Impact of the Electrification of the Economy on i-DE's Low Voltage

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***Abstract*—This project addresses the strategic imperative of enhancing the reliability and performance of low-voltage (LV) networks through digitalization. Particular emphasis is placed on voltage regulation, which constitutes one of the most critical challenges for Distribution System Operators (DSOs) in the context of increasing electrification of the economy. By integrating digital assets and data-driven methodologies, the project aims to support both grid modernization and broader energy transition goals.**

Initially, a preliminary analysis is performed to assess the current issues affecting the LV power network, with the objective of identifying key problems as well as the principal characteristics and patterns that enable the detection of critical Secondary Substations (SS). Based on these insights, a Key Performance Indicator (KPI) related to Voltage Events (VEs) is developed to establish a structured framework for streamlining the identification of problematic areas and facilitating the integration of digitalization technologies within the network.

Subsequently, an evaluation of existing digital voltage regulation technologies is carried out to assess their features and suitability for application in power distribution networks. Finally, a novel Multi-Criteria Cost-Benefit Analysis (MC-CBA) is implemented to determine the most advantageous option among three use cases, taking into account not only monetary costs but also technical, operational, and sustainability performance metrics.

***Index Terms*—Digitalization, Low-Voltage, Cost-Benefit Analysis, Voltage Events, Distribution System Operator, Smart Grid.**

I. Introduction

The global energy paradigm is shifting away from centralized, fossil-based electricity generation toward more decentralized and sustainable models. Electrification, driven by the need to reduce greenhouse gas emissions, is accelerating across sectors. Consumers are adopting technologies such as Electric Vehicles (EVs) and Heat Pumps (HPs), which offer significant efficiency gains and carbon reduction benefits. Concurrently, small-scale renewable energy sources, including rooftop photovoltaic (PV) systems and wind turbines, are being integrated into the grid, often in remote locations and with variable output, [1].

The integration of these Distributed Energy Resources (DERs) presents new operational challenges for Distribution System Operators (DSO), particularly in LV networks originally designed for unidirectional power flow. DERs induce variable and increasing voltage instability, phase imbalance, and thermal stress on network assets, [2]. Furthermore, the deployment of Battery Energy Storage Systems (BESS) is transforming customer load profiles, increasing demand in low-priced hours and decreasing it in more expensive hours, increasingly complicating system dynamics and factors affecting demand patterns.

Peak demand from EVs and HPs, especially when operated simultaneously, can lead to network congestion and overloading. Likewise, synchronized PV generation during midday, low-consumption hours, can result in reverse power flows and voltage rise issues, [3]. In Spain specially, regulatory measures have exponentially increased the number of PV installations over the last couple of years, with Royal Decree-Law (RD) 1183/2020, [4], permitting PV installations under 15 kW to connect without prior technical assessment by the utility company. This regulatory framework has contributed to very rapid and uncoordinated capacity growth which highlights the urgent need for updated grid planning and operational frameworks.

Medium-voltage (MV) networks, serving as the interface between high-voltage transmission and LV distribution systems, are also being affected, [5]. DER-related disturbances have the capacity to propagate upstream in the system, disrupting protection coordination and undermining grid reliability. As such, the role of MV networks is increasingly critical to maintaining overall system stability.

To address these challenges, digitalization is emerging as a foundational enabler, [6], [7]. Digital tools provide enhanced grid visibility, real-time control, and improved operational efficiency. They also open new opportunities for market-based mechanisms such as demand-side participation and dynamic pricing. The convergence of electrification and digitalization is fostering a more intelligent and resilient power system, often referred to as the *Internet of Energy*.

Modernizing LV networks through digitalization is essential not only for facilitating DER integration but also for achieving the broader goals of the energy transition. Voltage regulation, in particular, stands out as a critical area requiring immediate attention. This paper presents a systematic approach to analyze, prioritize, and improve voltage control strategies in LV networks using digital technologies.

II. State of the Art

A. Context

Digitalization offers significant opportunities to transform the operational paradigm of DSOs. It serves as a foundational pillar in the development of Smart Grids (SG), electricity networks that integrate digital technologies, sensors and advanced software to control and optimize energy flows. The addition of a digital layer enables SGs to substantially enhance system stability and cost-efficiency, [8]. Through bidirectional data exchange, digitalization improves grid observability and responsiveness, converting traditionally passive infrastructures into dynamic, actively managed systems capable of adapting in real time to evolving conditions.

One of the key applications of digitalization is the use of advanced analytics, which actively contributes to the optimized operation of distribution networks, [9]. By leveraging data-driven algorithms based on Machine Learning (ML) and Artificial Intelligence (AI), in combination with Internet of Things (IoT) devices, DSOs can significantly enhance predictive maintenance strategies and enable early fault detection and prevention. Moreover, digital platforms play a crucial role in facilitating consumer engagement and enabling demand-side flexibility within energy markets, fostering a more participatory and efficient energy system, [10].

B. Current Regulatory Frameworks

Within the European Union, the primary legislative framework in the power sector is the **Clean Energy for All Europeans Package**, which promotes renewable energy integration, energy efficiency, and active consumer participation, [11]. Among its eight mandates, the most important document supporting digitalization are the **Renewable Energy Directive II** (RED II) and the **System Operation Guidelines**(SOGL), which emphasize flexibility, enhanced Transmission System Operator (TSO) -DSO coordination, an more intelligent energy grids, [12], [13].

In the Spanish context, two key regulatory instruments are particularly relevant to the implementation of this project. **CNMC Circular 1/2024**, it revises the methodology and conditions for grid access and connection for demand-side installations in Spain, [14]. The circular emphasizes transparency and digitalization, including provisions to accelerate access for EV charging infrastructure and self-consumption projects. **Royal Decree (RD) 1183/2019** simplifies procedures for self-consumption systems, [4]. Installations under 15kW or without energy surplus located on urbanized land are exempt from requiring connection permits from the DSO, thereby facilitating faster deployment.

C. Remuneration for Digitalization & Smart Grids

Electricity transmission and distribution are regulated monopoly activities, and their remuneration frameworks are designed to ensure a fair return on efficiently deployed assets, while covering operational costs and maintaining reliability, security, and quality of supply—all while minimizing costs to consumers.

At the European level, the Electricity Directive 2019/944 establishes the overarching regulatory framework, outlining the roles and independence of TSO and DSO, [15]. Complementing this, the EU Grid Action Plan explicitly recognizes the need for remuneration schemes that incentivize strategic investments in digitalization and SG, which categorizes as essential for achieving the EU's energy transition goals.

In Spain, Law 24/2013 grants the administration authority over the remuneration regimes for regulated activities and defines the principle of financial self-sufficiency for the electricity system, mandating that system revenues must fully cover all costs, prevent tariff deficits, and enable automatic tariff adjustments, [16]. The current methodology is defined in CNMC Circular 6/2019, [17]. Significantly, this circular is the first to formally recognize digitalization-related investments as eligible for remuneration. These are classified as "Type 2" investments and are incorporated into the regulated asset base.

D. Challenges in Digitalization and Smart Grid Investment

Despite the formal inclusion of digitalization in Spain's regulatory framework, significant challenges persist that hinder effective digitalization investment. CNMC Circular 6/2019 remains grounded in a deterministic, asset-based model tailored to conventional infrastructure. This framework does not adequately capture the distinct characteristics, benefits, and risk profiles of digital assets. A key issue is the declining rate of return for DSOs, reduced from 6.503% (2015–2020) to 6.003% (2020–2025), and further set to decline to 5.58%, reducing investment incentives [18].

Moreover, the regulatory methodology favors CAPEX-intensive "wire solutions" (e.g., cables, transformers) over flexible, OPEX-based digital alternatives. This structural bias discourages investment in more adaptive and cost-effective solutions crucial meeting objectives of for DER integration, active network management and grid resilience. Additionally, the lack of a clear definition of eligible digitalization assets creates uncertainty for DSOs, raising the risk of stranded investments and inadequate cost recovery.

Further complications arise from RD 1183/2019, which exempts small-scale PV installations from capacity studies. While it has exponentially accelerated solar PV deployment, it has led to reduced network visibility, unbalanced phase connections, and increased voltage management challenges. CNMC Circular 1/2024 seeks to address these issues through enhanced transparency and flexible access, but its implementation remains delayed.

The analysis underscores a broader issue: while both EU and Spanish frameworks recognize the strategic role of grid digitalization, Spanish regulation remains reactive rather than anticipatory. Emerging challenges are often addressed only after their manifestation, leading to delayed responses and regulatory lag. This lack of regulatory agility poses a systemic risk, potentially slowing the deployment of essential SG technologies and jeopardizing national climate and energy targets.

E. Rethinking CBA for Digitalization

The current CBA methodologies are insufficient for fully capturing the value of digitalization in the energy sector [6]. Traditional frameworks focus primarily on direct monetary and technical metrics, often overlooking intangible and system-wide benefits. A revised approach must incorporate both tangible impacts, such as reduced outage durations and deferred CAPEX, and broader, non-monetary gains, including consumer empowerment, DER integration, and emissions reductions.

Digitalization enables distributed benefits across the energy system, such as demand-side markets, intelligent tariff structures and avoided reinforcements. A modernized CBA must be able to assess enhanced reliability, energy security and Quality of Service (QoS) [7], [19]. The failure to recognize these factors in conventional CBAs leads to underinvestment by DSOs, potentially resulting in suboptimal LV grid development. This regulatory and analytical gap may jeopardize national targets for DER integration and decarbonization.

Existing guides from EPRI and JRC offer partial frameworks for evaluating monetary and non-monetary benefits [20], [21], yet they admit that not all impacts can be effectively monetized. This is particularly relevant for digital solutions, where benefits and operational flexibility remain difficult to quantify under traditional models.

Given this, integrating Multi-Criteria Analysis (MCA) with CBA offers a path forward. A hybrid approach allows for multidimensional evaluation that accounts for diverse stakeholder priorities and aligns digitalization investments with broader strategic goals. By explicitly recognizing both monetary and non-monetary outcomes, this enhanced framework ensures that the systemic value of digital technologies is not underestimated.

III. Methodology

A. Justification

This project proposes the development of a systematic methodology to promote and streamline the deployment of digitalization solutions in LV distribution networks. It addresses a critical need in the energy sector: enhancing grid intelligence and operational efficiency while maximizing value for end-users and stakeholders.

The ultimate goal is to simplify and accelerate the adoption of digital solutions, demonstrating their tangible benefits not only to private distributors but also to regulators. By quantifying their contribution, not only technical, but also to energy transition strategic goal, such as improved Quality of Service (QoS), reduced emissions, and enhanced consumer benefits, the project aims to position digitalization as a strategic investment priority.

B. Project Development

This section presents the structured workflow and sequential phases followed throughout the project, detailing the decisions made, their rationale, and the main outcomes obtained. The methodology implemented for the MC-CBA framework is also described, offering insight into the criteria and structure used for the multidimensional evaluation of digitalization strategies in LV networks. An overview of the project methodology is provided in Figure 1.

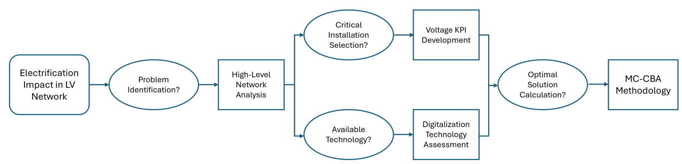

Fig. 1: Project Methodology

The initial phase, involved the examination of the LV network using structured SQL datasets provided by i-DE. These datasets included comprehensive information on SS, line configurations, and historical voltage measurements. The goal was to identify operational vulnerabilities and recurring voltage events (VE). Statistical analyses highlighted correlations between VE severity and factors such as line length and DER penetration. The results enabled the profiling of critical SSs and informed the selection of representative use cases.

In the second phase, a Voltage KPI was created to quantify the criticality of SSs. Six evaluation metrics were used to assess the frequency, intensity, and spatial distribution of VEs. These metrics were normalized and objectively weighted using the Entropy Method. The resulting KPI, scaled from 0 to 100, functioned as a weighted aggregate and aligned closely with internal prioritization strategies, effectively identifying high-impact installations.

The third phase, focused on assessing digital technologies applicable to LV networks. Based on relevance to voltage regulation and operational performance, four technologies were selected and examined with respect to their benefits, limitations, and appropriateness for addressing specific network issues.

The final phase, synthesized all prior analyses into a MC-CBA framework. This methodology integrates technical, economic, and environmental evaluation criteria through three analytical branches. The Economic Branch focuses on financial impacts, the Smart Grid Branch assesses technical and operational enhancements, and the Externality Branch captures environmental and societal contributions.

The digital technologies selected in the previous phase were applied to real-world use cases identified through the Voltage KPI. These were then assessed across the aforementioned dimensions using the MC-CBA framework. This approach enabled a structured comparison of technologies and configurations, offering DSOs a reliable tool for optimizing investment decisions in alignment with performance, cost-effectiveness, and sustainability goals.

A detailed schematic of the MC-CBA framework is presented in Figure 2, which visually outlines the structure and criteria used in this multidimensional evaluation.

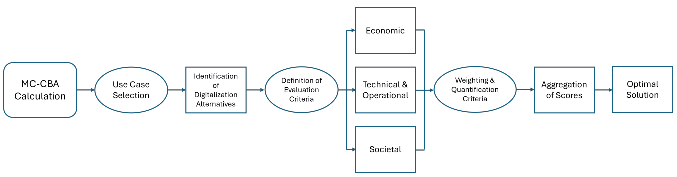

Fig. 2: CBA Methodology

IV. Low Voltage Network Analysis

This section presents the results obtained from the study of i-DE's LV grid through the characterization of SSs over and undervoltage event recordings. The first part outlines the methodology applied to the dataset, highlighting the observed patterns and key insights obtained during the exploratory analysis. The second part focuses on the development and application of a KPI designed to identify critical installations.

A. Characterization of i-DE's Dataset

This study's foundation lies in the comprehensive analysis of the LV grid operated by i-DE, leveraging an extensive dataset derived from smart meter event recordings. Meters are assigned to Main Distribution Boxes (MDB), which are grouped into logical units called micro-clusters, each belonging to a specific SS and electrical line. This structure enables the detection of localized VE patterns based on customer proximity.

Micro-cluster formation follows two main criteria. First, all MDBs in a micro-cluster must be on the same SS and feeder, ensuring electrical consistency. Second, a master MDB is selected using a hierarchical rule: if local generation is present, the MDB with the highest generation capacity becomes the master; otherwise, the one closest electrically MDB to the SS is chosen. Once the master is defined, all MDBs within 200 meters of electrical distance on the same line are included. If a new electrical line begins, a new micro-cluster is formed using the same logic. In cases where a SS has only one line and few MDBs, all MDBs are grouped into a single micro-cluster, even if the 200-meter rule is not met.

B. Evaluation Metric Definition

This section presents a preliminary assessment of the raw data contained within the SQL dataset. The objective of this initial evaluation is to identify, extract, and transform the most relevant variables into standardized evaluation metrics that facilitate comparative analysis. Based on the information available in the dataset, the data are aggregated and transformed into six distinct metrics, divided into two main categories

Aggregated Metrics: These metrics are intended to identify the SSs with the highest number and duration of events, as well as those impacting the largest number of clients.

- $N_{meter\ affected}$ (Total Number of Affected Customers). This metric quantifies the absolute number of unique customers impacted by VEs within a given micro-cluster. This metric directly reflects the scale of customer service disruption.
- Dur_{total} (Total Duration of Events). Measuring the cumulative duration of all VEs within a micro-cluster over a specified reporting period. This metric provides an absolute measure of the overall time customers spend experiencing voltage anomalies.
- Ev_{total} (Total Number of Events). Indicator of the absolute count of all VEs recorded within a micro-cluster over a specified reporting period. This metric provides an absolute measure of the overall frequency of voltage anomalies, indicating chronic issues.

Relative Metrics: After identifying the SSs with the highest number of events and affected clients, these metrics aim to assess the relative impact within each SS. Specifically, they highlight which SSs are disproportionately affected in relation to their size.

- N_{events} (Ratio of Events per Meter). This metric is calculated as the total number of events divided by the total number of affected meters within a specific micro-cluster. It provides a normalized measure of event frequency.
- Dur_{events} (Ratio of Event Duration per Event). Serves as an indicator representing the average duration of individual VEs. It is calculated as the total duration of events divided by the total number of events. This metric directly reflects the severity of individual voltage anomalies.
- $r_{meter\ ev}$ (Ratio of Affected Meters to Total Number of Meters). serves as an indicator of outage penetration within a given micro-cluster. It facilitates the identification of whether service interruptions are localized incidents or represent a widespread phenomenon.

The analysis also considers key SS characteristics, such as the type of VEs (overvoltage or undervoltage), presence of local generation in MDBs, and the timing of events across two periods (April–September 2024 and October 2024–April 2025).

C. Data Cleansing

Throughout the initial data evaluation, it was discovered that extreme outliers were present in the dataset. To ensure data reliability and avoid distortion from extreme outliers, the top 2% of values in accumulation metrics (event duration, count, and affected customers) were removed. Additionally, a 10% minimum threshold for $r_{meter\ ev}$ was set within micro-clusters to prevent single meters from disproportionately influencing results.

The top 2% threshold was selected as it was seen as the limit between reasonable and unreasonable readings. As shown in Figure 3, which presents the distribution of all three aggregated metrics across 5% percentile intervals. It clearly illustrates a sharp escalation in values beyond the 98th percentile, underscoring the presence of extreme outliers.

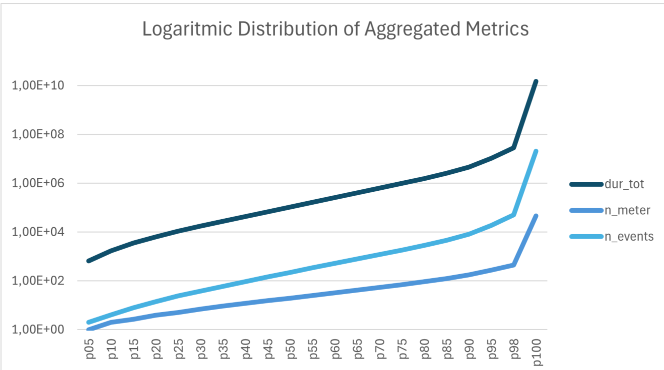

Fig. 3: Base 10 Logarithmic Scale Distribution of Aggregated Metrics

D. High-level Network Analysis

Once the initial dataset has been transformed into measurable metrics, the analysis of the network can proceed. This section examines the previously defined metrics in relation to additional parameters, with the objective of identifying the most influential characteristics associated with SSs exhibiting the highest levels of operational issues.

Table I provides an overview of the analyses performed, the underlying rationale, and the key outcomes achieved.

TABLE I: Summary of Network Analysis Performed

Study	Investigation Rationale	Outcome
Electrical Distance to SS	Longer electrical lines tend to have more faults, greater energy losses. More complex fault localization.	Medium-length lines had the highest number of affected clients. Event frequency and severity increased with line length.
Presence of Generation	Solar PV generation introduce voltage variability and operational challenges.	Installations with generation showed a higher VE (+13.88 on average), with overvoltages being 2.3x undervoltages VE.
Generation Capacity	Larger generation capacities can induce reverse power flow and voltage fluctuations.	Higher capacity micro-clusters (¿100 kW) correlated with longer and more frequent overvoltage events. Low-capacity sites had more balanced VE distributions.
Meter & Line Density	High meter/line density affects restoration prioritization.	SSs with many lines ($\geq$5) caused 40% of total events, despite being only 13% of SSs. Large SSs are more critical due to cascading effects.
Temporal Event Distribution	Event frequency may vary seasonally or diurnally due generation and load behavior.	No clear temporal patterns were found in the one-year dataset. More granular and long-term data is needed to identify time-based trends.

E. Voltage KPI

This section introduces the Voltage KPI, a composite indicator developed from detailed network and VE analysis. Its purpose is to objectively identify and rank critical micro-clusters in the LV network, guiding strategic investment in digitalization and flexibility. Higher KPI values signify greater urgency for intervention.

The proposed Voltage KPI is constructed using five out of the six metrics defined in Section **??**, with the sole exclusion being $r_{meter\ ev}$. This metric, which quantifies the proportion of affected meters relative to the total number of meters within each micro-cluster, was excluded due to its disproportionate influence in scenarios involving small micro-clusters.

After evaluating various methods for constructing the Voltage KPI, a weighted sum of selected metrics was chosen as the most suitable approach. To ensure comparability across differently scaled metrics, normalization was necessary. The two key challenges identified were selecting an appropriate normalization technique and defining the optimal weighting scheme for the metrics.

The normalization method selected is Min-Max normaization. This method preserves the relationships between values but compresses or stretches the data based on the minimum and maximum values, in this case, [0,1], respectively. Its calculation is shown in Equation 1.

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{1}$$

The determination of metric weights proved more complex. The two main weighting methods were studied. Objective and subjective weighting. However, initial consultations with experts to apply subjective weighting revealed a lack of consensus, with no single metric deemed universally more critical. Due to this disagreement and the need for transparency and reproducibility, objective weighting methods were preferred. Among several techniques assessed, the Entropy Method was selected for its compatibility with the adopted min-max normalization protocol and its suitability for data-driven analysis.

The **Entropy Method** quantifies the variability of each indicator across observations, assigning higher weights to those with greater dispersion. Rooted in information theory, it measures uncertainty, assuming that more variable indicators provide more information, [22].

The calculation process begins with the construction of a raw data matrix $Y = [y_{ij}]$, where y_{ij} represents the value of the

j-th indicator for the i-th evaluation object. This matrix is then normalized to obtain $Q = [q_{ij}]$, using the Min-Max normalization formula,present in Equation 1.

Once normalized, the entropy value e_i for each indicator is calculated using:

$$e_i = -k \sum_{j=1}^{n} t_{ij} \ln(t_{ij}), \quad \text{where } t_{ij} = \frac{q_{ij}}{\sum_{j=1}^{n} q_{ij}}, \quad k = \frac{1}{\ln n} \tag{2}$$

The degree of diversification is then computed as $d_i = 1 - e_i$, and the entropy weight for each indicator is:

$$u_i = \frac{d_i}{\sum_{i=1}^{m} d_i} \tag{3}$$

The analysis of the computed weights using the Entropy Method revealed a high level of uniformity across the eight evaluated data categories. All five variables received nearly identical weights. This implies that each variable contributes a similar amount of information, indicating balanced statistical distributions and variability across the dataset. No metric stood out as significantly more informative, suggesting a well-structured dataset in which all indicators play an equally important role in the formulation of the Voltage KPI.

Additional testing with alternative combinations of metrics produced comparable results, confirming a strong correlation among the variables. Despite this redundancy, all five selected metrics were retained in the final KPI formulation. The rationale behind this decision was to preserve the possibility of capturing nuanced patterns and combinations of conditions that might be critical for identifying high-impact micro-clusters. Even though the weights are similar, the multidimensional perspective offered by incorporating all metrics enhances the robustness of the KPI.

F. KPI Results

The analysis of the top 100 Voltage KPI-ranked micro-clusters revealed several important insights. Firstly, 52% of these micro-clusters are associated with local generation, significantly higher than the overall generation rate of 31.3%. This highlights the strong correlation between voltage disturbances and the presence of uncontrolled PV systems. Secondly, overvoltage events dominated, comprising 62% of all VEs recorded in these clusters. Thirdly, the KPI consistently identified the most critical SSs, with a majority of top-performing installations ranking above the 85th percentile across all five evaluation metrics. This situation is highlighted in Figure **??**.

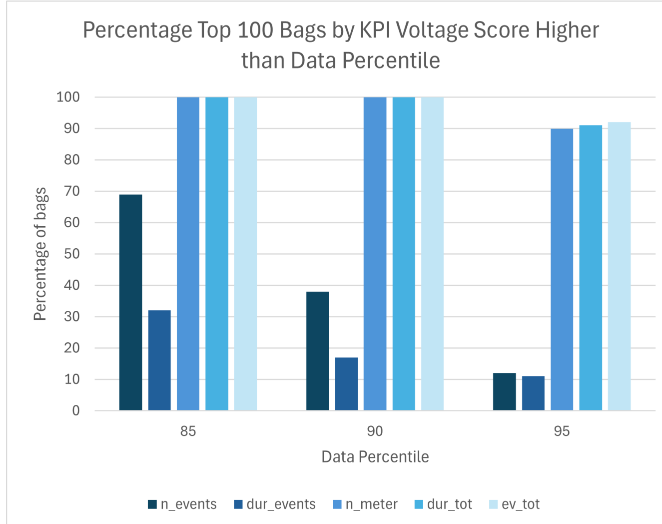

Fig. 4: Percentage Top 100 micro-clusters by KPI Voltage Score Higher than Data Percentile

The Voltage KPI proved particularly effective in identifying SSs with the highest values in aggregated metrics. More than 90% of the top 100 micro-clusters ranked above the 95th percentile in these metrics. Although its effectiveness in relative metrics was slightly lower, this is consistent with the KPI's design, which emphasizes aggregated indicators for initial prioritization and uses relative ones for secondary differentiation.

The KPI's practical utility was further supported through validation against ongoing internal projects aimed at deploying voltage regulation technologies. Of the three SSs currently prioritized for intervention by the i-DE, one was successfully analyzed and ranked 9th overall by the KPI, despite two others being excluded due to missing data.

G. Conclusions

The development of the Voltage KPI was the culmination of a comprehensive network analysis aimed at identifying and prioritizing critical areas within the LV grid. The results of the KPI analysis demonstrated its effectiveness in identifying high-impact areas. The information obtained in this section informs the profiling and selection of use cases in the CBA analysis.

V. Digitalization Solutions

This section examines digitalization solutions currently available for LV networks, with and emphasis on voltage regulator devices, as these would be the main focus of the project. It provides a comprehensive analysis of their utility, capabilities, functionality, and optimal application scenarios.

A. Strategic Benefits of Digitalization in LV Networks

Spain's push to digitalize its electricity distribution networks is supported by both national and European initiatives, particularly through the PRTR, which allocates 525 M€ —50% co-financed by the EU's Next Generation EU program—for grid modernization. However, while the funding does not explicitly prioritize MV over LV networks, its structure favors large-scale MV projects due to better execution certainty and scale, leaving LV initiatives at a disadvantage.

Component 8 of the PRTR focuses on transforming passive distribution grids into active, customer-centric systems, promoting smart grids, flexibility, and storage. Public funding is crucial in overcoming the high initial costs of digitalization, which otherwise would slow the sector's transformation. Successful digitalization also hinges on robust telecommunications infrastructure, enabling real-time, two-way communication for monitoring and automation. Though not covered in this project, telecom availability greatly influences digital deployment costs and feasibility.

B. Voltage Regulation

Voltage regulation is a key challenge in modern LV networks, especially with the increasing penetration of DERs. This section analyzes four devices and their role in managing voltage issues. Three main types of voltage regulators are considered: passive, active, and power electronic-based.

- **Passive** regulators are simple, cost-effective solutions installed in parallel with the feeder, aimed at improving local voltage and partially balancing phase currents, though they lack dynamic control.
- **Active** regulators, as understood in this project, refer to devices equipped with electronic control that enables progressive, under-load voltage adjustment by modifying parameters or tap positions in real time.
- **Power electronic**-based regulators are the most advanced solution. These hybrid devices can both regulate downstream voltage and correct phase asymmetries, making them ideal for grids with high DER penetration and unbalanced loads.

Each technology offers different levels of complexity, control, and suitability depending on network needs. This section focuses on the study of four devices and its utility in LV power network.

C. On-Load Tap Changer Transformers

On-Load Tap Changer Transformers (OLTC), referred to as i-Trafos in this work, are a recent innovation for dynamic voltage management at SS in the LV network. These transformers adjust their transformation ratio under load conditions, enabling real-time voltage regulation without interrupting supply, [23].

The device works by automatically shifting tap positions to maintain voltage within operational and regulatory limits. When the input voltage is low, the tap is raised to increase the secondary voltage, and lowered when the input voltage is too high. This dynamic control helps prevent undervoltages and overvoltages that can compromise power quality and reduce asset lifespan.

i-Trafos improve system efficiency by reducing losses and increasing DER hosting capacity through fast, dynamic voltage regulation. However, their high cost and complex deployment—due to size and installation requirements—have limited their adoption (only $\sim$200 units in the i-DE network), [24]. Therefore, their use should be prioritized in critical areas where persistent voltage issues cannot be solved with lower-cost alternatives.

D. Zig Zag Transformers

Zig-zag transformers (ZZT) are passive devices with an interconnected star winding that enables phase balancing and harmonic mitigation, [25]. Though not a digital solution, they complement digitalized investments and enhance grid flexibility, capacity, and performance. Unlike conventional transformers, ZZTs typically lack a secondary winding and use a winding configuration where fluxes cancel out under balanced conditions. By allow ing zero-sequence currents to flow, they stabilize voltages and reduce equipment stress in unbalanced load conditions. Furthermore, their configuration also traps triplen harmonics improving power quality, [26].

Furthermore, ZZTs are also effective in fault current management, [27]. Their design offers high impedance to positive- and negative-sequence currents and low zero-sequence impedance, ideal for line-to-ground faults. They can provide neutral grounding even without connected loads, helping to avoid overvoltages during neutral loss events.

However, ZZTs come with notable drawbacks. They require approximately 15.5% more copper winding turns, increasing cost, resistance, and short-circuit losses. Their complex structure also affects manufacturing and maintenance. ZZTs have a limited short-time rating, as neutral currents are typically minimal. Thus, they are not designed for sustained fault loads, requiring prompt disconnection of faulty circuits. Efficiency is optimal under high asymmetry, but under low asymmetry, power losses may be overestimated.

E. Autotransformers

Autotransformers (AT) are transformers with a single winding, where parts of the coil serve simultaneously as the primary and secondary windings. This design eliminates electrical isolation between input and output, as both are magnetically and electrically connected through the shared winding [28].

While not digital solutions, ATs, like ZZTs, are analyzed in this project for their operational benefits. Their single-winding design makes them more compact, lighter, and cost-effective than conventional transformers, with lower reactance, reduced losses, and higher VA ratings [29]. A key advantage is their voltage regulation capability, achieved by tapping into different winding points or using a sliding brush. Additionally, as part of the power bypasses magnetic transformation, efficiency improves through reduced heat losses and smaller size [30].

However, they present notable limitations. The lack of electrical isolation means surges or faults on the primary side may directly reach the secondary, risking equipment safety [31]. Their lower impedance also leads to higher short-circuit currents, increasing system vulnerability. Moreover, ATs do not provide phase shift or mitigate harmonic distortion, making them less suitable in networks with significant non-linear loads. Their benefits are most pronounced when input and output voltages are relatively close; for larger voltage differences, traditional transformers are more appropriate.

F. STATCOM

A Static Synchronous Compensator (STATCOM) is a second-generation FACTS device that uses power electronics to provide dynamic reactive power compensation. It consists of a shunt device connected via a reactance and operates as a source or sink of reactive power depending on the voltage difference between the converter and the grid. When the STATCOM voltage exceeds the system voltage, it injects capacitive reactive power; when it is lower, it absorbs inductive reactive power. This capability enables rapid and precise voltage regulation, improving voltage stability and power quality, [32], [33].

STATCOMs are increasingly relevant in modern grids, where they help mitigate voltage sags/swells, support unbalanced three-phase lines, and enhance the hosting capacity for DERs and BESS. In more advanced applications, they can provide grid-forming capabilities by maintaining voltage and frequency stability during disturbances, [34].

However, STATCOMs present certain limitations. Their reliance on power electronics makes them significantly more expensive than passive alternatives, both in capital and operational costs. They also exhibit higher operational losses and challenges which can complicate deployment [35]. Therefore, while their functionality is unmatched for dynamic voltage control, their use must be justified by the criticality of the application.

G. Conclusions

Voltage regulation technologies are essential in addressing the increasing complexity of LV networks, especially given the growing penetration of DER. The technologies analyzed in this study collectively contribute to improving the operational flexibility and resilience of the LV grid. However, their effective implementation necessitates a strategic deployment approach grounded in a comprehensive assessment of their technical characteristics, economic viability, and contextual applicability. This section presents a preliminary evaluation of the selected technologies, focusing on their operational capabilities and economic performance. The assessment is conducted through a CBA based on real-world use cases.

VI. CBA of Digital Solutions

This section applies the CBA methodology to a defined set of use cases, aiming to assess the relevance and effectiveness of digital solutions within the LV network. Use cases are selected and analyzed based on their voltage profile characteristics, as outlined in Section IV, ensuring representation of critical scenarios. Following the identification of representative cases, the digital technologies described in Section V are strategically implemented to address the identified challenges.

A. CBA Framework

The MC-CBA framework employed in this project follows the methodology developed by ISGAN [36] and the evaluation criteria proposed by the JRC [21], aimed at supporting strategic investment planning in SG projects. Unlike traditional CBA, which focuses exclusively on financial metrics, MC-CBA incorporates both monetary and non-monetary factors, allowing for a more comprehensive evaluation that reflects economic, technical, and societal dimensions.

The methodology begins by identifying relevant investment alternatives and evaluating them across a structured set of hierarchical criteria. These are grouped into three main branches:

- **Economic Branch:** Assesses direct financial impacts, including CAPEX, OPEX, avoided costs, and revenue streams. Standard economic tools such as Net Present Value (NPV), Internal Rate of Return (IRR), and Cost-Benefit Ratio (CBR) are used.
- **Smart Grid Branch:** Evaluates contributions to grid modernization, focusing on technical parameters such as operational reliability, flexibility, controllability, and DER integration. This branch quantifies technical benefits that may not be reflected in financial indicators.
- **Externalities Branch:** Captures broader environmental and social impacts, such as emissions reduction and social acceptance, internalizing external costs and benefits to promote sustainable decision-making.

Each branch includes multiple sub-criteria, which are individually scored, normalized, and weighted based on their relevance. These scores are then aggregated through a multi-criteria decision analysis process to form a single composite performance index per alternative. This enables decision-makers to rank projects not only by economic efficiency but also by sustainability and resilience.

Figure 5 illustrates the hierarchical structure and evaluation flow of the framework.

B. Evaluation Metrics & Hypothesis

The PlexigridSim software utilized for the electrical simulation identifies representative use cases, proposes targeted solutions, and allows for device customization and performance assessment. Following a critical review aligned with project goals and the MC-CBA framework, original metrics were revised to enhance analytical relevance.

Following the software rationale, all cases evaluated in this section follow the nomenclature presented in Table II.

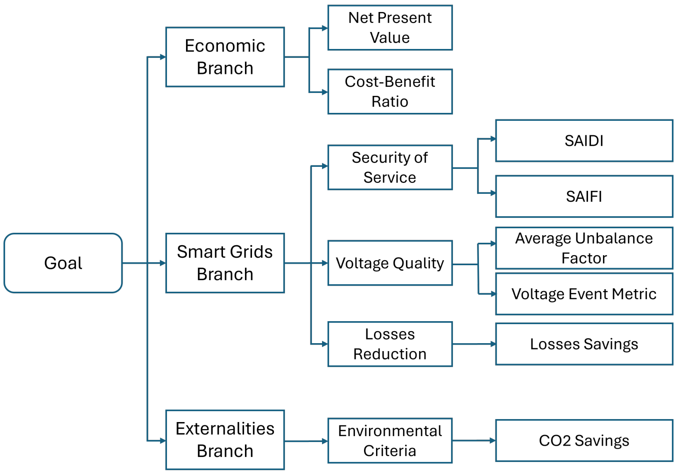

Fig. 5: Example Load Curve Case Selection

TABLE II: Digitalization Solutions per Use Case

Case Number	Digitalization Solution
Case 1	Base
Case 2	ZIGZAG (ZZT)
Case 3	iCOBT (STATCOM)
Case 4	iEBT (AT)
Case 5	iTRAFO (OLCT)

All solutions are evaluated relative to a baseline scenario (Case 1), representing the business-as-usual configuration. Metric variations—positive or negative—indicate respective improvements or deteriorations in performance. A uniform **12-year** equipment lifespan is assumed for all alternatives, ensuring consistency in the temporal analysis. Detailed justifications for metric adjustments are provided within this section.

C. Smart Grid Branch

he final CBA for the SG branch is structured around three main criteria:

Voltage Quality (VQ). This metric assesses the network's operational performance and service quality through two metrics:

- **Average Unbalance Factor (AUF):** Serves as an evaluation of the average voltage unbalance of the three phases in the network. Calculated as shown in Equation 4.

$$AUF = 100 \times \frac{V_{max} - V_{min}}{V_{avg}} \tag{4}$$

Where V_{max} is the maximum phase voltage in the network, V_{min} is the minimum phase voltage in the network and V_{avg} is the average voltage across all three phases.

- **Voltage Events Metric (VEM):** Is utilized as an indicator of the prevalence of VE in the network, the extent of problems across the network and clients affected. Its calculated as shown in Equation 5 and Equation 6.

$$VEM = \frac{1}{n} \sum_{i=1}^{n} \delta_i \times 100\%, \tag{5}$$

$$\delta_i = \begin{cases} 1, & \text{if } V_i < 215\,\text{V or } V_i > 245\,\text{V} \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

Where n is the total number of buses in the network, V_i is the voltage value in the i_{th} bus and δ_i is a binary variable indicating if the V_i is outside the allowed voltage range.

Security of Service (SoS), assesses the system's capability to maintain reliable electricity supply under adverse conditions. Based on scenarios occurring at least 3% of a simulated 11,000-hour period ($T \geq 330$ h), these events are treated as steady-state deviations. Consequently, regulators disconnect persistently affected buses. SoS is quantified using two metrics:

- **SAIDI:** Average total duration of power outages experienced by customers over a specific period, in this case a year. Its calculated as shown in Equation 7.

$$SAIDI = \frac{\sum_{i=1}^{n} U_i N_i}{\sum_{i=1}^{n} N_i} \tag{7}$$

Where n is the total number of buses in the network, U_i is the duration of outages and N_i the number of clients in the i_{th} bus.

- **SAIFI:** indicates how often the average customer experiences a power outage in a given year. In this project is calculated by estimating that all customers in outside the $\pm 10\%$ voltage threshold will be disconnected once during the each of critical days where the use case situation occurs. It is calculated as shown in Equation 8.

$$SAIFI = \frac{\sum_{i=1}^{n} \lambda_i N_i}{\sum_{i=1}^{n} N_i} \tag{8}$$

Where n is the total number of buses in the network, λ_i is the failure rate and N_i the number of clients in the i_{th} bus.

Losses Reduction (LR) criterion assesses the decrease in power losses achieved through the deployment of digitalization devices in the distribution network. It is quantified by one single metric:

- *Losses Savings (LS):* derived by comparing the power at the substation transformer with the aggregated power at all buses. To extrapolate annual energy losses from a single critical scenario, a representative set of operational cases is simulated using PlexigridSim. A scenario-specific coefficient α_s is used to scale losses to realistic yearly estimates. Its calculation is shown in Equation 9.

$$LS_0 = \left(P_{\text{SS}} - \sum_{i=1}^{n} P_{\text{bus}_i} \right) \sum_{s=1}^{S} \alpha_s h_s \tag{9}$$

Where, P_{SS} is the SS power, P_{bus_i} is the power at bus i, α_s is the scaling factor, and h_s the representative hours for each scenario s. Annual losses are adjusted for a 3% yearly demand growth rate across a 12-year lifespan, as shown in Equation 10.

$$LS = \sum_{t=0}^{T} LS_t, \quad \text{where} \quad LS_t = LS_0 (1+g)^t \tag{10}$$

Where g is the yearly demand growth at 3% and T is the lifespan of the project, 12 years.

D. Externalities Branch

Encompasses a single but critical criterion:
Environmental Criteria (EC). This dimension addresses the alignment of electricity sector advancements with global environmental and public health objectives. It iss quantified through a single metric:

- **CO_2 Savings**, which measures the reduction of greenhouse gas emissions attributed to the network's improved efficiency. Specifically, CO_2 savings are computed from the reduction in energy losses (*LS*) as evaluated in the Smart Grid Branch. An emissions factor of 110 gCO_2/kWh, is used throughout the 12-year project horizon. The total CO_2 savings over the project duration is calculated as shown in Equation 11.

$$CO_2\,Savings = \sum_{t=0}^{T} LS_t\, E_t \tag{11}$$

where LS_t denotes the annual energy losses avoided due to digitalization in year t, E_t is the emissions factor (assumed constant), and $T = 12$ is the total project lifetime.

E. Economic Branch

The cost-side analysis considers only **CAPEX** and **OPEX** associated with the deployment of digitalization devices. CAPEX is obtained as the real cost incurred by Iberdrola with the devices installed in their network. OPEX is derived from device failure rates, assuming full replacement upon failure, calculated as the product of the device's CAPEX and its failure rate. Routine maintenance is excluded. Failure rates and CAPEX values are informed by i-DE's internal estimates and pilot deployments, as summarized in Table III.

TABLE III: Device Cost and Reliability Data

Device	CAPEX(€)	Failure Rate (units/y)	OPEX (€/y)
ZIGZAG	4,500	1/2000	2.25
iCOBT	20,000	1/500	40.00
iEBT	15,000	1/500	30.00
iTRAFO	40,000	1/1000	40.00

Devices with power electronics (iCOBT, iEBT) show the highest failure rates due to their complexity. Active devices, such as the iTRAFO offers an intermediate failure rate, whereas the ZIGZAG, as a passive component exhibit superior reliability.

On the revenue side, benefits arise from:

- **Energy Loss Reduction**, monetized at 0.1 €/kWh saved in Year 0.
- **Quality of Service (QoS) Improvement**, where each hour reduction in SAIDI yields 840,000 €, scaled for 11.4 million customers.
- **CO_2 Emissions Reduction**, valued at 70 €/ton using the Externalities Branch's CO_2 Savings metric.

A 12-year project horizon is used. The analysis assumes a 7% discount rate (WACC), 3% annual growth for electricity prices and QoS remuneration, and 5% annual growth in CO_2 prices. These financial parameters ensure robust long-term viability of the investment. To evaluate the financial viability of the project, two key metrics are used:

- **NPV** quantifies the net monetary gain or loss over the project's lifespan by discounting future revenues and costs to present value. It is calculated as shown in Equation 12

$$NPV = \sum_{t=0}^{T} \frac{R_t - C_t}{(1 + \text{WACC})^t} \tag{12}$$

Where R_t and C_t are the revenues and costs at year t, respectively, WACC is the Weighted Average Cost of Capital (7%), and T is the project duration of 12 years.

- **CBR** evaluates the relationship between total present value of benefits and total present value of costs. A CBR less than 1 indicates that benefits outweigh costs, supporting investment approval. Values above 1 suggest economic infeasibility. I is calculated as shown in Equation 13.

$$CBR = \frac{\sum_{t=0}^{T} PV_t[Benefits]}{\sum_{t=0}^{T} PV_t[Costs]} \tag{13}$$

Where $PV_t[Benefits]$ and $PV_t[Costs]$ are the discounted benefits and costs at year t.

F. Weights of Terminal Criteria

The MC-CBA framework requires assigning weights to reflect the importance of each decision tree branch. Local weights indicate the relative importance of criteria within a branch, while global weights are calculated by multiplying local weights by their branch's weight.

In this project, all three branches are considered equally important, each assigned a branch weight of 0.3333. Following JRC guidelines, criteria at the same level are equally weighted. The final global weights are shown in Table IV.

TABLE IV: Global Weights of Terminal Metrics

Branch	Terminal Criterion	Global Weight
Economic Branch	NPV	0.1667
	CBR	0.1667
SG Branch	SAIDI	0.0556
	SAIFI	0.0556
	AUF	0.0556
	VEM	0.0556
	LS	0.1111
Externalities Branch	CO_2 Savings	0.3333

G. Case Studies

This section describes the three selected LV networks, (Network (N) 3, N5 and N8) used to assess digitalization solutions. All networks are three-phase, radial LV systems operating at 400V line-to-line and 230V line-to-neutral. They connect to the MV grid via a 20/0.4kV transformer at the SS, which serves as the sole interface between the MV and LV domains.

Network 3 (N3) is a medium-sized residential LV system with four feeders and 246 buses, 94 of which connect end-users via MDBs. It has high PV DER penetration and experiences a 220kW generation surplus under low demand, causing reverse power flow. While upstream impacts are noted, they are beyond this project's scope. N3 is highly unbalanced, with under- and overvoltage issues, making it a suitable case for evaluating digitalization solutions aimed at improving voltage regulation and system balance in DER-heavy residential networks. The network topology is illustrated in Figure 6.

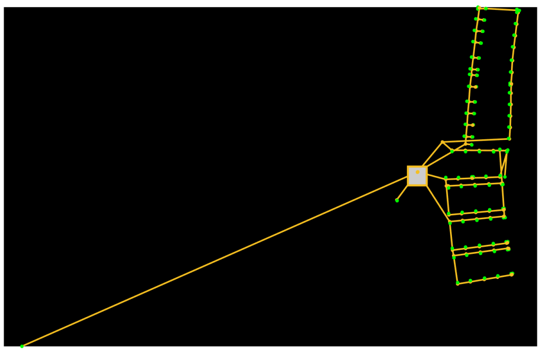

Fig. 6: Network 3 Topology

N5 is a large LV system with 317 buses and 193 MDBs serving end-users. It models a high evening peak demand scenario due to extensive integration of EVs and HPs, without smart charging strategies and with a high simultaneity factor. Despite well-dispersed demand and moderate phase unbalance, the network exhibits poor voltage profiles, with widespread undervoltage conditions across all phases. This case highlights the voltage challenges linked to uncoordinated, high-demand DER integration in dense residential areas. Its topology is shown in Figure 7.

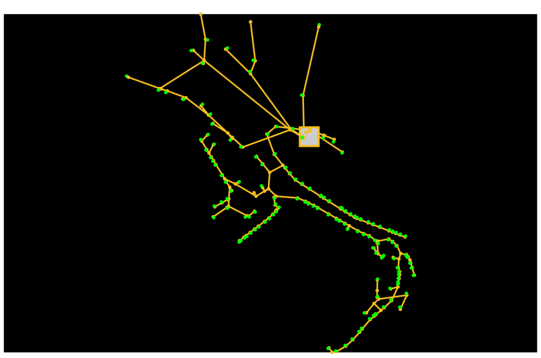

Fig. 7: Network 5 Topology

N8 case study analyzes a medium-sized LV network with 199 buses, 115 of which serve end-users via MDBs. Due to long distances from the SS, the network is prone to energy losses and voltage disturbances. The use case highlights the effects of significant phase unbalance under moderate loading, causing severe voltage deviations without peak demand. It shows the highest AUF and widest voltage variation among all cases, driven by concentrated single-phase demand. The findings stress the need for improved planning and phase balancing to maintain voltage stability.Its topology is shown in Figure 8.

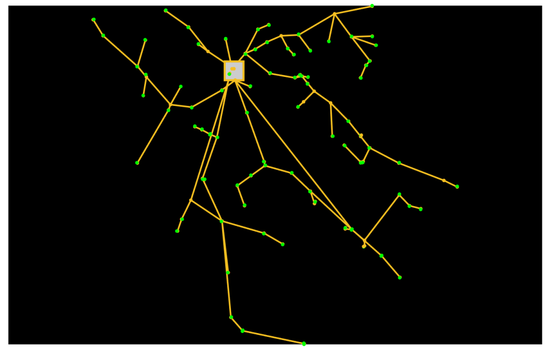

Fig. 8: Network 8 Topology

H. Evaluation Metric Analyisis

This section analyzes the numerical results that the evaluation metrics obtain with each of the use cases studied. All performance metrics for the three scenarios are summarized in Table V.

Analyzing the performance metric results for **N3**, Scenario 3.2 stands out as the most economically favorable alternative, being the only scenario with a positive NPV and CBR below 1, thus indicating financial viability. This is largely due to its minimal CAPEX and OPEX, alongside solid technical performance—slightly outperforming Scenario 3.4 in AUF, LS, and CO savings. Scenarios 3.2, 3.4, and 3.5 all perform equally well in maintaining acceptable SoS (SAIDI and SAIFI), but Scenario 3.5 excels in VEM thanks to the iTRAFO capabilities. Scenario 3.3 ranks lowest in both economic and technical terms and is not a viable option.

For **N5** an analysis of the evaluation metrics reveals a clear economic frontrunner: Case 5.5 stands out as the only alternative with a positive NPV and a CBR below 1, thereby representing the sole financially viable option for the utility. This situation highlight the utility of this solution as it is the highest CAPEX and OPEX alternative. Although Case 5.4 demonstrates comparable technical and operational performance and significantly outperforms the remaining alternatives, Case 5.5 ultimately delivers superior results in terms of overall solution effectiveness in all analyzed metrics.

N8 case study reveals two economically feasible options—Cases 8.2 and 8.4—with positive NPVs and CBRs

Case	NPV (k€)	CBR	SAIDI (min/y)	SAIFI (occ/y)	AUF (%)	VEM (%)	LS (MWh)	CO_2 Savings (ton)
3.2	9.28	0.84	571.24	1.27	7.07	21.51	46.69	5.14
3.3	-60.33	3.60	410.58	0.91	0.67	-0.72	18.32	2.02
3.4	-11.50	1.22	571.24	1.27	6.14	20.79	41.90	4.61
3.5	-24.97	1.56	571.24	1.27	6.14	27.24	35.62	3.92
5.2	-7.17	4.429	-468.21	-1.04	1.23	-7.65	1.68	0.19
5.3	-19.75	10.440	-468.21	-1.04	1.56	-7.41	1.68	0.19
5.4	-12.93	1.324	2258.43	5.01	1.15	6.42	30.15	3.32
5.5	7.49	0.893	2836.81	6.29	1.81	47.16	53.88	5.93
8.2	18.24	0.580	228.99	0.51	4.66	0.00	27.74	3.05
8.3	-36.51	2.383	-76.33	-0.17	1.61	-1.16	16.96	1.87
8.4	13.92	0.745	362.57	0.80	4.75	7.66	32.9	3.62
8.5	-10.14	1.196	362.57	0.80	4.96	10.34	31.6	3.48

TABLE V: Decision Variables Numerical Value

Case	Overall Score	Partial Score Economic Branch	Partial Score Smart Grid Branch	Partial Score Externality Branch
3.2	0.4324	0.4477	0.3652	0.4843
3.4	0.3002	0.3011	0.3014	0.2980
3.5	0.2260	0.2046	0.2952	0.1783
3.3	0.0414	0.0466	0.0382	0.0394
5.5	0.5244	0.5103	0.5637	0.4993
5.4	0.3035	0.2577	0.2795	0.3733
5.2	0.1009	0.1778	0.0614	0.0637
5.3	0.0711	0.0543	0.0954	0.0637
8.4	0.3833	0.3393	0.3945	0.4160
8.5	0.2950	0.1543	0.3698	0.3610
8.2	0.2808	0.4635	0.1958	0.1831
8.3	0.0409	0.0430	0.0399	0.0399

TABLE VI: Overall & Partial Scores

under 1. Case 8.2 has a better financial return due to lower CAPEX, but Case 8.4 excels in all technical and externality metrics. Case 8.5, although close in technical performance to 8.4 and leading in AUF and VEM, is limited by its high CAPEX and OPEX, reducing its financial attractiveness. Unlike the N3 and N5 studies, Case Study 8 does not present a clear optimal choice without applying the MC-CBA algorithm, emphasizing the need for a multi-criteria evaluation approach.

I. Results & Discussion

This section analyzes the numerical results that the evaluation metrics obtain with each of the use cases studied. The final assessment and comparative scoring of all alternatives are presented in Table VI. The analysis confirms that in **N3** , Case 3.2 as the optimal solution, validated by the MC-CBA algorithm. It consistently ranks highest across economic, technical, and externality branches. This solution involves installing twelve ZIGZAG devices at the most vulnerable nodes in the LV network. Despite the relatively high number of devices, it delivers the lowest CAPEX and OPEX, effectively improving SAIDI, SAIFI, voltage profiles, and power losses. It highlights the value of low-cost technologies like ZIGZAGs in enhancing reliability and QoS.

In **N5**, Case 5.5 emerges as the top-performing option, deploying both an iCOBT and an iTRAFO. The iCOBT proves especially effective in mitigating voltage unbalance on long feeders with many connected customers, outperforming ZIGZAGs in such scenarios. Though expensive, the iTRAFO excels in large-scale networks with consistent directional voltage issues, despite its inability to independently adjust phases. Together, these devices offer the best overall performance despite their high cost.

For **N8**, Case 8.4 is identified as the most favorable in Case Study 8, ranking highest in SG and Externalities and second economically. While Case 8.5 delivers better technical performance, its poor economic return lowers its overall ranking, highlighting the importance of a multidimensional evaluation. Case 8.4's solution includes one iEBT and six ZIGZAGs. The iEBT offers flexible, independent phase regulation at lower cost than the iTRAFO, making it ideal for feeders with localized over/undervoltage issues. ZIGZAGs complement the setup by improving phase balance, confirming their potential as scalable voltage regulation solutions in LV networks.

VII. Conclusion

This project supports the digitalization of LV networks by identifying critical SSs, evaluating emerging technologies, and applying a robust MC-CBA framework for investment planning. With increased DER integration and energy diversification, LV grids face new operational challenges.

A key objective of the project was to develop a KPI to quantify the criticality of SSs, enabling DSOs to make informed investment decisions. This was achieved through the Voltage KPI, based on a detailed analysis of LV network data from i-DE's SQL databases on VE. The KPI uses six metrics to assess the frequency, severity, and spatial spread of VEs, normalized and weighted via the Entropy Method to ensure objectivity. Scaled from 0 to 100, it effectively identified high-impact areas, with over 90% of the top 100 micro-clusters ranking above the 95th percentile. Its accuracy was validated by its alignment with internal assessments.

The KPI also revealed that long feeders and high DER concentrations worsen voltage issues and that a few large SSs account for most VEs. These findings provided a clear basis for prioritizing digital investments and selecting representative use cases. Ultimately, the Voltage KPI fulfilled its objective and laid the groundwork for a systematic, data-driven strategy for LV grid modernization.

The project aimed to analyze current digitalization technologies for LV networks, focusing on their use cases and effectiveness in enhancing voltage regulation. Key technologies evaluated include OLTCs, ZZTs, ATs, and STATCOMs. These devices improve real-time grid observability, automate fault response, and maintain voltage stability amid rising DER integration.

OLTCs offer dynamic voltage regulation but are constrained by high costs and complex installations. ZZTs and ATs are cost-effective for load balancing and minor voltage corrections but have limited downstream impact or fault isolation. STATCOMs provide advanced voltage compensation and grid-forming capabilities, making them ideal for critical DER scenarios, though their high cost restricts widespread adoption.

The MC-CBA framework successfully fulfills the project's main goal of delivering a comprehensive, multidimensional evaluation of digital investments in LV networks. By integrating economic, technical, and environmental dimensions, it provides a balanced and practical approach for assessing the value of digitalization strategies. Grounded in real-world parameters, the framework consists of three branches: SG (technical), Externalities (environmental/social), and Economic. These assess metrics such as VQ, SoS, LR, EC (via CO_2 savings), NPV, and CBR to capture the full scope of performance and impact.

A key feature is its equal weighting strategy, which ensures fair representation of all stakeholder priorities and avoids bias toward any single dimension. This makes the MC-CBA a robust decision-support tool for DSOs, while also offering a replicable, policy-aligned methodology for regulators.

A. Future work

New investigactions should include time-series analysis of SSs to identify VE patterns from load asymmetry or reactive power flow. Infrastructure evaluations (e.g., conductor sizing and aging) are also needed to find thermal bottlenecks. Implementing MC-CBA in pilot projects will validate the framework in field conditions, requiring stakeholder collaboration and contextual tuning. This would further enable informed DSO investment strategies in LV digitalization.

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