Application of a Computational Tool to Enhance the Electrical Resilience of a Distribution System During a Volcanic Eruption

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Abstract: - High-impact, low-probability (HILP) events, such as natural disasters, have increased the vulnerability of power distribution systems (PDS). PDS resilience refers to their ability to withstand these events and recover quickly. This study proposes a methodological framework and a computational tool to determine the optimal sizing and placement of battery energy storage systems (BESS) and power switches within PDS, thereby enhancing their resilience against lahars triggered by volcanic eruptions. The focus is on reducing energy not supplied (ENS) during PDS recovery. The results indicate that the proposal can improve PDS resilience to exogenous events by investing in BESS and switches, ensuring electrical supply to critical services such as hospitals, shelters, and police under demand-side management.

Key-Words: - BESS, Demand, Lahar, Resilience, Switches, Volcanic Eruption.

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1 Introduction

From the discovery of electricity to the most current ways of transforming it, electrical systems have proven to be a fundamental pillar for the development of modern society. However, this progress has generated a multidisciplinary dependence on this service, making it a critical element that can be threatened by various factors. Among these, high-impact low-probability (HILP) events stand out, such as natural disasters and the effects of climate change, which can cause prolonged interruptions in the power supply, resulting in millions in economic losses and affecting key sectors like health, education, and security, [1].

In this context, the electrical infrastructure faces significant challenges, such as damage to transmission lines, distribution, and substations, resulting in insufficient supply and system response capacity, [2]. Although many countries have implemented measures to address these events, the recovery time is often considerable, sometimes extending to weeks or even months, [3]. Therefore, the resilience of electrical infrastructure should not be understood as the absence of failures, but rather as the ability to maintain a minimum level of system operation at reasonable costs and times, [4].

In this sense, distributed energy resources (DERs) emerge as a promising solution to increase the resilience of electrical systems against low-probability, high-impact exogenous events, [5].

DERs, which include distributed generation sources and storage devices, allow for the generation, storage, and control of energy in a local and decentralized manner, reducing dependence on long transmission lines and making the grid less vulnerable to disasters, [6].

Moreover, these resources not only strengthen emergency response capabilities but also play a key role in decarbonization and the energy transition, empowering communities and regions in managing their own energy, [7].

With these considerations, the development of computational tools that assess the impact of low-probability and high-impact events, such as volcanic eruptions, on electrical distribution infrastructure becomes an urgent necessity, [8].

These tools will allow for the optimization of the use of available resources, strengthen the operation of distribution systems, and ultimately improve the resilience of electrical networks in the face of future challenges, [9].

1.1 Related Work

According to [1], the gradual manifestation of a series of natural events (tornadoes, tsunamis, earthquakes, wildfires, volcanic eruptions, etc.) has increased the vulnerability of infrastructure and the global population. These potential phenomena have numerous economic and social consequences, [10].

Among the social consequences, we can mention the event that occurred in 1977 when the New York power grid collapsed due to lightning strikes on a substation and power transmission lines. This caused overloads at various points in the network, and in the midst of the darkness, looting and acts of vandalism were carried out by the city's citizens.

Regarding the economic consequences, the Congress on climate, resilience, and power outages [11] analyzes the interruption of electrical service due to storms and precipitation. For the year 2012, it estimates annual losses between 20 billion and 50 billion dollars for the U.S. economy due to the lack of timely supply to factories, businesses, and sectors essential for the trade of this global power.

Given these circumstances, [12] suggests that improving the overall condition and efficiency of the electricity supply system increases the system's resilience, contributing to a faster recovery from outages related to natural events.

In this context, the resilience of electrical systems is defined as the ability of an energy system to quickly recover after a disaster or, more generally, as the ability to anticipate extraordinarily high-impact low-probability (HILP) events, quickly recovering from these disruptions and adapting its operation and structure to be better prepared for future similar events, [13].

1.2 Nomenclature

Function Objective

Variable	Definition
CI	Investment costs.
CO	Operating costs.
NT	Evaluation horizon expressed in hours.
FRC	Capital recovery factor in years.
C^{interr}	Cost of switches in USD.
$\varphi^{existente}$	Number of existing installed circuit breakers.

Function Objective

C^{Bess}	Cost in USD/ kW of installed BESS.
$Bess^{installed}$	BESS power installed.

Monte Carlo simulation

PD	Dynamic Pressure.
ρ_L	Density.
v_L	Speed.

Balance Equation

$f_{E_{t,l,e}}$	Existing network Flow.
$f_{C_{t,s,e}}$	Flow in loads.
$Aliment_{t,k,e}$	System power supply.
$PC_{BESS_{t,q,e}}$	BESS with its charging power.
$PD_{BESS_{t,p,e}}$	BESS with its discharge power.
$C_{t,d,e}$	Charge.
$ENS_{t,d,e}$	Energy not supplied.

Model BESS

E	Energy supplied.

Network power model

$Alim_{t,k,e}$	Feeder.
$Pmax_{grid}$	Maximum power.

Network Flow Models

Variable	Definition
$FE_{t,l,e}$	Distribution lines.
$\theta_{t,i,e}$	Voltage angle.
X_{LT}	Line reactance.
$Fmax$	Maximum Flow.
Nb	Number of bars.

Switch model

Nb	Number of bars.
$\theta_{t,i,e}$	Voltage angle.
M	Variable Big-M.
$\sigma 1$	Binary variable that determines the installation of the circuit breaker.
X_{LT}	Line reactance.
$FI_{t,l,e}^{Linea}$	Line flow for candidate circuit breakers.
$Fmax$	Maximum Flow.

2 Methods

The following are the stages that are part of the proposed methodology, which consists of three general stages, as shown in Figure 1.

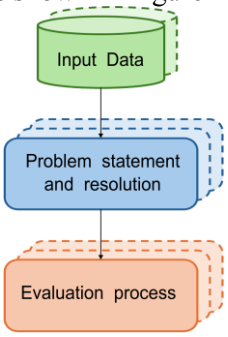


Fig. 1: Proposed methodology for the research
Source: created by the authors

2.1 Input Data

The first stage determines the Volcanic Explosivity Index (VEI), used as a volcanic hazard identifier. This index allows for the estimation of the magnitude, density, destructiveness, and dispersal capacity of a volcanic eruption. At this stage, the dynamic pressure (DP) is determined, which depends on the lahar flow, which is a function of the lahar's speed and density; these variables, in turn, are functions of the VEI (Figure 2).

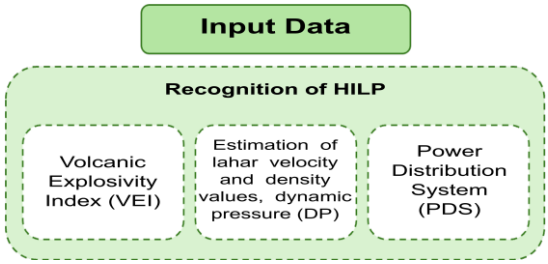


Fig. 2: Input data methodology
Source: created by the authors

2.2 Problem Statement and Resolution

In stage two, the optimization problem is posed and solved to establish the optimal sizing and location of the battery energy storage systems (BESS), as well as the switching of the proposed candidate switches. Additionally, an optimal DC/OPF (Direct Current-Optimal Power Flow) is solved, including various contingency scenarios defined by the Monte Carlo simulation method (Figure 3).

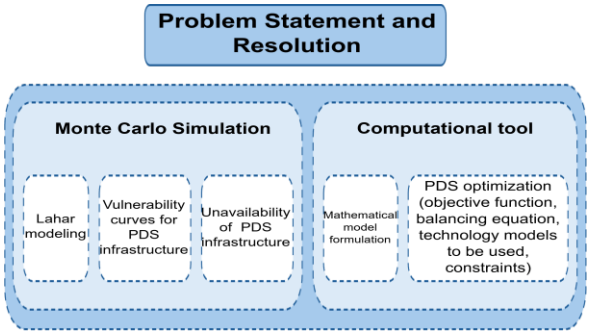


Fig. 3: Methodology for Problem Statement and Resolution
Source: created by the authors

2.3 Monte Carlo Simulation

With the purpose of characterizing the threat, several scenarios are generated using the Monte Carlo simulation method. In this particular case, to model volcanic lahars, two levels of uncertainty (the speed vL and the density ρL) are considered to determine the dynamic pressure (PD) of the lahar flows. The PD is determined using Eq. (1). The input data includes different velocities, densities, and risk maps (lahar flow paths) obtained from historical volcanic events.

$$PD = \frac{1}{2} * \rho_L v_L \tag{1}$$

2.4 Objective Function

The objective function presented in Eq. (3) minimizes the investment costs (IC) and operation costs (OC) of the system. Eq. (4) shows the investment costs corresponding to the evaluation horizon expressed in hours (NT), the capital recovery factor in years (FRC), the cost of switches in USD ($Cinterr$), the number of existing installed switches ($\varphi existente$), the cost in USD/KV of installed BESS ($CBess$), and the power of installed BESS ($Bessinstalled$), [14].

$$Min = FO = CI + CO \tag{2}$$

$$CI = NT\left[C^{interr}\sum_{e=1}^{Ninterr}\varphi^{existente} + C^{Bess}\sum_{e=1}^{NBessC}Bess^{installed}\right] \tag{3}$$

2.5 Balance Equation

Eq. (4) represents the system equilibrium formulation in which the existing network flow (fEt,l,e), the flow in the loads (fCt,s,e), the system feeders ($Alimentt,k,e$), the BESS with its charging power ($PCBESSt,q,e$) and discharging power ($PDBESSt,p,e$), as well as the load (Ct,d,e) minus the unsupplied energy ($ENSt,d,e$) are considered to evaluate the amount of distribution structure that remains standing in the system, [15].

$$\sum_{l=1}^{LTE} fE_{t,l,e} + \sum_{s=1}^{NInterr} fC_{t,s,e} + \sum_{k=1}^{NAlim} Aliment_{t,k,e} + \sum_{p=1}^{NBessC} PDBESS_{t,p,e} = \sum_{d=1}^{NC}\left(C_{t,d,e} - ENS_{t,d,e}\right) + \sum_{q=1}^{NBessC} PC\ BESS_{t,q,e} \tag{4}$$

2.6 BESS Model

To determine the optimal size of the BESS, the model proposed in [16] can be applied. Where the

amount of energy in the batteries is shown in Equations (5) and (6), one when the battery is installed and the other after each charge and discharge of the BESS, respectively. Likewise, the constraints on the BESS's charge and discharge limits are established in Eq. (7), (8), and (9), with Equation (10) ultimately modelling the care of the battery's lifespan.

$$E_{s,t,i} = E_{s,0,i} + n^{inv} * P_{s,t,i}^{B,char} - \frac{P_{s,t,i}^{B,dis}}{n^{inv}} \quad (5)$$

$$E_{s,t,i} = E_{s,t-1,i} + n^{inv} * P_{s,t,i}^{B,char} - \frac{P_{s,t,i}^{B,dis}}{n^{inv}} \quad t \geq 1 \quad (6)$$

$$0 \leq -P_{s,t,i}^{B,char} \leq \frac{P_i^{B,insta}}{n^{inv}} \quad (7)$$

$$0 \leq -P_{s,t,i}^{B,dis} \leq P_i^{B,insta} \quad (8)$$

$$0{,}2\ P_i^{B,insta} \leq E_{s,t,i} \leq P_i^{B,insta} \quad (9)$$

$$0{,}2 * P_i^{B,insta} \leq P_i^{B,insta} \leq 0.95 * P_i^{B,insta} \quad (10)$$

2.7 Network Power Model (Feeder)

The network power model is determined by the maximum demand required by the system as detailed in Equation (11).

$$0 \leq Alim_{t,k,e} \leq Pmaxgrid \quad (11)$$

2.8 Network Flow Model

The model represents the flow calculation for the existing distribution lines (FEt,l,e) and is determined by Equation (12), which considers the voltage angle ($\theta t,i,e$), the reactance of the lines (XLT), and a maximum flow restriction allowed by the existing lines ($Fmax$) detailed in Equation (13), [17].

$$FE_{t,l,e} = \frac{\sum_{i=1}^{Nb} \theta_{t,i,e}}{X_{LT}} \quad (12)$$

$$-Fmax \leq FE_{t,l,e} \leq Fmax \quad (13)$$

2.9 Switch Model

Switches are power elements that allow automatic response to planned and unplanned events that may occur in the electrical grid, commonly called reclosers, and are defined by three criteria: 1), class 2), interrupting capacity, 3), nominal current [18]. The switch model is formulated in Equation (14), considering a disjunctive technique called Big-M, where M represents a sufficiently large positive constant. This technique (Big-M) allows for the separation of bus voltage angles associated with distribution lines that disconnect due to a system contingency, meaning it is only applied to distribution lines available to operate in different scenarios; the approach also includes the binary variable ($\sigma 1$) which represents the availability or unavailability of the candidate switch, and a maximum flow restriction associated with the binary variable detailed in Equation (15), [19].

$$\frac{\sum_{i=1}^{Nb} \theta_{t,i,e} + M(1-\sigma 1)}{X_{LT}} \geq FI_{t,l,e}^{Linea} \geq \frac{\sum_{i=1}^{Nb} \theta_{t,i,e} - M(1-\sigma 1)}{X_{LT}} \quad (14)$$

$$-Fmax * \sigma 1 \leq FI_{t,l,e}^{Linea} \leq Fmax * \sigma 1 \quad (15)$$

2.10 Evaluation Process

At this stage, a test system will be selected to evaluate the proposed methodology, considering criteria such as the restoration time of the electricity supply, the reduction of unsupplied energy, and the use of resilience metrics (Figure 4).

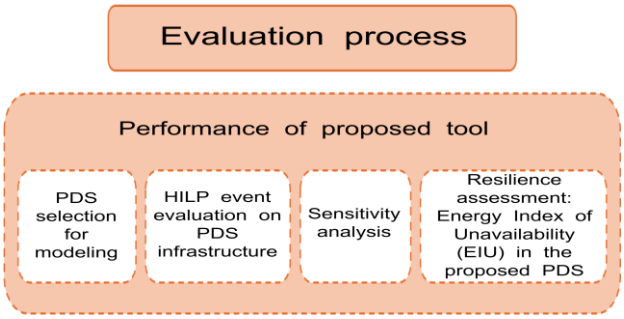


Fig. 4: Process evaluation methodology
Source: created by the authors

3 Numerical Simulation Results

3.1 System to be Evaluated

The proposed methodology is evaluated in the radial system detailed in [20]. This system describes seven feeders and/or substations, thirty-eight loads, thirty-eight sections, and three candidate circuit breakers, as shown in Figure 5. This system is widely used for reliability analysis of electrical systems, as mentioned in [21].

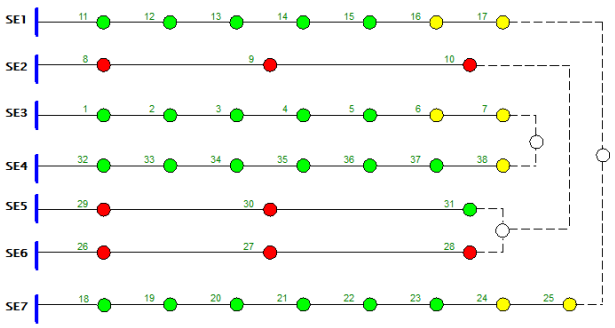
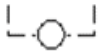


Fig. 5: Single-line diagram of the proposed system
Source: created by the authors

The loads are represented according to the description in Table 1. The demand profile is considered with an hourly resolution of 24 hours, taking into account three types of loads distributed as follows: 22 residential, 7 industrial, and 9 service, each with a maximum power of 100 MW. Additionally, a Value of Lost Load (VoLL) is considered for each type of load. The VoLL for commercial and energy service loads is 1.50 USD/kWh [22], while for residential loads it is taken according to the indication in [23]. For the switches, a reference value of 6400 USD is adopted as the cost of a 25 kV class recloser.

Table 1. Elements and symbolism of the model to be evaluated

Elements	Detail	Symbology
System feeders	7	
Residential (green), commercial (yellow), service (red) loads	38	
Line sections	38	
Candidate switches	3	

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3.2 Types of Loads and Elements Considered in the Analysis

Under the demand management criterion, loads are classified according to their order of priority as high, medium, and low. These criteria will be crucial when validating the computational tool, as, due to having differentiated costs, the proposal will prioritize the supply to emergency service loads. This classification is detailed in Table 2.

Table 2. Type of loads considered in the proposed model

Type of load	Description	Priority
Services	Hospitals, police, fire departments, and emergency services.	High
Industrial	Food and emergency services companies	Media
Residential	Typical local loads	Low

Source: created by the authors

The technologies considered to improve resilience are battery energy storage systems (BESS) and reclosers or power switches for distribution systems. The investment and operational costs of these technologies are described in Table 3.

Table 3. Investment and operational costs of the proposed technology

Element of the proposal	Investment/operation cost
BESS acid	$ 850 kW
Switch	$ 6400 (Class 25 kV)

Source: created by the authors

3.3 System Evaluation

The evaluation of the proposal considers failure scenarios based on the Monte Carlo Simulation (MCS) extended by MATLAB. Figure 6 shows the impact of the lahar on the distribution infrastructure.

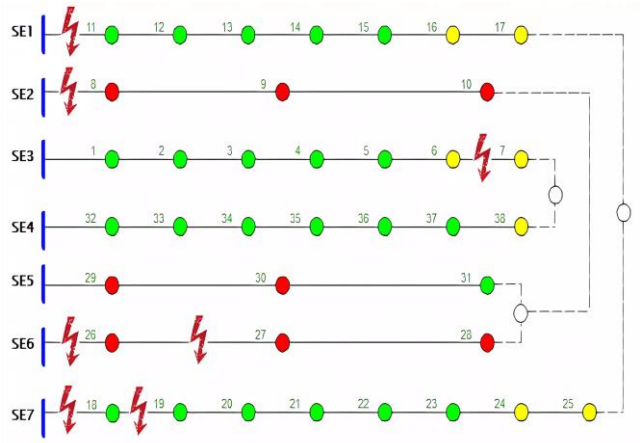


Fig. 6: System to be evaluated with faults
Source: created by the authors

Table 4 describes the sections in failure, as well as the restoration time in hours of the structures associated with the exogenous event.

Table 4. Structures in failure after the exogenous event

Failing structures		
Section		Restoration (H)
41	11	5
40	8	5
6	7	5
43	26	5
26	27	5
42	18	5
18	19	5

Source: created by the authors

Once the failure sections are described, Figure 7 details the loads (in black) that remain without electrical service after the HILP event. The evaluation of the proposal includes sensitivity analysis and graphically shows the difference

between investment costs, operation, and the amount of ENS for each case study:

a) Without proposed technologies or budget.
b) BESS energy storage technology.
c) Switch or Recloser Technology.
d) Combined proposal between options b and c.
e) Combined proposal between options b and c, including the Budget.

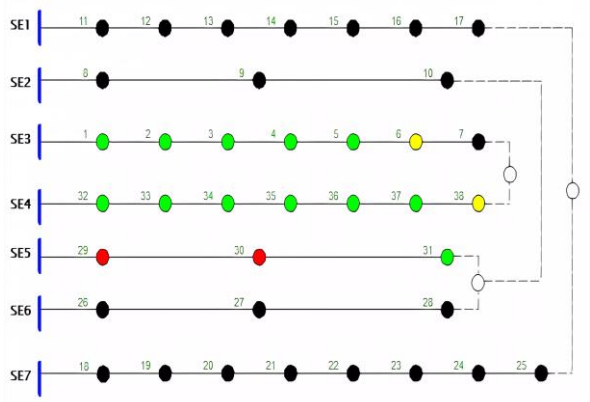


Fig. 7: Loads without electrical service post exogenous event
Source: created by the authors

Figure 8 comparatively shows an initial evaluation of the system without any technology installed, with BESS, with SWITCH, with BESS and SWITCH, as well as the inclusion of everything proposed, plus a reference budget. This represents the amount of ENS that the evaluated system can present after a HILP event.

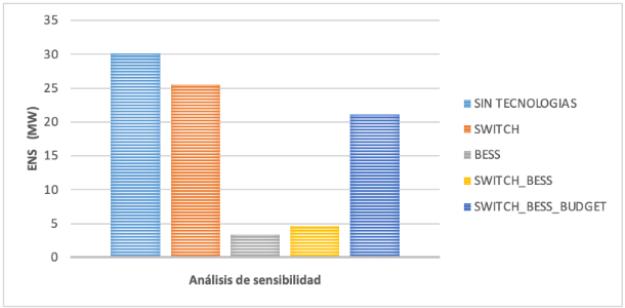
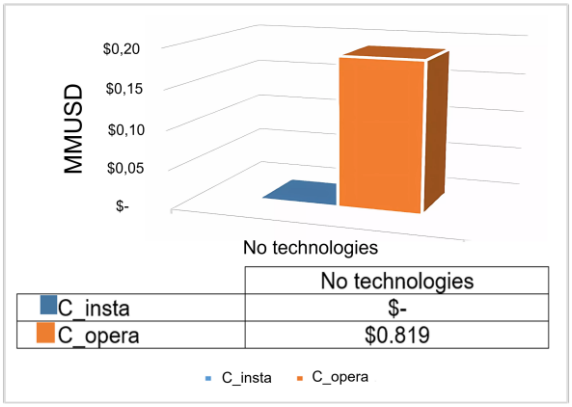


Fig. 8: ENS vs Sensitivity Analysis
Source: created by the authors

After the described analyses, although ENS is paramount, in our study, it is relevant that the installation and operation costs are manageable. Figure 9 shows a sensitivity scenario where installation costs are zero, while operational costs correspond to those of the network that remains operational after the exogenous event.



	No technologies
C_insta	$-
C_opera	$0.819

Fig. 9: Installation and operation costs without technologies
Source: created by the authors

3.4 BESS Energy Storage Technology

The results of the system with only BESS storage technology detail installation costs that approach 82.31 MMUSD and an operating value of 0.047 MMUSD.

3.5 Switching Technology or Reclosers

The sensitivity scenario considers reclosers as the only backup technology. The installation amounts to 0.026 MMUSD, and the operating costs of the entire system are 0.169 MMUSD.

3.6 Combined Proposal (Switch and BESS)

The installation and operation costs of the sensitivity scenario that combines switches and battery energy storage systems (BESS) are detailed below. The installation costs represent an investment of 69.308 million US dollars (MMUSD), while the operating costs amount to 0.052 million US dollars (MMUSD).

3.7 Combined Proposal (Switch, BESS, and Budget)

The installation and operation costs of the sensitivity scenario that combines switches and an investment budget associated with the BESS amount to 10.026 MMUSD. The operating costs amount to 0.136 MMUSD.

4 Discussion of Results

This section presents the analysis of data obtained through the application of the methodology to the case study. The joint implementation of battery energy storage systems (BESS), reclosers, and a budget of 10 million USD for batteries is considered. These technologies compete in terms of installation and operation costs over an evaluation horizon that includes various uncertainty scenarios.

Considering the stochastic nature associated with the exogenous event that causes the failure in the evaluated power distribution system (PDS), a failure matrix is obtained with 38 study nodes, 24 hours of evaluation, and 100 contingency scenarios. In this way, 91,200 data points are collected for the sensitivity analysis of each proposed scenario under linear programming in the FICO Xpress software. The evaluation time in the software for each scenario ranges from 2 to 25 minutes, depending on the technology used.

4.1 Number of BESS and Switches Installed Post-Contingency

After the exogenous event has occurred, the proposed methodology generates alternatives for the location and installation of switches and BESS. A total of 4 reclosers, 8 batteries, and a budget of 10 million USD for energy storage technology are considered. Figure 10 shows in detail what has been described.

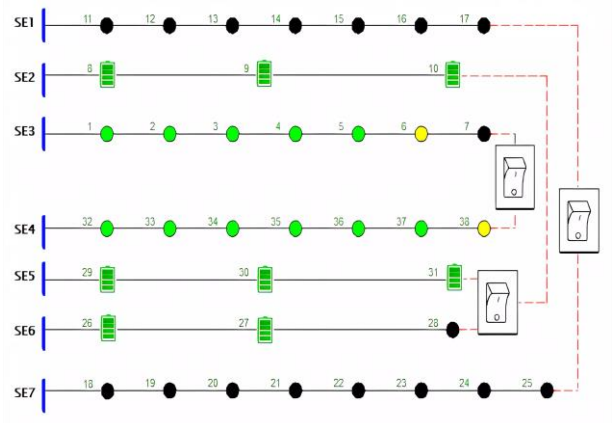


Fig. 10: Location of BESS and Switches
Source: created by the authors

4.2 Unserved Energy, Installation, and Operation Costs

The total ENS of the system has been measured according to the proposed sensitivity analyses and the probability of occurrence of the studied scenarios. According to Table 5, in the first sensitivity analysis, the ENS is 30 MW when no backup technology is used. Compared to this initial analysis, the installation of only reclosers reduces the ENS by 15.46%. On the other hand, the exclusive installation of BESS causes a considerable drop of 88.63% compared to the initial case.

Table 5. Structures in failure after the exogenous event

Proposal to be evaluated	EENS (MW)	CI + CO (MMUSD)
No Technologies	30,19159266	$ 0,189
Switch	25,51676658	$ 0,195
BESS	3,421882632	$ 82,355
Switch BESS	4,614610659	$ 69,360
Switch BESS BUDGET	21,14481698	$ 10,162

Source: created by the authors

A similar result is observed in the scenario that combines the installation of switches and batteries, reducing ENS by 84.69%. Finally, the last proposal results in a 29.96% reduction in ENS compared to the initial scenario.

At first glance, the installation of BESS and its combination with switches significantly reduces ENS. However, these proposals entail a high cost both in the installation and operation of the system, which puts them at a disadvantage and makes them compete with other alternatives. This aspect is illustrated in Figure 11.

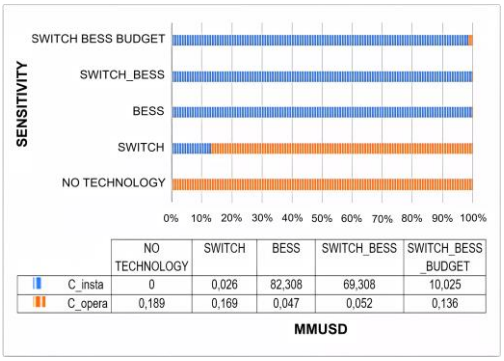


Fig. 11: Installation of BESS and its combination with circuit breakers
Source: created by the authors

Upon observing Figure 11, we can conclude that the proposal to integrate BESS technologies, switches, and BUDGET presents an economical alternative in terms of ENS and installation costs. However, the optimal option to minimize ENS is to use BESS technology, despite the high installation costs.

4.3 Energy Unavailability Index (EUI)

All sensitivity analyses are considered, that is, without existing backup technologies, as well as the joint implementation of BESS, automatic switches, and a budget during the restoration time horizon (Figure 12).

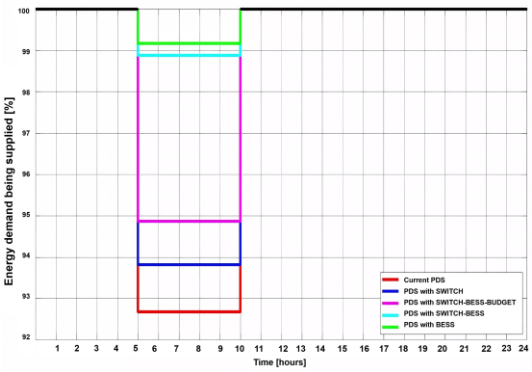


Fig. 12: Improvement of the EIU
Source: created by the authors

5 Conclusion

The evaluated ENS reaches a capacity of 30 MW without any type of backup technologies for HILP events. This capacity is reduced to 21 MW with the implementation recommended by the proposed computational tool, which includes the integration of BESS, switches, and an adequate budget. In percentage terms, this represents a 30% improvement compared to the system without backup technologies.

In terms of the Energy Unavailability Index (EUI), the computational tool shows that the PDS without technology backup goes from 94.87% to 92.68%. This indicates that the energy unavailability index improves by 2.19% with the installation of BESS and reclosers.

The proposed computational tool, based on linear programming, guarantees the achievement of the global optimum in relation to the results obtained. This means it ensures the best alternative in the location and sizing of the proposed technologies for the planning of resilient infrastructure against volcanic eruptions, thereby improving the resilience of an electrical distribution system and reducing both ENS and EIU.

The proposal to integrate technologies such as BESS, switches, and BUDGET represents the best economic alternative in terms of investment and operational costs. This ensures the feasibility of its application and offers alternatives for decision-making in planning for high-impact, low-probability (HILP) events.

The proposed methodology, although initially applied in a test system, can be implemented in a real electrical system. This is because the computational tool has been configured with the necessary flexibility to adapt to any required parameter and study.

The ENS can be implemented with a high initial cost; however, the allocated budget ensures the system's viability by strengthening resilience in energy distribution systems.

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Conflict of Interest

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