4 exposes a discussion about the findings and the position in state of the art. Finally, Section 5 summarises the conclusions of the work and discusses the achievements, possible improvements, and future work.

2. Methodology

The sizing of a backup system requires a comprehensive knowledge of the facility's power behaviour. It also requires information on the local costs of the energy sources and their operation and maintenance. This work proposes a H_2 system integrating an FC to supply the energy and a battery bank to support the power peaks. It also defines the best economic benefit of generating green H_2 or buying it. Figure 1 presents the system scheme that encompasses this methodology.

The methodological steps comprise *i)* the model of the grid, loads, and energy sources, *ii)* the load classification, *iii)* the definition of the TSP, *iv)* the cost function, and *v)* the source dispatch strategy. These steps are presented below:

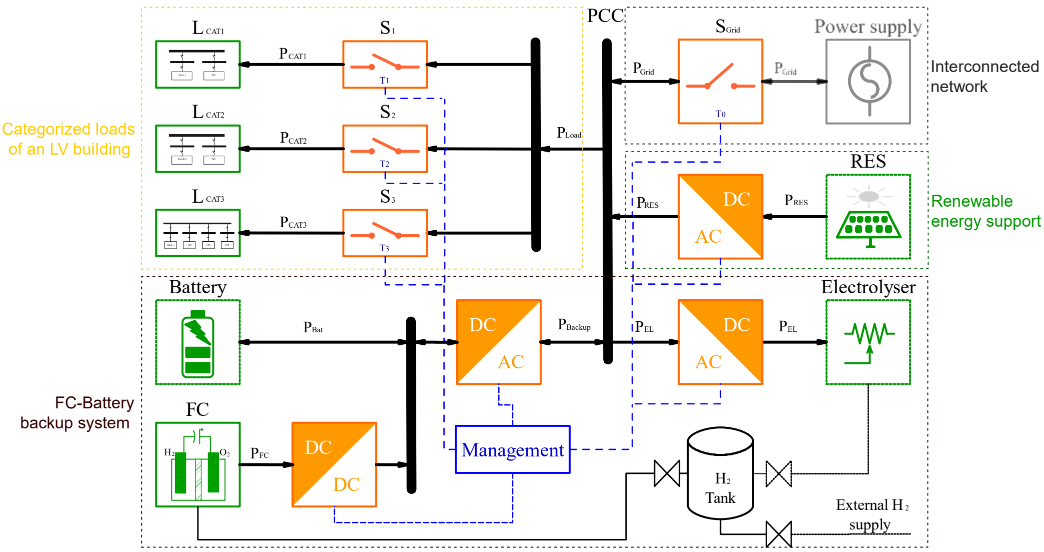

Fig. 1. Integration scheme of an FC-battery backup system for an LV building.

2.1. Model

The sizing uses grid wire impedances and the demand profiles of the building. The FC, the EL, and the batteries use a static model relating a nominal capacity to cost. Renewable energy sources (RES) use a maximum power point model based on meteorological conditions. The models used are described below.

- Load and weather profiles

It regards load profiles with at least 10 minutes of sampling time. It also requires solar irradiance and temperature since it integrates a PV system operating at the maximum power point.

It sets constant loads and weather conditions for the time of each sampling step. It also calculates a constant impedance for the wire conductors interconnecting the loads and sources.

- Batteries model

It uses the storage model proposed by Gomozov *et al.* (2017) shown in Eq. (1). Here, $SOC_{Bat}(t)$ is the battery's state of charge, dt is the time step, $i_{Bat}(t)$ is the current supplied by the battery system, η_{Bat} is the combined efficiency of the battery and converter. Moreover, $\beta = 1$ when the battery is recharging or $\beta = -1$ when the battery supplies power. Q_{Bat}^{rat} is the rated charge of the battery given by Eq. (2). Here N_{Bat}, Ah_{Bat}^{rat} are the number of battery cells and the nominal capacity in Ah, respectively.

$$SOC_{Bat}(t) = SOC_{Bat}(t-dt) - \frac{\eta_{Bat}^{\beta} \cdot i_{Bat}(t) \cdot dt}{Q_{Bat}^{rat}} \tag{1}$$

$$Q_{Batt}^{rat} = 3600 \cdot N_{Bat} \cdot Ah_{Bat}^{rat} \tag{2}$$

- Fuel cell model

It assumes a PEMFC for sizing and uses the polarisation model proposed by Kandidayeni *et al.* (2020). This model allows the FC to be monitored to not exceed the damaging current rate. The voltage of the single FC cell is given by Eq. (3) and the H_2 consumption by Eq. (4).

$$U_{cell}(t) = U_{OCV} - \eta_{act}(t) - \eta_{conc}(t) - \eta_{ohm}(t) \tag{3}$$

$$\dot{m}_{H_2}^{FC}(t) = \dot{m}_{OC} + m_{H_2} \cdot i_{cell}(t) \tag{4}$$

Here $i_{cell}(t)$ is the operating current of a cell, U_{OCV} is the internal induced voltage of the cell, which is assumed constant. η_{act}, η_{conc} and η_{ohm} are the activation, the concentration, and the ohmic voltage drops, respectively, as defined in Eq. (5). $\dot{m}_{H_2}^{FC}(t)$ is the H_2 mass flow rate in kg/s. $\dot{m}_{OC}$ is the H_2 flow in open circuit operation, and m_{H_2} is the hydrogen consumption factor.

$$\begin{aligned} \eta_{act}(t) &= C_{act} \cdot \log_{10}\left(i_{cell}(t)\right) \\ \eta_{conc}(t) &= C_{conc} \cdot \left(i_{cell}(t)\right)^{k_{sq}} \cdot \ln\left(1 - \frac{i_{cell}(t)}{J_{\max}}\right) \\ \eta_{ohm}(t) &= r_{cell} \cdot i_{cell}(t) \end{aligned} \tag{5}$$

The parameters for an FCvelocity-9SSL FC cell as a basic unit are given in Table 1. The sizing determines the number of cells to ensure the required power. It should guarantee to keep the FC in the acceptable current and current rate range. It is also expected to keep the FC close to the highest efficiency point to save H_2, avoid on/off and open-circuit operation.

Table 1. Parameters of an FC single cell used for sizing (Kandidayeni et al., 2020).

Parameter	Description	Value
U_{OCV}	Internal voltage induced	$0.8834\ V$
$\dot{m}_{OC}$	Hydrogen mass flow in open circuit operation	$1.39\ X\ 10^{-8}\ kg/s$
m_{H_2}	Hydrogen consumption factor	$9.71\ X\ 10^{-9}\ kg/s\ \ A^{-1}$
C_{act}	Activation constant	0.0278
C_{conc}	Concentration constant	$-5.6403\ X\ 10^{-11}$
k_{sq}	Concentration exponent	3
J_{max}	Maximum current	$250\ A$
r_{cell}	Single-cell equivalent resistance	0.5973 mΩ

- Electrolyser model

It takes the model proposed by Attemene *et al.* (2020) for an alkaline electrolyser. The sizing is determined based on the rated power P_{EL}^{rat}. EL operation must be maintained in the range $0.1 \cdot P_{EL}^{rat} \leq P_{EL}(t) \leq P_{EL}^{rat}$. The H_2 production is given by Eq. (6).

$$\dot{m}_{H_2}^{EL}(t) = \eta_{EL} \cdot n_{H_2} \cdot P_{EL}(t) \tag{6}$$

Here $\dot{m}_{H_2}^{EL}(t)$ is the H_2 produced by the electrolyser in kg/s, η_{EL} is the overall efficiency of the EL system. Furthermore, n_{H_2} is the hydrogen energy production factor. For sizing, it takes $\eta_{EL} = 0.85$ and $n_{H_2} = 8.33\ X\ 10^{-6}\ kg/J$. The sizing determines P_{EL}^{rat}.

- Hydrogen storage model.

It sets the maximum pressure of the hydrogen tank $p_{H_2}^{max}$ equal to the operating pressure of the electrolyser to avoid using a compressor. The minimum pressure $p_{H_2}^{min}$ is the minimum operating pressure of the PEMFC. It also sets a refuelling $p_{H_2}^{refu}$pressure between $p_{H_2}^{min}$ and $p_{H_2}^{max}$ to ensure the supply of hydrogen from the external source. Eq. (7) (Olatomiwa et al., 2015) gives the amount of available hydrogen.

$$m_{H_2}(t) = m_{H_2}(t-dt) + \left(\dot{m}_{H_2}^{EL}(t) + \dot{m}_{H_2}^{Ext}(t) - \dot{m}_{H_2}^{FC}(t)\right) \cdot dt \tag{7}$$

Here $m_{H_2}(t)$ is the mass of H_2 available in the reservoir tank. $\dot{m}_{H_2}^{Ext}(t)$ is given by Eq. (8) and represents the flow of H_2 from the external supply, which could be a H_2 bottle regulated at a supply pressure $p_{H_2}^{refu}$.

$$\dot{m}_{H_2}^{Ext}(t) = \begin{cases} 0 & if\ p_{H_2}(t) > p_{H_2}^{refu} \\ \dot{m}_{H_2}^{FC}(t) - \dot{m}_{H_2}^{EL}(t) & if\ p_{H_2}(t) \leq p_{H_2}^{refu} \end{cases} \tag{8}$$

The volume of the H_2 tank V_{Tank} is determined according to the maximum H_2 mass to be stored. If the electrolyser is avoided, the H_2 is supplied from an external source. Then, $\dot{m}_{H_2}^{FC}(t) = \dot{m}_{H_2}^{Ext}(t)$ and $p_{H_2}(t) = p_{H_2}^{refu}$.

2.2. Load classification

For the classification of the loads, it proposes three categories.

- L_{CAT1}: essential loads are the minimum necessary to ensure proper building operation. For instance, the security system and emergency lighting.
- L_{CAT2}: priority loads are the ones that contribute to better functioning of the building, but their absence does not imply a safety risk for the equipment or people.
- L_{CAT3}: non-priority loads could be dispensed without causing a significant impact on the operation of the building.

Classifying loads is subject to grouping them into circuits and taking them out of operation.

2.3. Loss of power supply probability and total supply probability

LPSP could be defined as the percentage of unmet load given by Eq. (9) (Attemene et al., 2020). Here $P_{def}(t)$ is the unserved power and $P_{load}(t)$ is the power demand by the network integrating L_{CAT1}, L_{CAT2}, and L_{CAT3}.

$$LPSP = \frac{\sum_{t=1}^{T} P_{def}(t)\cdot dt}{\sum_{t=1}^{T} P_{load}(t)\cdot dt} \tag{9}$$

This paper proposes an additional criterion, the total supply probability (TSP), defined as the probability of supplying the load during all an outage of duration T_{TSP}. It would allow defining the minimum survivability required to satisfy the target TSP. T_{TSP} would depend on typical power outage times for each facility. In this way, it is necessary to know the historical outage length of the electrical network.

The length data history of the electrical installation power outages is used to determine T_{TSP}. From this data, a probability density function (PDF) is constructed. Then, it generates the cumulative density function (CDF). T_{TSP} is given as the inverse of CDF. Figure 2 presents the procedure to obtain T_{TSP}.

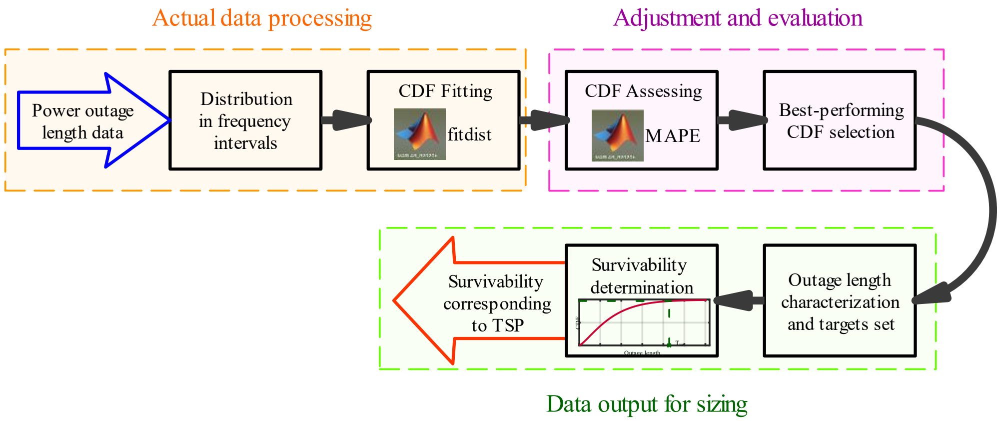

Fig. 2. Process for determining survival time to satisfy a target TSP.

The probability density functions considered in this work are Gamma, Weibull, Inverse Gaussian, and non-parametric. The function that allows a lower mean absolute percentage error (MAPE) of CDF is sectioned (Chen et al., 2020). In addition, it assigns a particular criterion for each load category. The sizing of the backup system must satisfy both criteria. For L_{CAT1}, it should be guaranteed to supply the entire load as many times as a power outage. Consequently, LPSP must be the minimum possible and TSP the maximum possible.

Similarly, for L_{CAT2} and L_{CAT3}, TSP and LPSP should be guaranteed according to the importance of the load. In any case, L_{CAT2} would have more priority than L_{CAT3}.

Table 2 shows the proposed LPSP and STP criteria. The LPSP values correspond to those Ayop *et al.* (2018) suggested. The TSP values correspond to this research proposal according to the categorisation of loads. It highlights that the criteria presented in Table 2 correspond to a typical operating scenario covering regular outages. The backup system should supply L_{CAT1} as much as possible during an extraordinary outage such as natural disasters or large-scale equipment damage. In this case, it should use the TSP to defend the survivability for L_{CAT2} and L_{CAT3}.

Table 2. LPSP and STP criteria for backup system sizing during an outage.

Category	LPSP	TSP
L_{CAT1}	$\approx 0\%$	$> 95\%$
L_{CAT2}	$< 10\%$	$> 70\%$
L_{CAT3}	$< 50\%$	$> 40\%$

2.4. Cost function

The backup system is intended to supply the power of the building in an outage. This way, it should satisfy the power balance Eq. (10).

$$P_{FC}(t)+P_{Bat}(t)+P_{PV}(t)=P_{L_{CAT1}}(t)+P_{L_{CAT2}}(t)+P_{L_{CAT3}}(t)+P_{loss}(t)-P_{def}(t) \tag{10}$$

Here $P_{FC}(t)$, $P_{Bat}(t)$ and $P_{PV}(t)$ are the power of FC, batteries, and PV systems respectively. $P_{L_{CAT1}}(t)$, $P_{L_{CAT2}}(t)$, and $P_{L_{CAT3}}(t)$ are the power of loads L_{CAT1}, L_{CAT2}, and L_{CAT3} respectively. $P_{loss}(t)$ corresponds to the resistance and conversion loss power. And $P_{def}(t)$ represents the unsupplied load power.

Likewise, the backup system must ensure the energy balance shown in Eq. (11). Here T_{total} is the total time of the test. T_{TSP1}, T_{TSP2}, and T_{TSP3} are the survival times calculated for each load category account for total supply probabilities TSP_1, TSP_2, and TSP_3, respectively.

$$\begin{aligned}&\sum_{t=1}^{T_{total}}\left[P_{FC}(t)+P_{Bat}(t)+P_{PV}(t)-P_{loss}(t)\right]\cdot dt=\\&\sum_{t=1}^{T_{TSP1}}P_{L_{CAT1}}(t)\cdot dt+\sum_{t=1}^{T_{TSP2}}P_{L_{CAT1}}(t)\cdot dt+\sum_{t=1}^{T_{TSP3}}P_{L_{CAT1}}(t)\cdot dt\end{aligned} \tag{11}$$

The cost function is defined by the annualised total cost C_{total} of the backup system. C_{total} considers the acquisition cost C_{acq}, and operation and maintenance cost $C_{O\&M}$. The annualised maintenance cost is defined as a percentage of C_{acq}, for each source. Also, the operation considers the cost of purchasing green H_2 from an external source. Eq. (12) presents the cost function subject to TSP and LPSP.

Here, NC_s, C_s, and C_{Ms} are the nominal capacity, acquisition cost per unit of capacity and maintenance cost per unit of capacity, respectively, for each s-component. $m_{H_2}^{Ext}$ is the amount of hydrogen supplied by the external source and C_{H_2} is the cost per kg of green H_2. CRF_s is the capital recovery factor shown in Eq. (13). Here, r is the annual rate of return and N_{Ls} is the lifetime years of each component.

$$\begin{aligned}
&\min: \sum_{s=1}^{N} CRF_s \cdot NC_s \cdot C_s + \sum_{s=1}^{N} C_{M_s} \cdot NC_s + m_{H_2}^{Ext} \cdot C_{H_2} \\
&s.t.: \quad TSP \\
&\qquad\quad LPSP
\end{aligned} \tag{12}$$

$$CRF_s = \frac{r \cdot (r+1)^{N_{LS}}}{(r+1)^{N_{LS}} - 1} \tag{13}$$

Table 3 presents acquisition and O&M costs for distributed generation sources, converters, H_2 tanks and fuel. The sizing proposal is implemented in MATLAB software. The PSO algorithm solves the optimisation problem presented in Eq. (12).

Table 3. Cost characteristics for backup system components.

Component	Acquisition cost		O&M cost	Lifetime
Diesel generator set (Timilsina, 2021)	250	EUR/kW	5.0% $of\ C_{acq}$	20 years
Batteries (Kosmadakis et al., 2021)	250	EUR/kWh	2.0% $of\ C_{acq}$	6 years
Fuel cell (Timilsina, 2021)	2 500	EUR/kW	3.0% $of\ C_{acq}$	5 years
Electrolyser (Attemene et al., 2020)	2 100	EUR/kW	4.0% $of\ C_{acq}$	8 years
H_2 reservoir tank (Attemene et al., 2020)	990	EUR/kg	1.2% $of\ C_{acq}$	20 years
Inverters (Attemene et al., 2020)	200	EUR/kW	1.0% $of\ C_{acq}$	15 years
Diesel (Tariff in France)	1.85	EUR/l	---	---
Green hydrogen (IRENA, 2020)	6.0	EUR/kg	---	---

2.5. Source dispatch strategy

The energy management of a backup system could significantly impact the operation cost. However, a light energy dispatch strategy could be acceptable for the sizing stage (Lorenzo et al., 2020). It proposes a rule-based dispatch strategy to determine the power participation of FC and batteries.

It attempts to keep $SOC_{Bat}(t)$ inside the operating values SOC_{Bat}^{min} and SOC_{Bat}^{max}. $P_{FC}(t)$ is set at the rated power P_{FC}^{max} as possible. If $SOC_{Bat}(t)$ exceeds a cut-off limit SOC_{Bat}^{cut}, $P_{FC}(t)$ must drop to the minimum value P_{FC}^{min}. FC is disconnected in the undesirable case that $SOC_{Bat}(t)$ exceeds the maximum value. Algorithm 1 describes the dispatch strategy.

3. Results

The proposed sizing methodology is applied to the Electrical Engineering Building (EEB) at the Industrial University of Santander (UIS). The Backup system solution must respect the demand conditions shown in Eq. (10) and (11) and the restrictions of the energy sources. The local electricity network operator provided the historical data on power outages for the distribution network of the case study. The load profiles were obtained from the meters of the building. The following presents the results of the case study.

Algorithm 1: Rules-based dispatch strategy

Data: SOC_{Bat}^{min} , SOC_{Bat}^{max} , SOC_{Bat}^{cut} , P_{FC}^{max} , P_{FC}^{min}

Input: $SOC_{Bat}(t)$, $P_{load}(t)$

Result: $P_{FC}(t)$, $P_{Bat}(t)$

initialization;

if $SOC_{Bat}(t) < SOC_{Bat}^{max}$ **then**

  while $SOC_{Bat}(t) \geq SOC_{Bat}^{min}$ **do**

    if $SOC_{Bat}(t) < SOC_{Bat}^{cut}$ **then**

      $P_{FC}(t) = P_{FC}^{max}$;

    else

      $P_{FC}(t) = P_{FC}^{min}$;

    $P_{Bat}(t) = P_{load}(t) - P_{FC}(t)$;

else

  $P_{FC}(t) = 0$;

  $P_{Bat}(t) = P_{load}(t)$;

3.1. Case study

EEB is located at GMS N 7° 8' 29" W 73° 7' 17" in Bucaramanga, Colombia. This electrical network is appropriate for this study since it has smart meters in the primary nodes of the network. Likewise, it has an automation system to control doors, lighting, window opening and climatisation.

It also has an interconnected PV system and a diesel generator set as a backup system. The sampling time is 10 minutes. Figure 3 presents the electrical connection diagram of the EEB. The more detailed information can be consulted in Parrado (2021) and Tellez (2020).

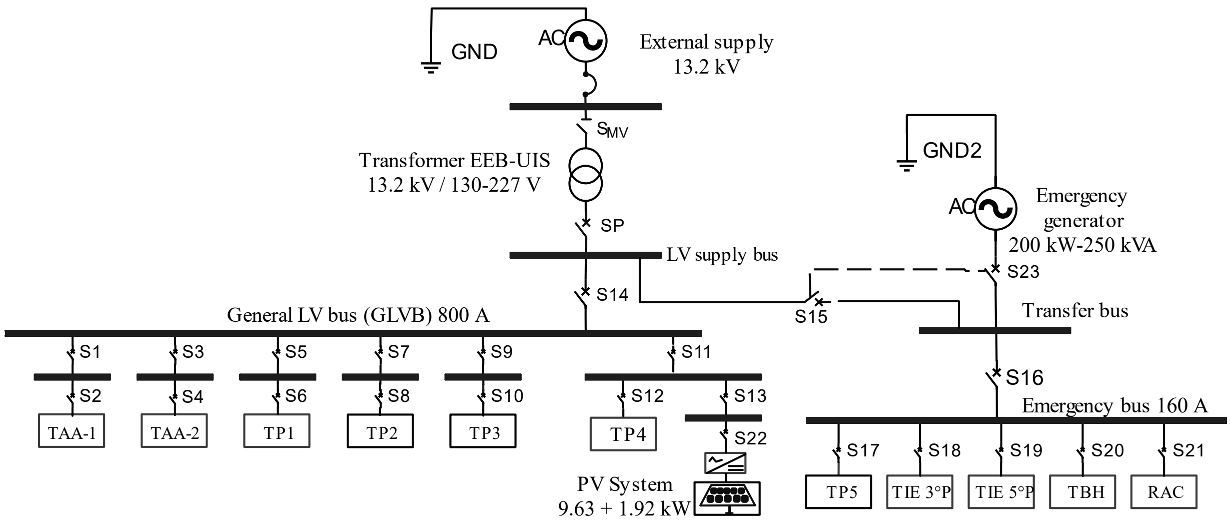

Fig. 3. Electrical connection diagram of EEB, Industrial University of Santander.

3.2. Loads characterisation

Before applying the sizing, it is necessary to characterise the distribution of outage length probabilities and categorise the loads. Thirty-five historical data samples of power outages from the last two years were used to develop TSP. When applying the PDF fit, it was found that the Inverse Gaussian distribution has the best fit with an 8.8% MAPE, followed by the Non-parametric and Gamma distributions with 16.9% and 18.1% MAPE, respectively. Figure 4 shows the CDF fit and cumulative probability for the historical data.

The loads are grouped according to their functionality and the disconnection via the circuit breakers for categorisation. Table 4 shows the categorisation of the loads, and Figure 5 shows the equivalent circuit to tackle the optimisation problem.

Table 4. Categorisation and description of the EEB load.

Category	Circuits	Average power	Maximum power	LPSP target	TSP target	Minimum survivability
L_{CAT1}	TP5, TIE 3P, TIE 5P, TBH, RAC	5.4 kW	11 kW	0%	99%	330 min
L_{CAT2}	TP4	1.0 kW	7 kW	0%	75%	91 min
L_{CAT3}	TP1, TP2, TP3, TAA-1, TAA-2	2.8 kW	23 kW	0%	50%	60 min

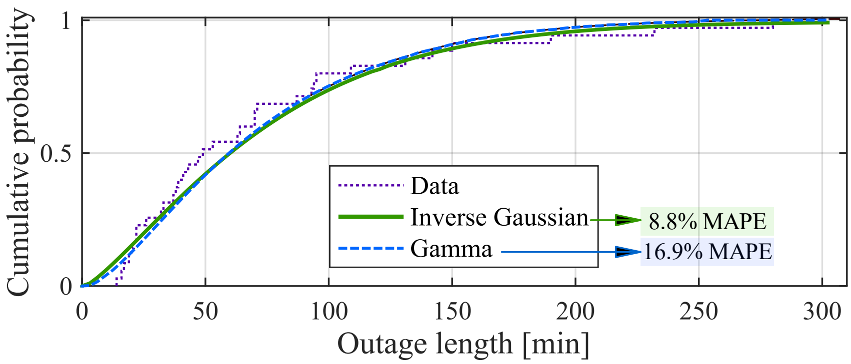

Fig. 4. Cumulative density function fit for outage length history.

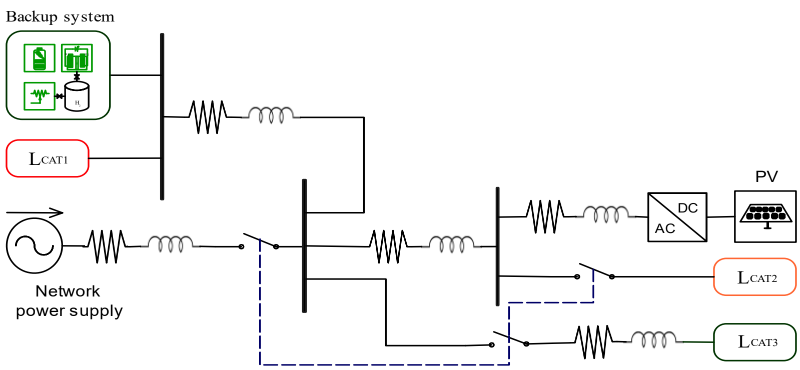

Fig. 5. EEB circuit model to simulate power flow.

3.3. Backup system sizing

For sizing, a period $T_{TSP}(99\%) = 330\ min$ with higher demand was sought according to the measured demand profiles of EEB. The period found corresponds to 17 October 2019, from 6:00 a.m. to 11:30 a.m. Although the base decision time is 330 min, it is highlighted that the backup system should be able to attend outages of longer duration.

In this sense, the sizing is according to the criteria for regular operation presented in Table 4. Then it tests the performance of the backup system in an unusual outage scenario lasting 48 hours. In the latter, L_{CAT3} and L_{CAT2} should be supplied 60 minutes and 91 minutes, respectively and L_{CAT1} the test's total.

Regarding energy sources, it defined in advance for FC the parameters presented in Table 1. For batteries, the limit estate of charges $SOC_{Bat}^{min} = 0.30$, $SOC_{Bat}^{cut} = 0.90$, and $SOC_{Bat}^{max} = 0.95$. It also fixes the nominal values for a battery cell $U_{Bat}^{rat} = 12.8\ V$ and $Ah_{Bat}^{rat} = 110\ Ah$. The acquisition cost uses $r = 9\%$ as the annual return rate and the lifetimes shown in Table 3.

The sizing strategy found that the solution with the lowest annualised cost integrates an FC and a battery bank. The solution satisfies the power, energy and LPSP and TSP requirements. For the study case, acquiring an electrolyser and a H_2 reservoir tank increases costs. It is therefore convenient to purchase green H_2. Table 5 summarises the description of the backup system and the costs for a typical power outage scenario.

It also tests the sizing solution in the adverse scenario of a 48-hour power outage. The backup system can supply the demand guaranteeing the LPSP and TSP criteria in this scenario. The cost of operation increases by EUR 1 113 due to hydrogen consumption.

Table 5. Characteristics and costs of backup system sizing for the case study.

Component	Nominal value	Description and possible configuration	Annualised C_{acq} cost	O&M cost
Fuel cell	5.6 kW	Energy source. E.g., 37 cells of rated power 150 W in series	EUR 3 567	EUR 416
Batteries	22.5 kWh 31 kW	Power source. E.g., 4 branches of 4 batteries in series of 12.8 V and 110 Ah	EUR 1 255	EUR 113
Inverter DC/AC	35 kW	AC/DC inverter interconnects the backup system with the building's network.	EUR 867	EUR 70
Converter DC/DC	5.6 kW	DC/DC converter interconnects the FC with the batteries.	EUR 138	EUR 11
Hydrogen	23.8 kg	Hydrogen is purchased from an external source.	EUR 143	---
		Total annualised cost	**EUR 6 580**	

Figure 6 presents the power demanded by the building and the power supplied by each source, and Figure 7 shows the SOC of the batteries. It evidences the drop in demand at minute 60 when the L_{CAT3} load is no longer served. Although L_{CAT3} is categorised as the least critical, the backup system expects to fully supply it at least half of the time there is a power outage.

Concerning the operation of the sources, the FC increases the power up to the rated value. The sizing takes advantage of the PV resource; in this way, the PV system contributes to meeting the load and recharging the batteries during sunny hours. The batteries supply the remaining power; it behaves similarly to the load. Also, the battery's state of charge (SOC_{Bat}) is kept in the appropriate range.

On the other hand, the essential load has a higher demand because it has a higher TSP. The demand of the building in the 330-minutes outage test is 41.2 kWh, and in the 48-hours test is 272 kWh. The FC supplies most of the load, followed by the PV system. The batteries also contribute as the SOC_{Bat} decreases by 5.5% at the end of the test. The results show 21.7 kWh losses between the conversion device and the grid wires. Then, the electrical efficiency is 92.6%. Figure 8 shows the energy distribution of the case study for the 48-hours test.

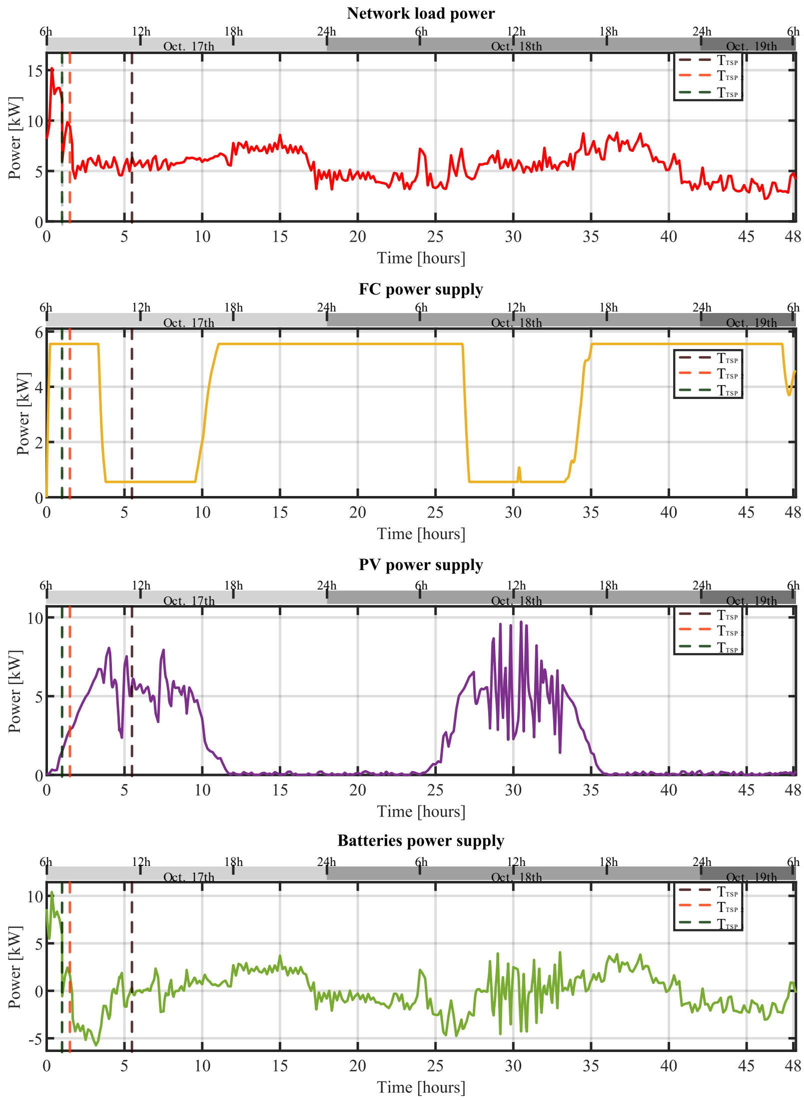

Fig. 6. Power distribution in an adverse scenario of a 48-hour power outage.

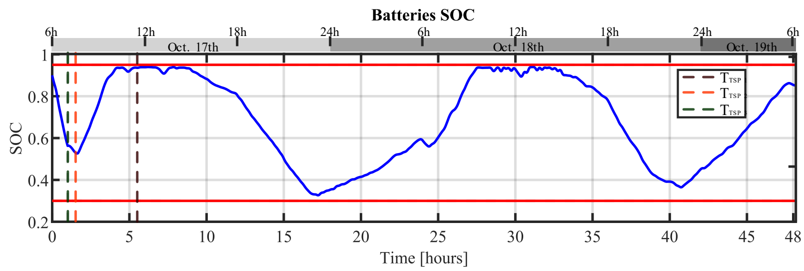

Fig. 7. Batteries state of charge in a 48-hour power outage test.

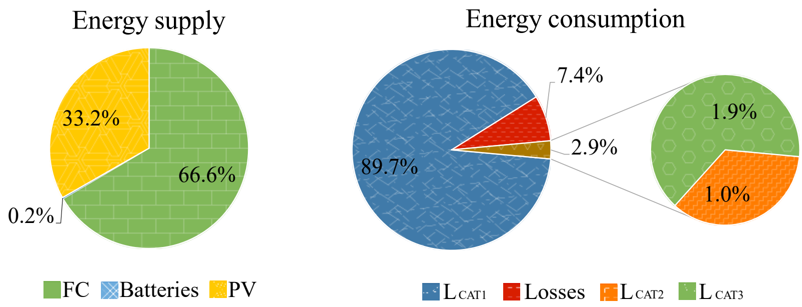

Fig. 8. Energy participation in a 48-hour power outage.

3.4. Cost comparison

Results show that the highest cost concerns the acquisition and maintenance of the FC, with 60.5% of the total cost. It also sizes a battery-only backup system with EUR 7 123 annualised cost under the 330-minutes scenario for usual power outages. It is found that the total cost of the only-battery system is 8.25% higher than the cost of the FC-battery system. It is due to the energy demand of the building. As energy demand increases, the FC-battery system improves convenience.

Although the difference in cost is slight, it stands out that the FC-battery system could supply the critical load of the building for longer. Such is the case of a catastrophic event where the outage time could be several days. In such a case, a battery-only system could be unworkable.

For example, in the case of an adverse 48-hour outage scenario, the annualised cost of the FC-battery system increased by 16.9% due to hydrogen consumption. However, the cost of a battery-only system would increase by 165.3% since it would be necessary to purchase more batteries to increase energy storage.

In addition, it analyses the behaviour of the cost of the backup system based on the survivability of typical power outages scenarios. For this, it assigns the same TSP to all categories of loads. Figure 9 presents the behaviour of cost and survival time required for the case study.

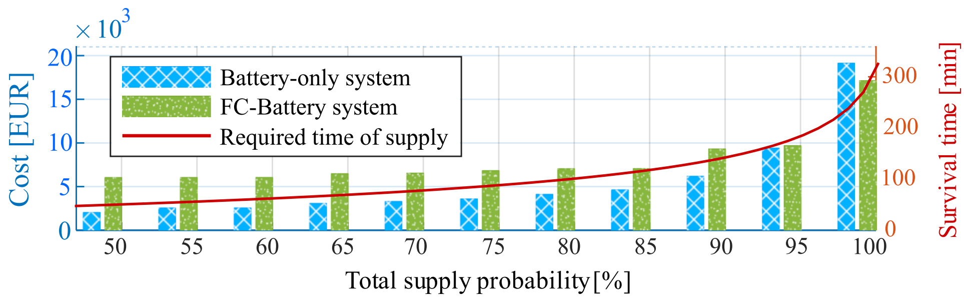

Fig. 9. Cost of battery-only and FC-battery backup systems over TSP for the case study.

4. Discussion

H_2 backup systems appear to be distant and perhaps unfeasible due to the need for structural modifications in the facilities and the possible risks of hydrogen management. However, researchers like Mubaarak *et al.* (2021) and Samy (2021) have shown that H_2 backup systems could be viable today under certain conditions. Especially in lengthy power outages and integral use for electricity and heat.

Although the considerations on the conditioning are unclear and little detailed, technological development could simplify these stages (Lin et al., 2020). In addition, the prospective H_2 recharging points for vehicles in houses and buildings could increase the feasibility of implementing H_2 backup systems.

Some researchers like Robledo *et al*. (2018) consider the application of H_2-Vehicles as backup sources in case of catastrophic events heading towards an opportunity for greater H_2 integration in residential and commercial buildings.

On the other hand, diesel backup systems have the advantage of the inertia of tradition, and users could show greater confidence, and they are oversized to ensure they will respond to demand. However, in the case of an FC backup system, an oversizing implies a significant over cost and, in turn, a possible poor operation of the FC (Eren, 2022). Therefore, the sizing of an FC backup system requires much attention.

At this point, this sizing proposal comes into play. Its primary considerations are: *i)* determine the probability of service of the backup system, *ii)* operate the FC close to the maximum efficiency point to save H_2, *iii)* avoid FC on/off to decrease degradation, and *iv)* supply essential loads during a power outage.

Most of the above are goals commonly planted in research. However, *i)* goes further since the definition of the TSP allows it to define the certainty that the backup system could supply the load during all the outages in a year. Thus, depending on the loads' priority, a TSP could be fixed, representing a saving in implementing the FC-backup system.

The research presented by Marqusee *et al.* (2021) uses a similar concept to define the probability of supplying the entire critical load in a blackout. However, the measurement is based on the test results after sizing. Otherwise, this proposal uses historical data from power outages to define the TSP and the corresponding survivability.

Although this research is extensible to all electrical systems, it is mainly oriented to interconnected buildings. It requires historical information on the behaviour and performance of the electrical system. It has a focus on improving performance by establishing an increase in the building's electrical resilience.

This way, it could get a building to withstand usual power outages and face extraordinary blackouts for several days. Getting a little ahead in the age, the facilities could generate their green H_2 to supply heat loads and recharge their H_2-vehicles.

5. Conclusions

This paper proposes a methodology for sizing a backup system for low-voltage buildings. The proposal uses historical power outages data to adjust a probability density function and define the survivability of the backup system. The sizing is approached as an optimisation problem subject to satisfying the loss of power supply and the total supply probabilities. The methodology is applied to a university building with 10-minute sampling time demand profiles.

The case study results find a suitable FC-battery system with an external green hydrogen supply. Integrating an electrolyser and a reservoir tank could make the system economically unviable. However, this finding corresponds to the assumed feasibility of purchasing green hydrogen and transporting it to a residential or industrial facility. In the case of buildings in remote areas that are difficult to access, this requires a more detailed cost study. In these cases, generating and storing green hydrogen may be more convenient.

This paper compared the cost of battery-only and FC-battery backup systems. For the case study, FC-battery is 7.6% cheaper than battery-only under a scenario of usual outages lasting 330 minutes. However, for a scenario of unusual outages lasting 48 hours, FC-battery is 59.3% cheaper. It also made a cost comparison over the total supply probability (TSP). The results show a break-even point at 95% TSP for the case study. If TSP increases, the FC-battery system is more convenient since the increase in TSP implies an increase in survivability and energy backup.

The analysis of this research only covers the power supply in an outage. It does not consider the operating conditions before and after the outage event. Hence, it is recommended for future research to make a comprehensive study assessing the pre-and post-event operation to define the feasibility of using renewable energy sources and an electrolyser to store energy in green hydrogen for the outage.

This paper mainly studied the case of a typical power outage. It highlights that the outages caused by severe weather conditions or disaster events could reach several days. In this case, a battery-only system would be unworkable. In this sense, an FC-battery system stands out to supply survival times before extraordinary power outages.

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