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Electrical resilience assessment of a building operating at low voltage

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ABSTRACT

Resilience is becoming increasingly important in power systems, microgrids (MG) and buildings. It evaluates their performance against disruptive events. The approaches mainly correspond to high-impact, low-probability events such as natural disasters and intentional attacks affecting the electrical systems infrastructure. However, resilience can encompass medium and low-impact events such as minor civil structural accidents, light faults and supply disturbances. Some resilience assessment advances are in buildings at the low-voltage (LV) level. They include vulnerability to natural disasters, reliability of supply, and service quality. These works usually use approaches independent of each other, leaving a gap between their relationship and interpretation. Therefore, there is a need to consolidate a resilience assessment strategy to guide the analysis of vulnerabilities and strengths in the same direction. This paper proposes a comprehensive approach to evaluate electrical resilience for buildings. It compiles quantitative strategies for studying electrical resilience, focusing on LV systems. It proposes a methodology for integrating the electrical system infrastructure's vulnerability, the supply's continuity and the voltage service's quality. Implementing this approach in a university building equipped with smart metering demonstrates the effectiveness of the proposed methodology for assessing electrical resilience. The results show a comprehensive resilience analysis and the possibility of extending the methodology to MG and LV distribution networks.

1. Introduction

One of the first definitions of *resilience* was established by Holling in 1973 [1] as a measure of a system's performance in absorbing disruptions without changing the relationship between state variables. This concept evaluated the performance of ecological systems in the face of extreme weather conditions and human-caused changes. Over time, resilience analysis expanded to the economic, social, organisational, and engineering domains [2,3]. According to the literature survey developed by Yodo and Wang [4], engineering resilience refers to the ability of a system to survive and recover from damage caused by disruptive events or accidents. The diversity of applications in engineering sectors makes it difficult to reach a universal agreement on its quantification and associated measurement techniques. Additionally, the UK Cabinet Office [5] has delved deeper into critical infrastructure resilience. It refers to the ability of assets, networks, and systems to anticipate, absorb, adapt, and recover quickly from disruptive events. Power systems play a crucial role as they are upstream-dependent critical infrastructure. The analysis of power systems' resilience is gaining strength. One key factor is climate change, which is expected to increase the effects of extreme weather. It could increase the frequency of outages in power systems [6].

In this way, Xu et al. [6] analysed the resilience of renewable power systems when facing climate risks. Power systems with high renewable penetration are more vulnerable to climate variability events, have lower inertia and flexibility, and have longer post-event recovery times. They have considered lessons from past blackouts to define a perspective on the vulnerability of power systems that increase renewable energy penetration. They also indicate mechanisms to strengthen power system resilience by establishing decentralised generation through re-

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newable microgrids (MG). Similarly, Perera and Hong [7] conducted a detailed systematic review on the vulnerability and resilience of urban energy ecosystems in the face of climatic events. They classified the state of the art using the COVID analogy, which focused on understanding the propagation of disruptions within and beyond the energy ecosystem. The literature review revealed that the interaction and interdependence between critical infrastructures make resilience analysis complex. It is also advisable to analyse both the immediate impacts of a disruption and the indirect and future impacts of a disruption.

The researchers consulted have mainly studied the resilience of electrical power systems to extreme and high-impact events. The main events analysed are earthquakes [8–10], strong winds [11–13], intentional attacks [14,15], floods [16], and ice storms [17]. They evaluate the ability of the electrical systems' critical civil structure (CCS) to withstand a high-impact disruptive event. The CCS are the strategic civil works for the electrical network's operation, such as towers, poles, substations and power lines. Resilience is measured by a factor of critical loads supplied during an emergency and the restoration time to supply the entire load. Studies on electrical systems resilience facing medium and low-impact events are addressed to a lesser extent [18,19]. These assessments include power outages of common origin [20,21] and alterations in electrical operating parameters [22,23]. These disturbances are considered low-impact high-probability (LIHP) events, and their study is mainly oriented to distribution networks, MG and buildings.

In distribution networks, resilience analysis is focused on the continuity of power supply in the case of contingency [24,25]. For example, Sabouhi et al. [12] analysed the resilience of the IEEE 14-bus system against wind storms up to 40 m/s. They consider three regions with different wind speed profiles. Thirumalai et al. [26] propose prosumer-centric networked electrical MGs as a solution to strengthen electrical resilience. The MG integrate distributed energy resources (DER) as photovoltaic (PV) systems, energy storage system (ESS), and battery-electric vehicles (BEVs). This research used a multi-agent systems analysis approach to identify the appropriate allocation of DER and BEVs to ensure continuity of supply to users. Prosumers act as energy producers and consumers. BEVs function as mobile energy storage units during emergencies. Cases of moderate and severe damage under variable weather conditions were studied here. The proposed approach was validated in the IEEE 69-bus radial distribution testing system. Galvan et al. [27] evaluate the contribution of PV systems and battery energy storage to the distribution networks' resilience against natural disasters. They use the total customer hours of outage and customer energy not supplied as a resilience metric. Amini et al. [28] present a two-stage stochastic formulation to build MG and increase the resilience of distribution networks to earthquakes. It uses geographic and earthquake data to model the seismic event, then applies linear programming and graph theory to optimise MG formation. It examines the influence of different components, including diesel generators, renewable energy, and electric vehicles, and it also considers uncertainties such as line faults and resource availability. Its main contribution lies in improving electrical resilience through efficient MG formation and evaluating multiple sources of uncertainty.

For buildings operating in low-voltage (LV), some researchers have studied resilience by the capacity of the electrical system to operate in the isolated mode during power outages. For instance, Sunny et al. [29] analyse the implementation of a stand-alone hybrid energy system to enhance the energy resilience of a university institution in Bangladesh. Hussain et al. [30] study the use of electric vehicles (EV) to support the electrical networks in outages. It also discusses reusing discarded EV batteries as home and building backup systems. Tian et al. [31] propose using EVs as a backup system for commercial and residential buildings, where a shared parking station would interconnect the EVs and the buildings. The proposed configuration provides a backup supply for 7 hours in case of an outage. Other authors like Gupta et al. [32] consider the resilience of a building as an energy independence level. Integrating an ESS allows energy source diversification and energy management strategies (EMS). Therefore, a building could be disconnected from the local supply network in the event of a malfunction and be able to self-supply in power outages. Likewise, Lagrange et al. [20] and Rosales et al. [21] analyse the ESS as a strategy to increase resilience against outages and, in turn, integrate EMS to reduce operating costs and strengthen the performance of the operation of the electrical system. On the other hand, Nowbandegani et al. [33] and Parrado et al. [22] address electrical resilience with a focus on the quality of operation and user comfort. They analyse resilience both in contingencies and in normal conditions. The research [22] evaluates the performance of specific electrical parameters such as voltage regulation, frequency, unbalance and harmonic distortion. It defines a strategy for assessing electrical resilience by operation resilience indices. Similarly, Masrur et al. [34] propose measuring resilience regarding the probability that critical loads will survive in an outage and go on to define a criticality weight for loads.

All approaches consulted on the electrical resilience of LV systems point to the networks' ability to overcome adverse events and recover normal operating conditions after disruptions, guaranteeing the continuity and quality of the supply. Some definitions of resilience are qualitative, and the relationship between the approaches needs to be clarified. According to the literature review, it is remarkable that researchers have developed independent approaches to analysing the electrical resilience of buildings and LV networks. These approaches show potential for proposing their integration and developing a comprehensive analysis. This paper identifies the opportunity to relate the electrical resilience approaches for LV buildings and establish a comprehensive assessment. It guides the existing definitions towards applicability in LV systems with a quantitative approach. It classifies the resilience analysis according to the type of event and the recovery term in search of a comprehensive resilience (R_{comp}) assessment. It uses the concept of the vulnerability of the civil structure of a power system to hazard events. It links the reliability of the supply service in the resilience assessment and associates the analysis of service quality. The R_{comp} assessment proposal's effectiveness is tested through its application in a university building that integrates smart metering and power backup.

In the context of the related work, this paper contributes to consolidating a methodology for the comprehensive electrical resilience assessment of LV buildings. Its major contributions are:

- A categorisation of the disturbances faced by the electrical system of a building according to the level of impact and the frequency of occurrence.
- A methodology to assess electrical resilience for each category of disturbance.
- A comprehensive resilience assessment proposal for buildings involving the robustness of civil structure, service continuity, and supply quality.
- The proposed methodology is applied to a university building that integrates critical loads, a backup system, and smart metering.

The remainder of the paper is organised as follows: Section 2 focuses on the resilience assessment in LV networks. Section 3 proposes the methodology for assessing the resilience of LV buildings. Section 4 applies the proposal in a case study. Section 5 discusses the buildings' electrical resilience assessment. Finally, Section 6 presents the conclusions of the research.

2. Remarks on low-voltage electrical resilience

Given the advances in the electrical resilience assessment for LV networks, buildings cover aspects to perform a resilience analysis. This section describes the electrical resilience approaches oriented to LV networks and the proposal to adjust them to buildings.

2.1. LV networks resilience analysis

A conventional LV electrical network comprises a feeder, a set of poles, electrical conductors, and users. The feeder is the means to supply power to the network. It could be a power transformer, an electrical substation or a medium-voltage (MV) electrical circuit. Poles and conductors interconnect users and DER. In this sense, the feeder represents the critical civil structure (CCS) of the LV networks. LV electrical resilience approaches relate to supply continuity in an emergency due to an adverse event. The supply could be interrupted before high-impact low-probability (HILP) disturbances, affecting the feeders' CCS. There are three essential parameters in a resilience analysis against HILP events: *i)* The probability distribution of the HILP event occurrence. *ii)* The vulnerability of the system before that HILP event. And *iii)* the service restoration time before the damage by the HILP disruption [12]. The system's *vulnerability* corresponds to the probability of collapse of its CCS in the event of a high-impact disruptive event [35].

Disruptive events could also affect the quality of power service. Resilience approaches to the quality of supply focus on electrical network performance before low-impact disturbances that affect electrical parameters and user comfort [33]. These disturbances can be classified into two groups: *i)* Low-impact high-probability (LIHP) events such as accidents of common origin, light failures and repairs causing power outages of short duration. And *ii)* permanent-effect (PE) events, such as the integration of energy sources or significant loads that could permanently affect the performance of the electrical system. These PE events mainly affect the voltage at the network nodes [36]. Some researchers such as Rodriguez et al. [37], and Baroud et al. [38] measure the supply quality by a performance function $\phi(t)$ based on a normalised operating parameter. They represent LIHP and PE events with a $e(t)$ function at time t_e. Once $e(t)$ has finished, the system experiences a transient state until it seeks stability. After time t_r, the restoring reaches a stable normal operating mode. The quality of supply performance could then be used to assess electrical resilience to PE events, indicating the risk of a building's electrical installation losing continuity of service due to poor quality issues. It is essential when the electrical grid integrates renewable sources of distributed generation. Against this background, this paper proposes an approach to electrical resilience for buildings operating in LV that is set out below.

2.2. Resilience approach setting for LV buildings

A building's electrical system is exposed to adverse events of the HILP, LIHP and PE types. The building's feeder is the CCS that could expose HILP events affecting the long-term power supply continuity. There are also LIHP events affecting electrical installations and could alter the medium or short-term supply. Consequently, PE events could affect the supply quality, increasing the probability of an outage. This research proposes a comprehensive resilience (R_{comp}) assessment for LV buildings relating to the possible adverse events. It classifies resilience into three types according to the disruption level, damage scale, and effect term. Fig. 1 shows the resilience classification, which is described below.

- **Type I resilience (R_I):** It is the ability of the CCS of the LV electrical system that powers the building to withstand a HILP event keeping the integrity of the civil structure and the power supply continuity. The CCS includes feeders, poles, and electrical lines. HILP events include natural disasters and high-impact disruptions. R_I depends on the CCS's vulnerability, the HILP events' intensity and occurrence probability.
- **Type II resilience (R_{II}):** It is the electrical system's capacity to maintain continuity of service against LIHP disturbances under normal operating conditions. LIHP events involve outages of common origin that do not damage the electrical system's civil structure. They could be scheduled power outages, switching under load, and short-circuit failures. R_{II} depends on the feeder's reliability and corresponds to a mid-term analysis.
- **Type III resilience (R_{III}):** It is the electrical system's ability to guarantee service quality at a supply point despite PE events. R_{III} is focused on short-term analysis. It considers PE events to be variations in load and power affecting supply voltage. Although poor supply quality might be imperceptible to users, it could cause a power outage or equipment damage.

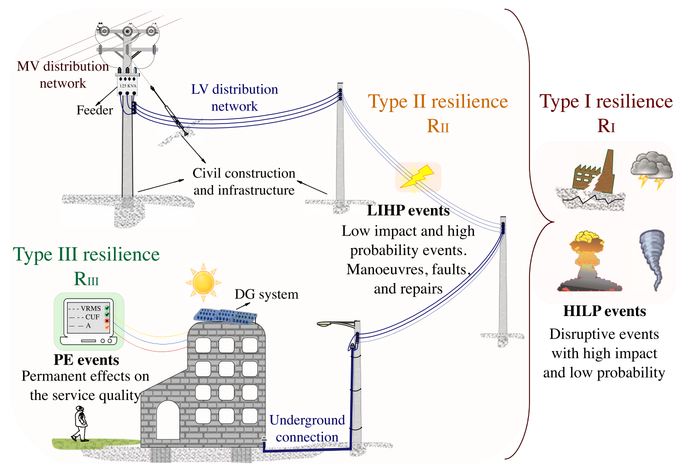

Fig. 1. Resilience analysis classification proposal for LV buildings.

Table 1 outlines the type-resilience classification, the focus of each and the disruptive events to which they relate. The following section outlines the proposed electrical comprehensive resilience (R_{comp}) approach.

3. Electrical resilience assessment methodology for low-voltage buildings

This paper proposes a comprehensive resilience (R_{comp}) assessment comprising three parts. The first is the characterisation of the building to be studied. Here, information is collected about the HILP events in the study region that represent a risk. It determines the vulnerability of the feeder's CCS regarding HILP risk events and uses historical data on power outages and electrical measurements. The second part is the evaluation of the types of resilience. The third part integrates the types of resilience analysis to assess R_{comp}. Fig. 2 presents the methodology for the R_{comp} assessment. The information collected in Part 1 is used in Part 2 to evaluate the resilience types individually, following a specific approach for each one. In Part 3, the results are synthesised to analyse their relationship and contribution to the R_{comp} characterisation. This section describes the assessment of the three types of resilience and their analysis. It is organised as follows: Section 3.1 presents the resilience assessment facing HILP events. Section 3.2 describes the strategy to assess resilience regarding LIHP events. Section 3.3 proposes the methodology for evaluating resilience against PE events. Finally, Section 3.4 exposes the comprehensive electrical resilience (R_{comp}) analysis.

3.1. Type I resilience before high-impact, low-probability events

The R_I resilience assesses the capacity of the electrical network's CCS to withstand a HILP event. It evaluates the probability that the feeder will not collapse conditioned on HILP events. The R_I assessment has three stages: *i)* The characterisation of HILP risk events. *ii)* The analysis of the CCS vulnerability regarding risk events. And, *iii)* the integration of risks to determine R_I. This R_I assessment approach considers the occurrence of a single HILP event simultaneously. Therefore, HILP events are considered independent. The analysis of composite HILP events will

Table 1
Classification of electrical type-resilience for buildings operating in LV.

Type-resilience	Approach	Disturbance coverage
Type I (R_I)	Ability of the critical infrastructure of the electrical system to resist high-impact civil disturbances.	High-impact low-probability (HILP) events affecting the civil structure of the electrical grid. These could be natural disasters, hurricanes, earthquakes and floods. It also includes terrorist attacks, major power failures and similar disruptions.
Type II (R_{II})	Reliability of continuous supply to the critical loads of an electrical installation.	Low-impact high-probability (LIHP) events that produce short-term restoration power outages. These could be minor asset accidents, short circuit failures, scheduled power outages and power grid maintenance.
Type III (R_{III})	Capacity of the electrical installation to guarantee the quality of the supply in the event of permanent changes in operation.	Events with permanent-effect (PE) in the electrical operation, such as the incorporation of new energy sources, the reconfiguration of the grid, the inclusion of unbalanced loads and the occurrence of harmonic pollution, among others.

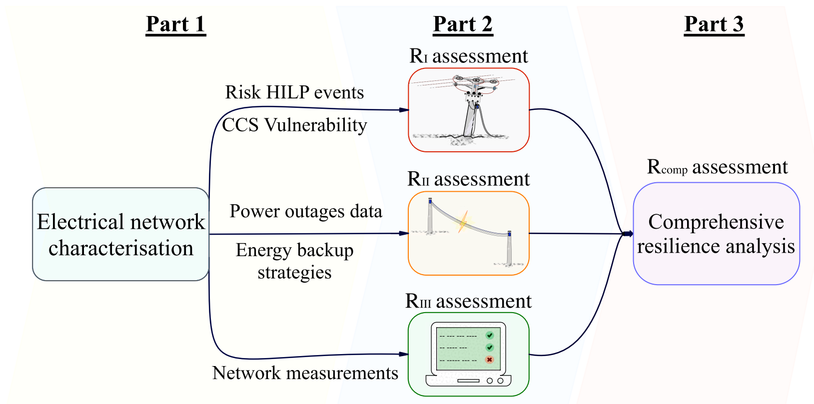

Fig. 2. Methodology for the comprehensive electrical resilience assessment.

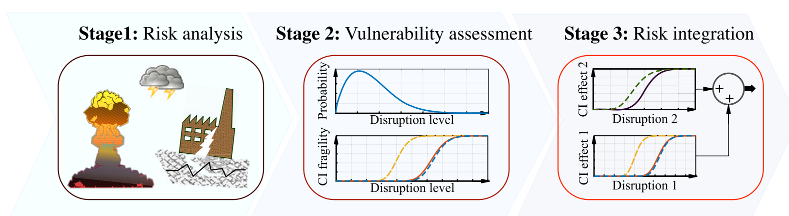

Fig. 3. Methodology to assess R_I resilience.

need to be addressed in more detail to determine the CCS's vulnerability to simultaneous HILP events. Fig. 3 shows the methodology for assessing R_I resilience; then, the stages are described.

3.1.1. Stage 1: analysis of HILP risk events

This stage analyses the threats representing a risk for the feeder's CCS of the building under study. Then, it determines the HILP events to be analysed, their recurrence and risk level. The outputs of this stage are the number N_D of HILP events representing a risk of collapse for the CCS, The probability of occurrence ρ_d and the probability distribution function PDF_d of intensity for each d-event.

3.1.2. Stage 2: assessment of vulnerability against risk HILP events

CCS vulnerability is its loss of structural integrity as a function of the disturbance intensity of a disruptive event. CCS vulnerability is an increasing monotonic function in which, as the level of a disruption increases, the probability of the CCS failure increases. It could be represented by a cumulative distribution function (CDF) [39]. Determining the vulnerability functions requires an extensive study for each type of CCS and event. The CCS has a vulnerability performance to face each HILP d-event. It is necessary to characterise the vulnerability of the feeder's pole $Fr_{[p|d]}$ and electrical lines $Fr_{[ln|d]}$ concerning the d-event. This characterisation could be obtained through experimental methods, statistical methods, analytical techniques, expert judgement, or the combination of the aforementioned methods [40,7]. Based on [39] and [41], the integral of an adapted log-normal distribution could model the vulnerability curve. Consequently, this paper proposes a structural stress index $SSP_{|d}$, representing the probability that the CCS collapses when the d-event occurs. According to [42], the probability $\rho[F_i|d]$ that the i-structure fails given the d-event depends on the event's x-intensity. It is obtained from the infinite sum of the intercepts for each x_j intensity. The sum represents the infinite integral between the product of the probability $\rho[d_{|x}]$ that the d-event has the x-intensity and the probability $\rho[F_{i|x}]$ that the i-structure collapses at the x-intensity. Its mathematical development is shown in (1).

$$\rho\left[F_i|d\right] = \int_0^{\infty} \rho[d_{|x}] \cdot \rho[F_{i|x}] \cdot dx \tag{1}$$

The probability functions $\rho[d_{|x}]$ and $\rho[F_{i|x}]$ correspond to the probability density function $PDF_d(x)$ and the vulnerability function $Fr_{[i|d]}(x)$ respectively; they are x-intensity functions. $\rho\left[F_i|d\right]$ must be evaluated for the N_D HILP risk events identified in Stage 1. For buildings operating in LV, the CCS is considered to be the poles and power lines of the power feeder. Each one has a vulnerability referring to the d-event, $\rho\left[F_p|d\right]$ for the poles and $\rho\left[F_{ln}|d\right]$ for the power lines. Thus, the stress state index $SSP_{|d}$ is considered to be the maximum value between $\rho[F_p|d]$ and $\rho[F_{ln}|d]$ as (2) shows. The following section deals with the integration of stress due to risk events.

$$SSP_{|d} = max\left\{\rho\left[F_p|d\right];\rho\left[F_{ln}|d\right]\right\} \tag{2}$$

3.1.3. Stage 3: integration of stress from HILP risk events

The R_I assessment considers the N_D risk events determined in Stage 1 and analysed in Stage 2. The total stress state probability $SSP_{|HILP}$ is the union of the partial probabilities $SSP_{|d}$. $SSP_{|HILP}$ represents the probability that the system's CCS will collapse due to HILP events. Considering that HILP events occur independently; the union of events equals their sum as (3) shows. R_I resilience is the probability that the feeder's CCS will not collapse facing HILP events. Then R_I is the complement of $SSD_{|HILP}$ as (4) presents.

$$SSP_{|HILP} = \sum_{k=1}^{N_D} SSP_{|d_k} - \sum_{k=1}^{N_D}\left(\sum_{j=k+1}^{N_D} SSP_{|d_k}\cdot SSP_{|d_j}\right) \tag{3}$$

$$R_I = SSP^C_{|HILP} = 1 - SSP_{|HILP} \tag{4}$$

3.2. Type II resilience against low-impact, high-probability events

The R_{II} resilience is the capability of the power grid to guarantee supply service facing LIHP events. It evaluates the probability that the feeder supplies power in normal operating conditions. The R_{II} assessment has three stages: *i)* The characterisation of power outages due to LIHP events. *ii)* The reliability analysis of backup systems. And, *iii)* the evaluation of the capacity to guarantee supply. Those stages are described below.

3.2.1. Stage 1: power outages characterisation

LIHP events have of different origins, for example, manoeuvres, repairs, short circuits by tree branches, minor asset accidents, and scheduled power outages. Generally, the LIHP events do not cause significant damage to the electrical system's CCS. However, an LIHP could lead to a power outage, usually overcome in minutes. These LIHP events are grouped in the power outage category defining a power outage state factor ρ_{out} shown in (5). ρ_{out} represents the probability that the electrical network is without supply. Here, T_{tot} is the observation time, N_{out} is the total number of outages during T_{tot}, and i is the outage indicator. T_{out_i} corresponds to the i-outage length.

$$\rho_{out} = \frac{1}{T_{tot}}\cdot\sum_{i=1}^{N_{out}}\left(T_{out_i}\right) \tag{5}$$

3.2.2. Stage 2: backup systems reliability analysis

Buildings could integrate energy backup systems such as diesel generators or batteries. These systems increase the supply continuity capacity. A total supply probability (TSP) index is defined to evaluate their contribution. TSP is the probability that the backup system will meet the demand load during all outages in T_{tot}. Determining TSP involves four steps:

- *Information acquisition:* This step collects historical data on the power outage lengths for at least one year. It also characterises the demand of the load that the backup system supports.
- *Power outages characterisation:* This step organises historical outage length (lgh) data into frequency intervals fitting a probability density function $PDF(lgh)$ based on the length of outages lgh. It characterises the parameters of the PDF to make a cumulative distribution function $CDF(lgh)$.
- *Backup time determination:* This step analyses the electrical network supported by the backup system. Then, it determines the backup time T_{bk} that would be necessary to supply the demand.
- *TSP definition:* This step evaluates T_{bk} at $CDF(lgh)$ determined in the second step to define TSP; $TSP = CDF(T_{bk})$. It also proposes the backup factor η_{bk} shown in (6) as the ratio between the load supported in outages $Load_{bk}$ and the total load $Load_{tot}$ of the building.

$$\eta_{bk} = \frac{Load_{bk}}{Load_{tot}} \tag{6}$$

3.2.3. Stage 3: evaluation of the supply continuity capacity

R_{II} resilience represents the capacity to ensure power supply continuously. It integrates the two previous stages by determining the probability of non-supply ρ_{off} as (7) presents. ρ_{off} is the probability that building loads will not be supplied through the feeder or a backup system. R_{II} is the complement of ρ_{off} shown in (8).

$$\rho_{off} = \rho_{out}\cdot\left(1 - \eta_{bk}\cdot TSP\right) \tag{7}$$

$$R_{II} = \rho^C_{off} = 1 - \rho_{off} \tag{8}$$

3.3. Type III resilience in the face of permanent-effects

The R_{III} resilience indicates the quality of the electricity supply service, focusing on vital parameters to guarantee electrical service. The electrical quality of an LV building is mainly reflected in the voltage supply [22]. R_{III} indicates the probability that the electrical supply is in acceptable frequency, balance, and voltage ranges. The range of R_{III} is $[0,1]$. Here $R_{III} = 0$ implies that the electrical parameters are in unacceptable operating ranges. Consequently, the feeder cannot supply the building. $R_{III} = 1$ indicates that the electrical parameters are consistently maintained at ideal values. The R_{III} assessment comprises four stages: *i)* The measurement of electrical quality parameters (QP). *ii)* The normalisation of QPs in quality indices. *iii)* The evaluation of operational resilience indices. And *iv)* the integration of the operation resilience indices to find R_{III}. Fig. 4 shows the R_{III} assessing methodology; the stages are described below.

3.3.1. Stage 1: quality parameters

There are standards on electrical service quality with an international scope, such as IEC 61000-3-6 [43], EN 50160 [44], ANSI C84.1 [45], and IEEE Std 519 [46]. They establish criteria for the supply points for loads and the interconnection of new components. This paper analyses the voltage quality at the buildings' supply point. The QPs studied are voltage regulation ($\%\Delta u$), frequency (f), voltage unbalance factor (VUF), and total harmonic distortion of voltage ($THDv$). These parameters are measured and processed in the following stages.

3.3.2. Stage 2: normalisation of quality parameters

A normalisation operator $\Gamma(QP_k)$ based on quality standards is proposed to process the QPs. Here, QP_k is the k-quality parameter analysed. $\Gamma(QP_k)$ is a correspondence function that assigns a value ϕ_k between 0 and 1 depending on the measured QP_k-value. The quality indices $\phi_u(u_{pu})$, $\phi_f(f_{pu})$, $\phi_{VU}(VUF)$, and $\phi_{VHD}(THDv)$ correspond to $\%\Delta u$, f, VUF, and $THDv$, respectively. Here, the u_{pu} is the supply voltage per unit, defined as the ratio of the supply voltage and the nominal voltage (u/u_n). f_{pu} is the frequency per unit, defined as the ratio between the supply voltage frequency and the nominal system frequency (f/f_n). VUF, and $THDv$ represent percentage.

A normalised index $\phi_k(QP_k)$ has a range $[0,1]$. Five characteristic resilience conditions are proposed to build $\Gamma(QP_k)$: *i)* Ideal condition, here $\phi_k(QP_k)$ is equal to 1. *ii)* Acceptable condition that has a range $[0.9\ ,\ 1)$. *iii)* Alert condition with a range $[0.7\ ,\ 0.9)$. *iv)* Emergency condition, range $(0\ ,\ 0.7)$. And, *V)* non-functional condition, here $\phi_k(QP_k)$ is equal to 0. A matching range of QP_k is identified for each operation resilience condition. The operator $\Gamma(QP_k)$ is formulated as a piecewise linear function. The terms of the QPs are described, allowing the determination of the correspondence ranges.

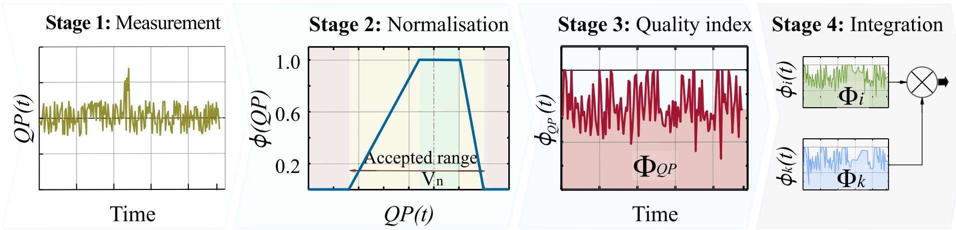

Fig. 4. Methodology to evaluate the operation electrical resilience.

Table 2
Quality parameters ranges defining the operation resilience normalised indices.

Condition	Resilience range	QP range			
		u_{pu}	f_{pu}	$\%VUF$	$\%THDv$
Ideal	1.0	[0.98, 1.02]	$f_{pu} = 1.0$	[0.0, 0.5]	[0.0, 1.0]
Acceptable	[0.9, 1.0)	[0.95, 0.98); (1.02, 1.05]	[0.99, 1.01]	(0.5, 1.0]	(1.0, 3.0]
Alert	[0.7, 0.9)	[0.90, 0.95); (1.05, 1.10]	[0.97, 0.99); (1.01, 1.02]	(1.0, 1.5]	(3.0, 5.0]
Emergency	(0.0, 0.7)	(0.85, 0.90); (1.10, 1.15)	(0.94, 0.97); (1.02, 1.04)	(1.5, 2.0)	(5.0, 8.0)
Non-functional	0	$0.85 \geq u_{pu} \geq 1.15$	$0.94 \geq f_{pu} \geq 1.04$	$VUF \geq 2\%$	$THDv \geq 8\%$

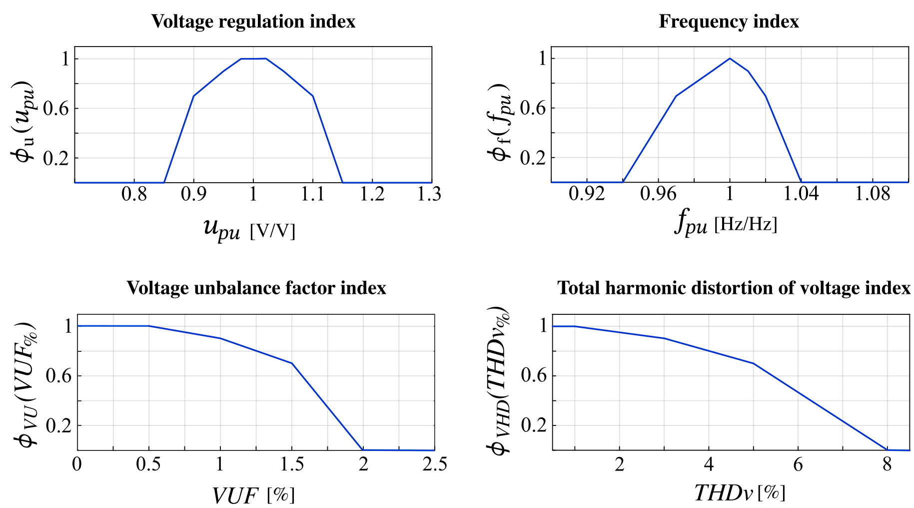

Fig. 5. Normalisation operators for voltage supply quality parameters.

- *Voltage regulation index* $\phi_u(u_{pu})$*:* According to the EN 50160 [44] and the ANSI C84.1 [45] standards, the voltage in LV installations must not exceed $\pm5\%$ under normal operating conditions. A $\pm10\%$ voltage regulation is acceptable in a contingency. $\%\Delta u$ exceeding 15% is fatal, and the system would be out of operation.
- *Frequency index* $\phi_f(f_{pu})$*:* The EN 50160 Standard [44] and the ANSI C84.1 [45] standards indicate an admissible frequency variation of $\pm1\%$ in normal operating conditions. Under contingency, they permit variation of up to -6% and $+4\%$.
- *Voltage unbalance index* $\phi_{VU}(VUF)$*:* Following EN 50160 [44] and IEC 61000-2-2 [47], the VUF must be less than 2% at a supply point in LV. Usually, a VUF less than 0.5% is expected.
- *Voltage harmonic distortion* $\phi_{VHD}(THDv)$*:* The EN 50160 [44], and IEEE Std 519 [46] indicate that the voltage's $THDv$ in the LV supply must be less than 8%. Likewise, individual harmonic distortion must be less than 5%.

Table 2 presents the ranges of resilience conditions and the proposed correspondence for the QPs. Fig. 5 shows the correspondence of the normalisation operators $\Gamma_k(QP_k)$. The quality index function $\phi_k(t)$ results from the application of $\Gamma_k(QP_k)$ on $QP_k(t)$ as (9) expresses.

$$\phi_k(t) = \Gamma_k\left[QP_k(t)\right] = \left(\Gamma_k \circ QP_k\right)(t) \tag{9}$$

3.3.3. Stage 3: operation resilience indices evaluation

The Φ_k index indicates the probability that the associated QP_k parameter is in the accepted range during a measurement time T_{meas}. Φ_k is calculated by the average value of the normalised quality index function $\phi_k(t)$ as (10) presents. Φ_k has a range $[0,1]$ and represents the voltage quality concerning the k-parameter, indicating one for the best quality and zero for the worst condition.

$$\Phi_k = \frac{1}{T_{meas}} \cdot \int_0^{T_{meas}} \phi_k(t) \cdot dt \tag{10}$$

3.3.4. Stage 4: operation resilience integration

R_{III} is the probability that the voltage's quality parameters are acceptable. It is the compound probability $\rho[\Phi_u \cap \Phi_f \cap \Phi_{UV} \cap \Phi_{VHD}]$ as (11) shows.

$$R_{III} = \Phi_u \cdot \Phi_f \cdot \Phi_{UV} \cdot \Phi_{VHD} \tag{11}$$

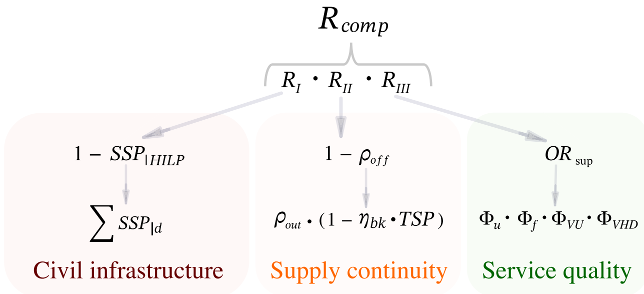

Fig. 6. Comprehensive electrical resilience split.

3.4. Comprehensive resilience assessment for low-voltage buildings

The types of resilience are independently evaluated. However, there is an implicit hierarchy. There must be a power supply to evaluate the R_{III} resilience. Likewise, the feeder must have an active infrastructure to assess R_{II}. In this sense, R_I has the highest rank in the hierarchy, followed by R_{II} and R_{III}. A comprehensive assessment of electrical resilience requires analysing each type of resilience. The R_{comp} analysis indicates the overall likelihood that the electrical network operates correctly in an integral way. If any resilience type is null, R_{comp} is null. It makes sense since a system without electrical infrastructure, supply continuity, or operation quality could not operate. Fig. 6 shows the split of R_{comp} and the participation of the type-resiliences.

Each type of resilience has an evaluation term and a refreshing time. Regarding R_I, historical data on natural disasters and other high-impact events spans decades of records. Power outage data could be analysed yearly in the case of R_{II}. Monthly, weekly or daily analysis is recommended for R_{III}. Each assessment of R_I, R_{II}, and R_{III} allows for the electrical system's capacity to face and overcome adverse events to be identified. A non-evaluated resilience index should be considered equal to one since that implies it is not a risk for the electrical system.

4. Application in a case study

The proposed comprehensive resilience assessment is applied to the Electrical Engineering Building (EEB) at the *Universidad Industrial de Santander* (UIS), Colombia. The local electricity network operator provided historical data on power outages for the electrical circuit feeder. The voltage supply parameters were obtained by measurement. The following sections present the assessment for the case study.

4.1. Case study building

EEB-UIS is located at GMS N 7° 8' 29" W 73° 7' 17" in Bucaramanga, Colombia. It is a five-story building intended for university classes and administrative work. The building's feeder is a 630 kVA three-phase Dyn5 transformer in an underground station fed by a 13.2 kV overhead circuit. The building has a 128 kVA installed demand and uses a 250 kVA diesel generator as a backup system for critical loads. It also integrates smart meters in electrical distribution boards. The critical load is 56 kVA installed demand [48]. Detailed information can be found in [22], [48] and [49].

4.2. R_I assessment

The EEB-UIS feeder is in an underground substation. It has a high level of protection against natural threats. The assessment identifies the MV overhead circuit supplying the feeder as CCS. It is a 13.2 kV three-phase circuit with 12-meter concrete poles. The R_I assessment is developed for the defined CCS.

Table 3
Vulnerability characterisation of the feeder's CI.

HILP event	Element	μ_α	σ_α	Ref.
Earthquake Sa [g-force]	12 m pole	-0.772	0.353	[53]
	Wire conductor	-0.772	0.353	[53]
Wind [m/s]	12 m pole	4.170	0.112	[39]
	Wire conductor	3.701	0.150	[12]

Table 4
R_I assessment results.

HILP event	Pole $\rho[F_p\|d]$	Wire conductor $\rho[F_{ln}\|d]$	Feeder's CCS $SSP_{\|d}$
Earthquake	5.77×10^{-9}	1.65×10^{-9}	5.77×10^{-9}
Winds	1.58×10^{-63}	1.20×10^{-31}	1.20×10^{-31}
$SSP_{\|HILP}$		5.77×10^{-9}	

4.2.1. Determining the HILP risk events

The review by Abedi et al. [50] on the vulnerability of electrical power systems showed that the main natural threats are hurricanes, earthquakes, and lightning strikes. In the case of distribution systems, Li et al. [51] found that gale-force winds usually cause line breaks and pole damage. Moreover, the research by Rodriguez et al. [52] shows that civil constructions in Bucaramanga, Colombia face risks of rupture by earthquakes. No information on intentional attacks is reported for the case study location. Hence, the potential hazards are earthquakes and strong winds.

Earthquake characterisation: The fundamental natural frequency of a 12 m concrete pole is 1.2 Hz [53]. The National Seismic Hazard Model for Colombia [54] provides the seismic hazard information for Bucaramanga. The mean probability of intensity exceedance data for the 0.7 s oscillation period is used to fit the two-term exponential function shown in (12). Here, Sa is the spectral acceleration as the intensity parameter in g-force. $\rho[E \geq Sa|Sa]$ corresponds to the exceeding probability for each Sa-value of the earthquakes in one year.

$$\rho[E \geq Sa|Sa] = 0.457 \cdot e^{-383.1 \cdot Sa} + 0.252 \cdot e^{-54.5 \cdot Sa} \tag{12}$$

Winds characterisation: Hourly wind speed data from the last ten years is used to characterise the probability of wind in the case study area. This data was obtained from the NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program on 2023/01/20 [55]. The data is fitted to a Weibull density function, which finds 1.69709 and 1.86989 as the scale and shape parameters, respectively. Here, the intensity parameter is the wind speed measured in m/s. The abscissa is the probability of each wind speed.

4.2.2. CCS vulnerability

Researchers [53,12,39], model the structural vulnerability as the cumulative distribution function (CDF) of a logo-normal function, then, $fr_{[CI|d]} = \Phi(x|\mu_\alpha, \sigma_\alpha)$. x represents the intensity variable of the disruptive event. μ_α and σ_α are the x-log values' mean and standard deviation, respectively. The assessment uses the vulnerability characterisation of poles before earthquakes by Baghmisheh & Mahuli [53]. Furthermore, the vulnerability characterisation of distribution lines in the face of wind by Sabouhi et al. [12] and Salman et al. [39]. Table 3 presents the characteristic parameters of the CCS vulnerability. Fig. 7 presents the probability of intensity of earthquakes and winds for the case study. Moreover, it shows the characterisation of CCS vulnerability.

4.2.3. Integration of stress by HILP risk event

Equations (1) and (2) are applied to calculate the stress state probability $SSP_{|quake}$ and $SSP_{|wind}$ according to the preceding CCS vulnerability characterisation. Then, (3) and (4) are use to compute $SSP_{|HILP}$ and determine R_I. Table 4 summarises the results of the R_I assessment.

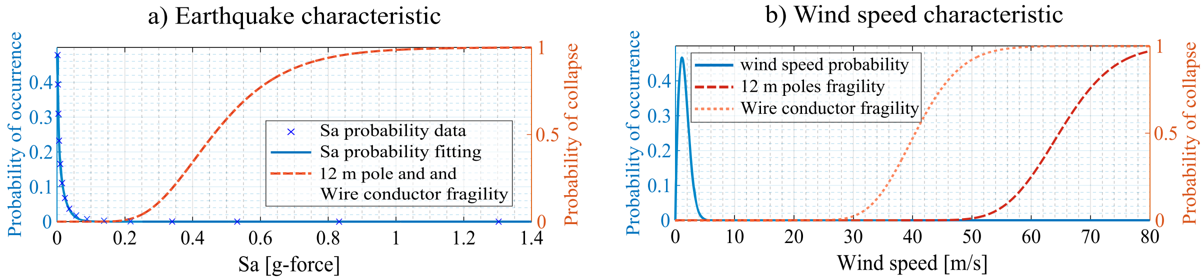

Fig. 7. Characterisation of CCS vulnerability, a) before earthquakes, b) before high-wind speed.

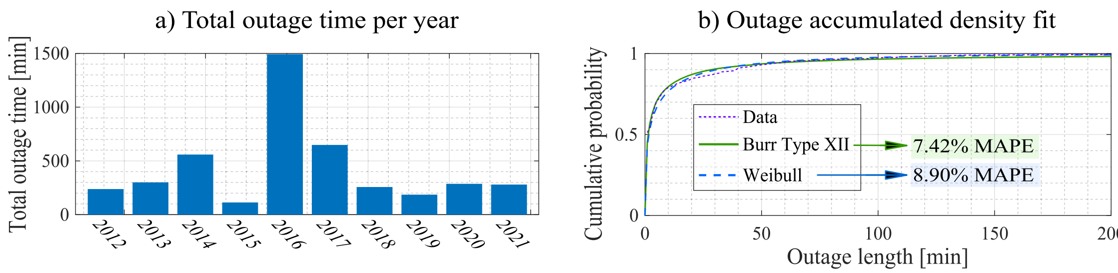

Fig. 8. Historical power outage, a) Annual outage time, b) Cumulative density function fit for outage length.

Table 5
R_{III} assessment results.

Quality parameter QP_k	Voltage u_{pu}	Frequency index f_{pu}	Unbalance VUF	Distortion $THDv$
Resilience index Φ_k	0.9474	0.9958	0.9998	0.9683

Results show $R_I \approx 1$, indicating a low probability that the feeder's CCS collapses due to HILP events. Earthquakes are the ones that result in the most significant probability of collapse.

4.3. R_{II} assessment

The R_{II} assessment refers to the information provided by the local electrical network operator and the load characteristics of the case study building.

4.3.1. Power outages characterisation

The local electricity company *Electrificadora de Santander S.A E.S.P.* (ESSA ESP) provided the historical data on power outages of the ten years 2012–2021 for the MV circuit supplying the EEB-UIS feeder. In the ten year period that was studied, there was 301 outage events from various causes. The total duration of the outage is 72.7 hours for 2012–2021. According to (5) the outage probability is $\rho_{out} = 8.30 \times 10^{-4}$.

4.3.2. Backup systems reliability

The historical outage data is used to build the $CDF(lgh)$. The CDF fitting found that the Burr Type XII distribution has the best fit with 7.42% mean absolute percentage error (MAPE), followed by the Weibull and Gamma distributions with 8.90% and 17.60% MAPE, respectively. The Burr distribution function parameters are $\alpha = 10.910$, $c = 0.516$, and $k = 2.368$. Fig. 8 presents the power outage time per year for the EEB-UIS and the fit of historical outage data to a CDF. The EEB-UIS has a 250 kVA diesel generator backup system for critical loads. It could supply power for up to 12 continuous hours. The critical load is 55.8 kW, representing 43.8% of the EEB-UIS installed demand. Then, the backup system offers $TSP = CDF(720) = 0.99$, and $\eta_{bk} = 0.44$.

4.3.3. Supply continuity capacity

The equations (7) and (8) are applied to characterise the continuity supply capacity. The non-supply probability is $\rho_{off} = 4.65 \times 10^{-4}$. The backup system helps reduce ρ_{off} by 44%. As a result, $R_{II} \approx 1$; however, the EEB-UIS could be in an outage state for 244 minutes per year.

4.4. R_{III} assessment

Quality parameters QP are measured with an AcuRev 2020 2 EM meter, 0.5 class (ANSI C 12.20) and 0.5 s class (IEC 62053-22). It is installed on the leading LV supply node of the EEB-UIS. It has a 10-minute sampling time corresponding to 31 days of measurement from May 1^{st} to May 31^{st}, 2023. The assessment normalises the QP according to the transformer operators $\Gamma_k(QP_k)$ and calculates the operation resilience indices by (10). Table 5 presents the results of the R_{III} assessment, and Fig. 9 presents the evolution of R_{III} with a one-day refresh time. It shows that the voltage index strongly influences total operational resilience. The supply voltage is the most vulnerable QP. Results indicate $R_{III} = 0.9133$; the supply QPs are acceptable during the measurement time.

Knowing how resilience indices are developed is essential in identifying vulnerable issues. Here, the voltage regulation PQ shows the highest variation and lowest level of resilience. The monthly average is acceptable; however, there are days when it rises to the alert range in the daily-performance. The daily development of the R_{III} indices allows for the vulnerabilities of QPs and possible patterns of variations and low values to be identified. Table 6 presents the minimum (*min*), maximum (*max*), average (*mean*) and standard deviation (*std*) values, for the R_{III} indices of the EEB-UIS. May 24 is the day that exhibits the lowest Φ_u. The issue could be due to an overvoltage in the supply through the power distribution network and not to a failure of the EEB-UIS electrical network.

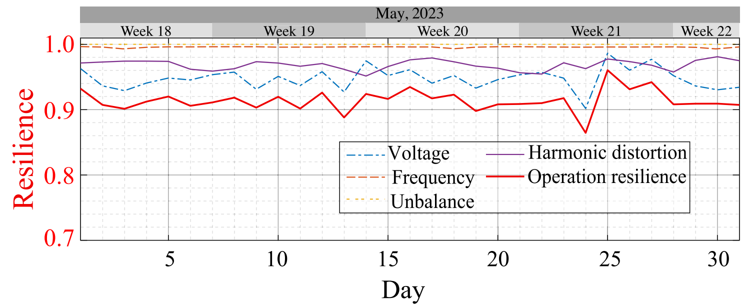

Fig. 9. Daily evolution assessment of the operation resilience indices for the EEB-UIS.

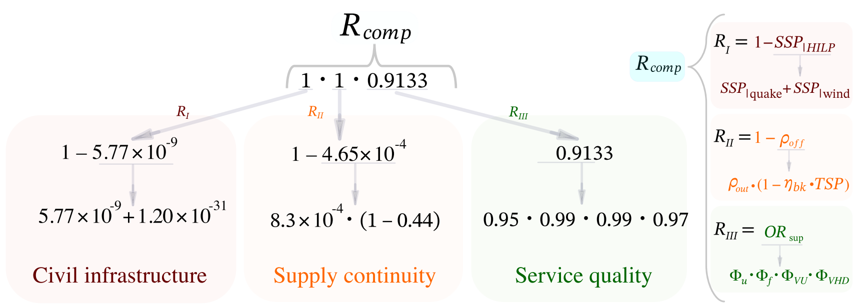

Fig. 10. Splitting of the EEB-UIS's electrical resilience assessment.

Table 6
Variation of EEB-UIS R_{III} indices when considering a one-day update time.

Rate	Φ_u	Φ_f	Φ_{VU}	Φ_{VHD}	OR_{III}
min	0.9018	0.9954	0.9998	0.9515	0.8645
max	0.9865	0.9965	0.9998	0.9810	0.9604
mean	0.9456	0.9958	0.9998	0.9683	0.9133
std	0.0168	0.0003	0.0000	0.0077	0.0169

4.5. Comprehensive resilience

The comprehensive resilience (R_{comp}) analyses the type-resilience assessments to reach conclusions on the electrical resilience of the EEB-UIS. Fig. 10 presents the split of the R_{comp} assessment. It indicates that the EEB-UIS is lowly vulnerable to losing power supply due to high-impact natural disturbances. The feeder has high supply reliability under normal operating conditions. EEB-UIS's backup system increases resilience against regular power outages. However, due to high supply voltage values, R_{III} indicates an alert regarding the operation's quality. Then, an opportunity to improve the electrical resilience of the EEB-UIs is mainly concerned with measures to adjust voltage regulation.

5. Discussion

This paper attempts to integrate the electrical resilience approaches addressed in the literature for LV systems. It proposes three resilience classifications and an assessment methodology for LV buildings. The resilience classification is as follows: R_I resilience for electrical critical civil structure (CCS) in the face of high-impact events; it follows the vulnerability analysis of critical infrastructures outlined in [5,8,11]. R_{II} resilience for the local electrical network in the face of regular power outages; it is in the same direction as the supply reliability studies developed in [20,21,24]. And lastly, R_{III} resilience for the network operation against events that alter the supply quality. This recent approach is discussed in [22,23,33] and further developed in this paper. Regarding the practicality of the R_{comp} methodology developed in this research, it is remarkable that the R_I assessment is focused on capacity expansion. However, it is possible to extend the scope of the methodology to address other challenges, such as the integration of backup power systems and quality of service enhancement measures. For example, in the research by Rodriguez [56], the R_{II} resilience index is used to analyse the feasibility of installing a hydrogen-based power backup system in the EEB-UIS building. In addition, the effectiveness of energy management strategies is compared by periodically evaluating the R_{III} index.

The R_I, R_{II} and R_{III} resilience indicators provide information on the capacity of the building's electrical system to face disruptive events. They allow for identifying the events for which the building is vulnerable, affecting the supply capacity. R_I helps to identify infrastructural changes that could improve the robustness of the feeder and the related circuit before HILP events. It focuses on network operators responsible for the feeder circuit's electrical infrastructure. R_{II} also allows for the identification of the continuity of supply before outages of common origin. This way, the local network operator could improve supply reliability by including assets. On the other hand, the user could analyse the contribution of an energy backup system and plan its appropriate sizing, finding a tradeoff between the investment for the backup system and the contribution to resilience. R_{III} allows for the identification of the quality of the service and the likelihood of incurring a violation of the quality parameters. It also defines the feasibility of including new energy sources or loads by analysing their effect on R_{III}. In the forthcoming work, it is desirable to analyse the applications of the comprehensive electrical resilience methodology to enhance its usefulness.

The proposed methodology is limited by the study case's specific information required to develop the comprehensive resilience assessment. It requires identifying and characterising risk threats, each involving the characterisation of probability, frequency of occurrence and CCS vulnerability. There are already HILP event reports, such as those from earthquakes and hurricanes. However, characterising an exceptionally high-impact event requires thorough work that will depend on valuable years of sampling and high-resolution simulations. For the characterisation of power outages of common origin, the network operator must contribute to compiling historical data from at least one year of registration. Measuring quality parameters requires installing meters for concrete parameters such as voltage, frequency, unbalance and harmonic distribution. Not every building integrates smart metering. Applying this integral methodology requires a total contribution between the network operator and the user and specific conditions for a correct assessment.

The case study has considered earthquakes and strong winds since risk studies have identified them as potential threats to the study area. There is also a characterisation of CCS vulnerability for these two events as they are widely analysed in vulnerability studies. For the case study, there are no records of significant accidents or intentional attacks. If there are any, they could be integrated into the R_I assessment according to the proposed methodology. It requires a detailed review for each type of event, involving specialised tests and measurements or simulations. The R_I resilience analysis developed in this research mainly considered high-impact events that affect the civil integrity of a power system. However, it should be noted that high-impact events, such as droughts and cold or heat waves, also affect energy integrity. Thus, future development of comprehensive resilience analysis should expand the scope of HILP events analysed in the resilience assessment, cover multidimensional impacts and establish methods for quantification.

The next step in analysing comprehensive electricity resilience is to assess the interdependence of the resilience types. It is understandable that increasing the resilience R_I strengthens the robustness of the electrical system's CCS and thus decreases the probability of common outages. It could also improve the quality of service performance. Since assessing the interdependence between type-resilience is complex, developing specific research in this field is advisable. Improvement opportunities have also been identified for the proposal, including analysing specific medium-impact events with a moderate frequency of occurrence, such as the rupture of power lines due to common accidents. Also, the R_{III} approach could be strengthened by expanding its application to specific nodes of the building's electrical network, such as particular load nodes and common coupling nodes of energy sources. On the other hand, the proposed assessment could be complemented with feedback stages where R_{III} is measured continuously and with a one-hour refresh time using it as a decision parameter and applying energy management strategies. Then, the feedback could increase R_{III} in real-time and reduce the probability of a power outage due to low quality of service issues.

6. Conclusions

This paper proposes a methodology for assessing the electrical resilience of LV buildings. It classifies resilience according to the disturbance events the electrical network could face. It proposes resilience indices and an assessment methodology for each type of event. R_I to HILP events assesses the ability of the LV network's CCS to withstand natural disasters. R_{II} resilience to LIHP events assesses the capability of the LV network to recover from common cause outages. R_{II} also considers the contribution of energy backup systems to support common outages. R_{III} resilience analyses the service quality provided to users. Then, the three types of resilience are integrated.

The methodology is applied to a university building. The case study results find R_I and R_{II} close to the maximum value, and R_{III} shows vulnerability in the supply quality. The main parameter to strengthen is voltage regulation followed by voltage unbalance. The proposed methodology shows consistency in the case study's application. It is expected that R_I and R_{II} are high. Although there is a high seismic hazard in the case study region, the intensity of the earthquakes is more likely at values that represent a low risk of collapse for the CCS. Similarly, the electrical distribution network feeding the case study has reliability close to 100%, and the building studied has a backup system that decreases the probability of a non-supply state by 44%. The methodology presented in this paper is consistent with the proposals found in the scientific literature. It could be extended to the resilience analysis of MG and LV distribution networks.

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CRediT authorship contribution statement

Rusber Rodriguez: Writing – original draft, Validation, Methodology, Investigation. **German Osma:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Data curation, Conceptualization. **David Bouquain:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Gabriel Ordoñez:** Writing – review & editing, Funding acquisition, Data curation, Conceptualization. **Damien Paire:** Writing – review & editing, Supervision, Conceptualization. **Javier Solano:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Robin Roche:** Supervision, Formal analysis, Conceptualization. **Daniel Hissel:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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