Master's Degree in Industrial Engineering
& Master's Degree in Smart Grids

Master's Final Project

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

Author: Juan de Gracia de Dios

Academical supervisor: Néstor Rodríguez Pérez

Industrial supervisor: Ramón Cerero Real de Asúa

Madrid
Aug 2025

Juan de Gracia de Dios, declares under his own responsibility that the Project titled **Impact of the Electrification of the Economy on i-DE's Low-Voltage Network**, submitted to the School of Engineering (ICAI) at Universidad Pontificia Comillas during the academic year 2024/25, is his own work, original and unpublished, and has not been previously submitted for any other purpose. The Project is not a copy of another work, either in whole or in part, and all information taken from other documents is properly referenced.

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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.

Key Words: Digitalization, Low-Voltage, Cost-Benefit Analysis, Voltage Events, Distribution System Operator, Smart Grid.

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.

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.

State of the Art

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, [3]. 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, [4]. The current methodology is defined in CNMC Circular 6/2019, [5]. 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.

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 [6].

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.

Rethinking CBA for Digitalization

The current CBA methodologies are insufficient for fully capturing the value of digitalization in the energy sector [7]. 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) [8, 9]. 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 [10, 11], 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.

Methodology

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.

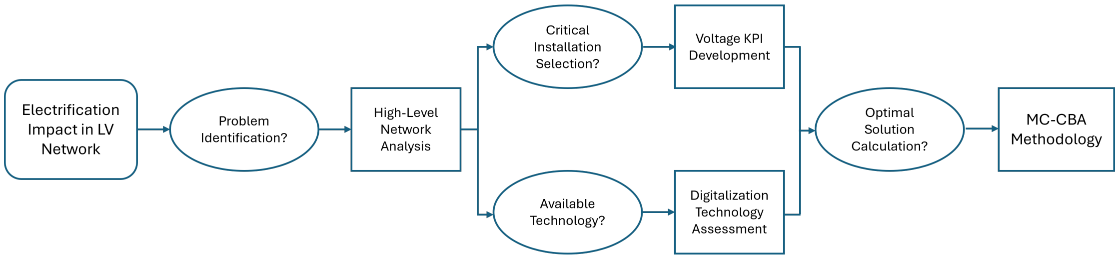

Figure 1: Project Methodology

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.

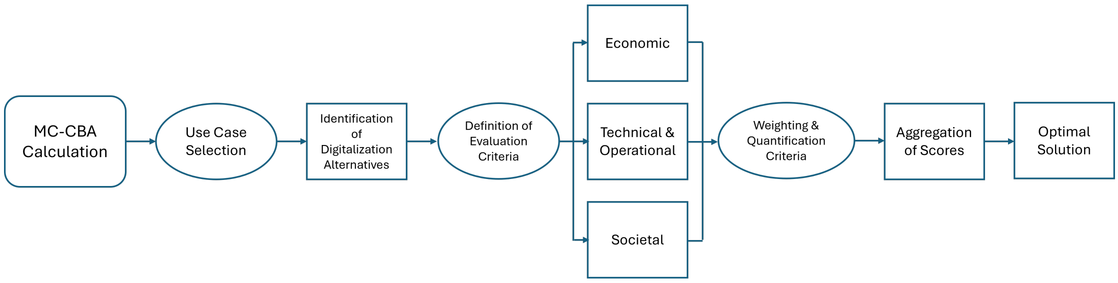

Figure 2: CBA Methodology

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.

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.

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.

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.

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).

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

Table 1: 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 (≥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.

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.

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 normalization. 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. 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.

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 3.

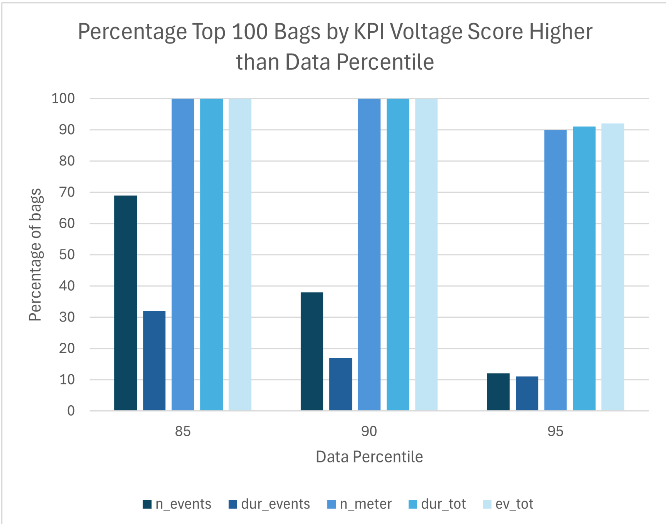

Figure 3: Percentage Top 100 micro-clusters by KPI Voltage Score Higher than Data Percentile

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.

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.

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.

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, [12].

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 ∼200 units in the i-DE network), [13]. Therefore, their use should be prioritized in critical areas where persistent voltage issues cannot be solved with lower-cost alternatives.

Zig Zag Transformers

Zig-zag transformers (ZZT) are passive devices with an interconnected star winding that enables phase balancing and harmonic mitigation, [14]. Though not a digital solution, they complement digitalized investments and enhance grid flexibility, capacity, and performance. ZZTs are effective in fault current management, [15]. Their design offers high impedance to positive- and negative-sequence currents and low zero-sequence impedance, ideal for line-to-ground faults.

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.

Autotransformers

Autotransformers (AT) are transformers with a single winding, where parts of the coil serve simultaneously as the primary and secondary windings. 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 [16]. A key advantage is their voltage regulation capability, achieved by tapping into different winding points or using a sliding brush.

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 [17]. 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.

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, [18, 19].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, [20].

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 [21]. Therefore, while their functionality is unmatched for dynamic voltage control, their use must be justified by the criticality of the application.

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.

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 4, ensuring representation of critical scenarios. Following the identification of representative cases, the digital technologies described in Section 5 are strategically implemented to address the identified challenges.

CBA Framework

The MC-CBA framework employed in this project follows the methodology developed by ISGAN [22] and the evaluation criteria proposed by the JRC [11], 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 4 illustrates the hierarchical structure and evaluation flow of the framework.

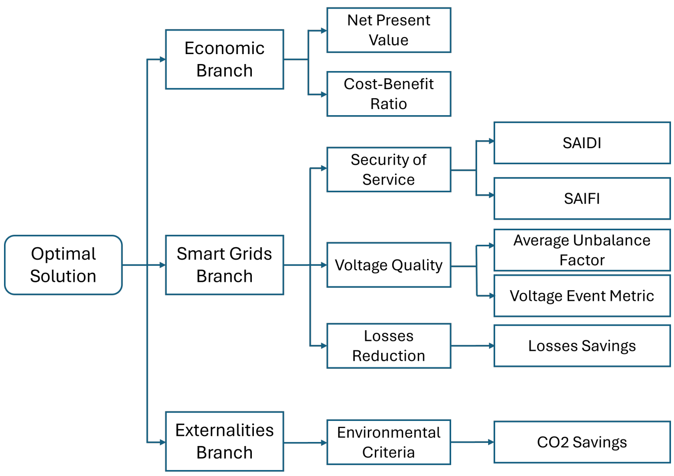

Figure 4: Example Load Curve Case Selection

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 2.

Table 2: 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.

Smart Grid Branch

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.
- **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.

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.
- **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.

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.

Externalities Branch

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.

Economic Branch

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.

- **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.

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 3.

Table 3: 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

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.

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.

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.

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 4.

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 4: Decision Variables Numerical Value

For **N3**, S3.2 is the only case with positive NPV and CBR < 1, driven by low CAPEX/OPEX and strong technical results, slightly surpassing S3.4 in AUF, LS, and CO_2 reduction. 3.2, 3.4, and 3.5 maintain comparable SoS (SAIDI, SAIFI), while 3.5 excels in VEM via iTRAFO. 3.3 is both economically and technically unviable. For **N5**, 5.5 is the only financially viable option (NPV > 0, CBR < 1) despite highest CAPEX/OPEX, offering superior results across all metrics. 5.4 matches technical performance but ranks lower in overall effectiveness. In **N8**, 8.2 and 8.4 are economically feasible; 8.2 offers better returns via lower CAPEX, while 8.4 leads in technical and externality metrics. 8.5 approaches 8.4 technically and leads in AUF and VEM but is limited by high CAPEX/OPEX. Unlike N3 and N5, N8 presents no clear optimal choice without applying MC-CBA, underscoring the need for integrated evaluation methods.

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 5.

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 5: Overall & Partial Scores

In **N3**, 3.2, validated by MC-CBA, is optimal, using twelve ZIGZAGs at vulnerable LV nodes to achieve the lowest CAPEX/OPEX while improving SAIDI, SAIFI, voltage profiles, and losses, demonstrating the value of low-cost devices for reliability and QoS. In **N5**, 5.5—combining iCOBT and iTRAFO—offers top performance: the iCOBT mitigates voltage unbalance on long feeders better than ZIGZAGs, while the iTRAFO addresses large-scale directional issues despite lacking independent phase adjustment. Though costly, their synergy delivers superior results. In **N8**, 8.4 ranks first in SG and externalities and second economically, balancing performance and cost. While C8.5 leads technically, poor economic returns reduce its ranking. 8.4's setup, one iEBT and six ZIGZAGs, leverages the iEBT's efficient phase regulation for localized issues and ZIGZAGs' phase-balancing benefits, confirming their scalability for LV voltage regulation.

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.

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Acronyms

i-DE	Electricity Distribution Arm of Iberdrola Spain
LV	Low Voltage
MV	Medium Voltage
HV	High Voltage
DSO	Distribution System Operator
TSO	Transmission System Operator
SG	Smart Grid
EV	Electric Vehicle
HP	Heat Pump
PV	Solar Photovoltaic
DER	Distributed Energy Resources
DEMRS	Distributed Energy Resources Management Systems
SS	MV/LV Secondary Substation
MDB	Main Distribution Low-Voltage Box
VE	Voltage Event
BESS	Battery Energy Storage Systems
OLTC	On-Load Tap Changing Transformer
FACTS	Flexible Alternating Current Transmission Systems
ZZT	Zig-Zag Transformer *AT*
Autotransformer	Joint Research Centre
JRC	
KPI	Key Performance Indicator
QoS	Quality of Service
MC-CBA	Multi-Criteria
CBA	Cost Benefit Analysis
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
NPV	Net Present Value
CBR	Cost-Benefit Ratio
VEM	Voltage Event Metric
SoS	Security of Service
VQ	Voltage Quality
LR	Losses Reduction
LS	Losses Savings
EC	Environmental Criteria
WACC	Weighted Average Cost of Capital
CNMC	Comisión Nacional de los Mercados y la Competencia
BOE	Boletin Oficial del Estado
RD	Royal Decree
IoT	Internet of Things
AI	Artificial Intelligence
ML	Machine Learning
M	Million
B	Billion

Chapter 1. Introduction

The global economy is shifting away from a model based on non-renewable resources and centralized electricity generation, traditionally dominated by a small number of large fossils fueled or nuclear power plants. In its place, a new paradigm is emerging, one that is more decentralized, sustainable and environmentally conscious. Societies are increasingly aware of the need to reduce greenhouse gas emissions and mitigate climate change, which is leading to the widespread electrification of the economy.

Electrification is becoming a cornerstone of the energy transition, marking a decisive shift in society's move away from fossil fuel dependence toward cleaner, more sustainable energy practices. Consumers are now buying Electric Vehicles (EV) and heat pumps (HP) as cleaner alternatives to internal combustion engines and gas-based heating systems, driven by their superior efficiency and significant reductions in CO_2 emissions.

At the same time, electricity generation is becoming more distributed, with small-scale renewable energy sources such as rooftop solar photovoltaic (PV) panels and wind turbines being integrated across the grid, often in remote locations and far away from consumption centers. These generation sources, while environmentally friendly, are inherently variable and difficult to predict, posing new challenges for grid stability and reliability, [1]. Additionally, as technology improves, Battery Storage Systems (BESS) are being developed in the network, which could drastically change the load profile of clients by storing or producing energy.

For this reason, the traditional "build and forget" model of grid infrastructure is becoming obsolete. Distribution networks, once considered passive components of the energy system, are now gaining strategic importance as the backbone of the energy transition. The integration of Distributed Energy Resources (DER), is significantly transforming the dynamics of power flow in modern electrical grids. Unlike traditional centralized operation, the introduction of DERs is inducing highly variable power flows. In some cases flows could turn bidirectional, challenging the conventional design and operation [23].

With increasing penetration of new DERs, these fluctuations are occurring more frequently and with greater magnitude, challenging voltage regulation, load balancing, and protection schemes. If DERs are not strategically located, which for devices in the LV usually is not the case, these devices can cause substantial voltage variability and phase imbalances, [2, 1] Such conditions can induce neutral current flow and impose thermal stress on electrical components that were not design to withstand these operational situations. Moreover, the shift in load and generation profiles due to DERs alters the spatial and temporal characteristics of electricity demand, making traditional models less effective.

The integration of new demand-side technologies such as EVs and HPs is expected to significantly increase power demand, particularly during peak hours. The simultaneity factor, where many users operate these devices at the same time, can lead to severe congestion and overloading in both LV and MV networks. Similarly, the simultaneity of PV generation, which typically peaks around midday across all installations, can result in widespread reverse power flows in periods of low demand. These situation could inject power back to the MV grid, causing voltage rise issues and threatening stability.

In Spain, this situation is exacerbated by legislation that allows PV systems under 15 kW to connect to the grid without requiring prior technical assessment or approval from the distribution system operator, as established by Royal Decree-Law (RD) 1183/20 [24]. As a result, distribution companies like Iberdrola have reported a threefold increase in connected PV capacity in recent years. This rapid and largely uncoordinated growth poses significant operational challenges, underscoring the urgent need for regulatory updates and grid reinforcement.

In this context, the role of MV networks becomes even more critical, as they form the essential link between HV transmission and LV distribution systems, playing a vital role in ensuring efficient power delivery and operational stability for end users. Increasingly, system operators are recognizing that the challenges posed by DERs are not confined to LV networks; rather, they propagate upstream, potentially affecting a broader range of customers across higher voltage levels.

The bidirectional and variable nature of power flows introduced by DERs is increasingly contributing to voltage instability and disrupting traditional protection coordination schemes, thereby compromising grid reliability and accelerating the degradation of network assets [25]. This evolving operational landscape necessitates the deployment of advanced monitoring, control, and planning tools capable of managing the decentralized and dynamic behavior of DERs. In this context, the integration of technologies such as Advanced Distributed Energy Resource Management Systems (DERMS) becomes essential to safeguard power quality and ensure the overall resilience of the power system. Additionally, flexibility solutions are gaining prominence, both on the retailer side, through temporal arbitrage strategies such as purchasing electricity during low-price periods and selling during peak-price hours, and on the grid side, where they support congestion management and adaptive access regulation [26].

Herein, digitalization is emerging as a key enabler of the modern grid by enhancing network visibility and enabling real-time monitoring, control and automation. Digital solutions allow operators to manage variability more efficiently and avoid unnecessary investments in new infrastructure. Furthermore, the increased capabilities that digitalization offers opens the door to new market opportunities, such as demand-side participation, dynamic pricing, and flexibility services, concepts that were unthinkable just a few years ago. The emergence of concepts like the *Internet of Energy* reflects a growing emphasis on user empowerment and energy democratization.

The convergence of energy transition and digitalization is prompting a profound transformation of the electricity sector, potentially creating a virtuous cycle where digital tools accelerate the shift toward sustainability and innovation [9]. Therefore, modernizing and digitalizing distribution networks is not only essential for integrating DERs but also for achieving the broader goals of the energy transition. It is becoming a central focus for both grid operators and regulators seeking to address the challenges of the 21st century.

Among the many challenges posed by this evolving landscape, voltage control in LV distribution networks stands out as a critical issue. This project focuses specifically on addressing that challenge, proposing an innovative approach for conducting a systematic analysis and developing a targeted improvement plan for LV networks. By enhancing voltage regulation capabilities, the initiative aims to support the broader goals of electrification and ensure that distribution systems can reliably accommodate the growing presence of DER.

1.1 Motivation

The electrification of the economy is placing unprecedented demands both at industrial (HV and MV) and domestic (LV) levels. While MV adaptation is enabled by local industries and the influence of economic stakeholders, LV grid reinforcement is often considered a lower priority, even when countries such as Spain facilitate the deployment of renewable generation at domestic level (RD 1183/2000 Art. 17), [24].

LV distribution networks, were originally designed for unidirectional power flows. As DERs, EVs, and flexible loads proliferate, these networks must evolve into smarter, more adaptive systems. Digitalization is becoming a crucial driving force of this transformation, offering enhanced visibility, real-time control, and operational efficiency. However, current regulatory and investment frameworks do not fully capture the value of digital technologies, often limiting their deployment due to narrow, financially focused evaluation criteria.

The project seeks to support the modernization of the electric grid by developing a comprehensive assessment framework that enables both operators and regulators to more effectively evaluate the significance and impact of digital solutions within the network. A key objective is the creation of a strategic decision-making tool designed to identify the most critical network segments, those that can deliver the highest value to the largest number of end-users while significantly enhancing the overall system's reliability and resilience.

The framework aims to demonstrate that the impact of digital solutions can be assessed not only through economic metrics but also by incorporating technical indicators, such as voltage quality and reliability indices, as well as social and environmental factors, including consumer benefits and emissions reductions. These dimensions are essential for aligning with broader energy transition goals. By leveraging real-world datasets on VE, modeled grid scenarios, and advanced evaluation methodologies, the project conducts in-depth analyses using data analytics tools. Ultimately, a Multi-Criteria Cost-Benefit Analysis (MC-CBA) will be implemented to identify the most impactful digitalization strategies for LV networks.

The project aims to be a practical tool for both utility companies, such as i-DE (Iberdrola's networks company in Spain), which can use the project's outcomes to better assess the integration of digital assets into the grid, improving visualization, control, and operational efficiency, and regulatory bodies, which are responsible for establishing the frameworks within which these utilities operate.

1.2 Project objectives

- **Voltage KPI Development**. Overvoltage and undervoltage violations, along with asset overloading and protection miscoordination, represent the three principal challenges in LV distribution networks. This study focuses specifically on voltage-related issues and proposes the development of a KPI to quantify the criticality of LV areas under each SS based on their exposure to voltage disturbances. By analyzing historical voltage data, the project aims to extract meaningful insights and identify recurring patterns that reflect the operational stress and reliability risks associated with individual substations. The resulting KPI will serve as a strategic decision-support tool for DSOs enabling them to prioritize and optimize digital investments by targeting the most vulnerable areas of the network.

- **Analysis of Digitalization Technologies in the Low Voltage**.

A key target of the project is to conduct a comprehensive evaluation of the digitalization alternatives currently available in the market, focusing on their technical capabilities, practical applications, and inherent limitations. By systematically reviewing a range of digital assets, such as smart sensors and devices, or grid automation tools, the study seeks to identify their most relevant use cases within the context of modern power distribution networks. The analysis will explore how these technologies contribute to enhanced monitoring, control, and optimization of grid operations, while also addressing challenges such as interoperability, scalability, and cybersecurity. Through this assessment, the project will highlight the transformative potential of digital assets in shaping the networks of the future, offering valuable insights into how Distribution System Operators (DSO) can leverage these tools.

- **Operational & Economic Evaluation of Digitalization Technologies**.

  This study aims to perform a detailed economic and technical assessment of digital assets. The economic analysis will leverage real-world industry data, implementation costs, deployment timelines, and appropriate discount rates. This approach will serve to quantify the financial impact of digital investments on power distribution networks, providing a clear understanding of their cost-effectiveness and long-term value. In parallel, the project will assess the operational effects of these technologies through simulations conducted on modeled power networks. These experiments will evaluate the integration of digitalization and its influence on network reliability and performance. By combining economic analysis with technical validation, the study will offer a holistic perspective on how digitalization can reshape investment strategies.

- **Comprehensive CBA of Digital Investments**.

  This project is driven by the need to establish a comprehensive CBA framework that extends beyond traditional technical and economic assessments. By applying a MC-CBA approach, the project will assess not only the financial viability of digital technologies but also their contributions to societal well-being and environmental benefits. This holistic evaluation will enable the identification of the most impactful digitalization strategies, and its purpose is to support DSOs in aligning their investment decisions with broader policy objectives and long-term sustainability goals.

1.3 Report Structure

The structure of this thesis outlines the core contributions of the project through a sequential methodology aligned with the research objectives. To ensure clarity in presenting the analytical methods, practical applications, and supporting case studies, the thesis is organized into four main sections.

- **Chapter 2: State of the Art**, is associated with performing a comprehensive review of traditional developments within the energy sector, with special emphasis on the electricity industry. It gives overviews the developments in energy transition, studying the context and strategic plans in Spain and other major economies. Here, a comprehensive study of grid digitalization benefits and challenges is to be performed, establishing the current deployment of these technologies. Then, the regulatory framework is to be evaluated, highlighting its strengths and shortcomings and proposing improvements. Finally, current and novel CBA methodologies and proposals are to be studied and compared.
- **Chapter 3: Methodology**, highlights the technology and specific tools that are utilized during the completion of the project, explaining the approach taken and the reasoning

behind important project decisions and challenges encountered. Additionally, it includes a section explaining the main considerations and hypothesis of the project as to clarify reading and understanding. Finally, a detailed work plan of the project development is to be explained and compared against expectations.

- **Chapter 4: Low Voltage Network Analysis**, presents the results obtained from the study of i-DE's LV grid through the characterization of SSs over and under VE recordings. The first section explained the patterns and insights obtained in the analysis as well as the approach taken with the dataset. The second section focuses on the construction and results of the KPI for the identification of critical installations. It explains the variables utilized and the reasoning behind their selection or discarding. It explains the algorithm developed and the results obtained.

- **Chapter 5: Digitalization Solutions**, explores the characteristics, capabilities and utility of the main digitalization technologies in the market. It analyzes the availability and technology readiness of each solution and its deployment, highlighting the main benefits and challenges each faces.

- **Chapter 6: CBA of Digital Solutions**, utilizing insights from previous chapters this section focuses on the development of the CBA to choose the optimal solution for each use case. It explains the methodology implemented, the metrics (economical, technical and environmental) selected to conduct the evaluation and the use cases studied, as well as all the hypothesis utilized.

- **Chapter 7: Conclusions**, a synthesis of all the results obtained through out the project is conducted, giving and overall overview of the project's findings, the implications for the future of digitalization developments. It highlights recommendations of future work and strategic evaluation within the context of the overall energy sector.

Chapter 2. State of the Art

This section provides an in-depth analysis of the role of digitalization technologies and devices within LV distribution networks, emphasizing their contribution to the evolution toward Smart Grids (SG). For a comprehensive overview of the current state of the global energy sector, the Spanish context, and the main challenges arising from the electrification of the economy, refer to Annex B.

2.1 Smart Grids and Digitalization

According to the IEA, a SG is defined as an electricity network that leverages digital technologies, software, and sensors to effectively monitor and manage the transport of electricity from all generation sources to meet the varying demands of end users, all while maintaining stability at the minimum cost [27, 28]. The intelligent integration of new technologies aims to enhance the monitoring and control of electrical systems, from generation to distribution, and crucially, to incorporate the actions of end-users.

Discussing SGs inherently involves addressing the broader process of digitalization, as the two are fundamentally interdependent. A SG cannot exist without the integration of digital technologies that enable real-time monitoring, control, and optimization of energy flows. Digitalization provides the foundational infrastructure that transforms traditional power systems into intelligent, adaptive networks. Digitalization offers a wide array of benefits that are transforming electricity distribution networks, enhancing their capabilities across planning, operations, and market interactions.

Digital technologies profoundly enhance grid planning by improving forecasting accuracy enabling more robust infrastructure design [29]. In the realm of operations, technologies such as AI, IoT, and AMI facilitate real-time management, advanced fault detection, and predictive maintenance, thereby significantly improving grid reliability and operational efficiency. Furthermore, in the energy market domain, digitalization supports more efficient energy trading mechanisms and aids in achieving regulatory compliance, fostering greater transparency and competitiveness.

SGs enable real-time monitoring and control of electricity usage, leading to a reduction in energy waste and optimized distribution networks. This optimization can reduce the need for new power generation sources or additional infrastructure investments [30, 31]. By deploying sensors and automation technologies allows DSOs to rapidly identify and respond to power outages or voltage fluctuations, reducing their frequency and duration. Beyond operational improvements, digitalization also bolsters grid resilience and enhances cybersecurity protection and capabilities [32, 33]. Furthermore, SGs play a crucial role in enabling the seamless integration of DER. They effectively address the challenges posed by demand fluctuations and mitigate cybersecurity risks associated with a more decentralized energy landscape [34, 35].

Digitalization signify a fundamental transformation in the traditional utility-consumer relationship. This evolution moves the grid from a conventional "supply-follows-demand" model to a more interactive and flexible "demand-responds-to-supply" or "prosumer-enabled" paradigm. The shift fundamentally redefines how electricity is managed and consumed, promoting active consumer participation and flexible energy management as essential parts of grid optimization.

2.2 Challenges and Opportunities for Distribution Network Operators

The LV distribution network, the final frontier of the electricity grid, faces unique and escalating challenges due to the rapid electrification of the economy. These challenges are particularly pertinent for DSO like i-DE.

2.2.1 Challenges in Low Voltage Networks

Historically, LV networks have been the least "intelligent" segment of the electricity system, traditionally operating passively with limited real-time observability [36, 37]. This inherent lack of centralized visibility, often relying on outdated paper records or static Geographical Information System (GIS) maps, leaves distribution operators largely unaware of dynamic supply and demand patterns, and potential risks to grid reliability at this granular level. For the majority of LV networks, the actual operational state cannot be directly measured but must instead be estimated, introducing uncertainties in network management.

The rapid deployment of PV self-consumption systems in Spain, while contributing to decarbonization, introduces significant logistical and management challenges for the LV grid. Although these systems effectively reduce demand from the national grid during daylight hours, electricity generated but not immediately consumed must be fed back into the grid. This bidirectional power flow can create stress due to excess energy, leading to substantial energy losses. For instance, in 2022, an estimated 19% (1,067 GWh) of the total energy produced by self-consumption was lost due to problems with surplus discharges to the grid, resulting in approximately 160 M€in losses [38].

Conversely, the increasing adoption of new electricity-intensive loads, forces LV networks to adapt rapidly and dynamically. High EV penetration, particularly in residential LV networks, and as mentioned in Section B.2.1 can challenge grid stability by causing voltage variations and straining limited feeder capacity. While Spain's grid possesses some capacity to accommodate initial EV deployment by leveraging the significant drop in nighttime energy demand, a large-scale transition will necessitate considerable improvements to both production and distribution systems due to the inherent variability of renewables and the complexities associated with daytime fast charging [39]. Similarly, the widespread integration of HPs contributes to increased peak demand at the LV level, due to its high simultaneity factor. A smart scheme to regulate demand-side technologies is crucial for the stability and security of the network.

Many existing electrical infrastructures, particularly at the distribution level, are decades old and were not built with the integration of modern digital technologies in mind [40]. Retrofitting or replacing this aging infrastructure requires substantial investment and meticulous planning to avoid compromising the continuity of electricity supply during the modernization process. The widespread lack of real-time visibility into these networks exacerbates all other issues, making it difficult to detect, diagnose, and manage problems effectively. This implies that the modernization of LV network infrastructure is not a peripheral or incremental task but is central and foundational to the overall success and stability of the broader energy transition.

2.2.2 Opportunities for Digitalization Technologies

With the advent of digitalization, DSO are no longer forced to make assumptions about power flow or the quality of service delivered to customers [36]. The influx of high-resolution data provides a significantly greater scope, enabling a shift towards predictive and prescriptive operational practices. This allows utilities to anticipate potential issues, implement proactive measures, and thereby minimize the frequency and duration of outage. AI and ML are particularly vital in this context, as they can accurately predict energy demand and supply fluctuations, leading to improved planning and more efficient resource allocation [31].

Digital solutions are instrumental in enabling active demand-side management and flexible integration of DER within a controllable LV distribution grid. This capability facilitates the precise identification of where and under what conditions network reinforcement might be necessary, optimizing investment decisions. Furthermore, digitalization supports decentralized control by enabling the automation of LV outage dispatch without direct operator intervention, enhancing grid responsiveness and resilience.

Digitalization effectively transforms the LV network from a "black box", a largely unobservable and passively managed system, into a "smart nervous system." This transition from a state of limited observability to one of comprehensive, real-time visibility, and from passive operation to active management, is critical for unlocking the full potential of DER and new electrified loads. It enables these previously challenging elements to evolve from potential liabilities into valuable grid assets, capable of providing flexibility and support to the overall power system. Table 6 outlines the main challenges facing LV networks and highlights how digital solutions can help address them.

Table 6: Challenges and Digital Opportunities in Low Voltage Networks

Challenge	Challenge	Digital Opportunity
Lack of Visibility/Data	Historically passive networks with limited real-time data and reliance on outdated records [37].	Real-time monitoring via smart meters and sensors; enhanced situational awareness; improved operational decision-making [36].
High PV Penetration	Bidirectional power flows, potential grid saturation, energy losses from unconsumed surplus discharge, overvoltage issues, [38].	Advanced forecasting for demand and generation; active demand management; flexible integration solutions; optimized control algorithms [36].
EV Charging and HP Integration	Voltage variations, limited feeder capacity, introduction of new peak loads, and shifts in demand profiles [41, 42, 39].	Smart charging management systems; demand response programs; predictive analytics for proactive load management, higher complexity in protection schemes [43, 44, 45].
Aging Infrastructure	Decades-old infrastructure not compatible with modern digital technologies, requiring costly retrofitting or replacement [40].	Predictive maintenance leveraging data analytics; AI-driven asset health monitoring; optimized asset management strategies to extend lifespan and reduce failures [29].
Power Quality Issues (Harmonics, Voltage Fluctuations)	Inverter-based DER inject harmonics; variable generation causes voltage swings and instability [46].	Smart inverters with grid-forming capabilities; advanced voltage and reactive power controls; real-time power quality monitoring and mitigation systems [47, 48].

2.3 Current Regulatory Framework

2.3.1 European Union

The European Union (EU) has established a robust and evolving regulatory framework designed to modernize its energy sector and accelerate the transition towards a climate-neutral economy.

The **Clean Energy for all Europeans Package**, is the main regulatory framework established by the European Commission,[49]. It addresses all five dimensions of the Energy Union: energy security, the internal energy market, energy efficiency and decarbonization, research and innovation, and competitiveness. The Package's three overarching goals are: putting energy efficiency first, achieving global leadership in renewable energy, and providing a fair deal for consumers.

Comprising eight key legislative acts, the Package most important directive impacting the study proposed in this work is the **Revised Renewable Energy Directive 2018/2001 (RED II):** Sets a binding EU-level target of at least 32% for renewable energy by 2030, simplifies administrative procedures, promotes market-based support schemes, and empowers self-consumers and renewable energy communities. Emphasizes the necessity of a more flexible and intelligent grid, [50]. Commission Regulation 2017/1485, known as the **System Operation Guideline (SOGL)**, establishes comprehensive minimum requirements for electricity transmission system operation across the EU, [51]. Its primary aim is to safeguard operational security, maintain power supply frequency quality, and ensure the efficiency of the interconnected European transmission system. It mandates enhanced cooperation between TSO, DSOs, and Significant Grid Users (SGUs).

2.3.2 Spain

The two most relevant documents regarding the implementation of this project would be:

Comisión Nacional de los Mercados y la Competencia (CNMC) Circular 1/2024: Published on October 11, 2024, this circular updates the methodology and conditions for accessing and connecting to Spain's electricity networks for demand-side installations, [52]. It distinguishes between "firm or ordinary access capacity" and "flexible access capacity," which is designed to manage network constraints by allowing demand installations to potentially curtail consumption. A cornerstone of Circular 1/2024 is its strong emphasis on transparency and the digitalization of administrative processes for grid access and connection. Network managers are required to publish up-to-date information on available capacities, and digital platforms are mandated to streamline the permit application and monitoring process. Special provisions expedite processes for EV charging infrastructure and self-consumption, and the circular amends Circular 1/2021 to integrate energy storage installations. However, the full operationalization of flexible access requires further specific regulatory development by CNMC resolution.

RD 1183/2019: This RD (note: often cited as RD 1183/2020 in official Boletín Oficial del Estado (BOE) for access/connection) aimed to facilitate self-consumption installations by simplifying administrative procedures, especially for smaller capacities, [24]. This RD allows installations with a rated power of less than 15kW or without surplus energy that are located in urbanized land to be exempt from connection permits from the DSO.

2.3.3 Remuneration for Digitalization & Smart Grids

Electricity network activities (transmission and distribution) are regulated monopolies. Their remuneration aims to provide a reasonable return on efficiently deployed assets and cover operational costs, ensuring reliability, security, and quality of supply while minimizing consumer costs.

At the European level, the Electricity Directive 2019/944 sets the broad framework, delineating the independence and operational responsibilities of DSOs and TSOs, and mandating independent national energy regulators, [3]. The EU Grid Action Plan explicitly calls for a "Supportive Regulatory Framework" including "future-proof regulatory principles" and "guidance on anticipatory investments" to accelerate grid development, recognizing the need for remuneration to incentivize forward-looking investments, especially in digitalization and SGs.

In Spain, Law 24/2013 established the pivotal principle that electricity system revenues must fully cover system costs, with mechanisms to prevent tariff deficits and allow automatic tariff adjustments, [4]. It also empowered the administration to fix the remuneration regime for regulated activities. The current regulatory methodology for calculating the remuneration of the electricity distribution activity in Spain is the CNMC Circular 6/2019, [5]. The circular introduces a more transparent and simplified model that enhances regulatory oversight and incentivizes efficiency. Additionally it is the first legislative piece that formally acknowledges investments in digitalization within the Spanish electricity distribution sector. These investments are classified as "Type 2" and are explicitly incorporated into the remuneration scheme for electricity DSO. This represents an important step towards integrating digital assets into the regulated asset base, moving beyond a sole focus on conventional, physical infrastructure.

2.3.4 Challenges in Digitalization & Smart Grid Investment

Despite the formal acknowledgment, the methodology established by CNMC Circular 6/2019 continues to rely heavily on a deterministic, asset-based approach that was primarily designed for conventional, physical infrastructure. This approach inadequately reflects the unique cost structure, risk profile, and long-term benefits of digital assets. A significant limitation identified is the reduction in the rate of return for DSOs, which decreased from 6.503% to 6.003% for the 2020-2025 regulatory period, and is set to further decline to 5.58% for the subsequent five years [6]. Such reductions inherently discourage substantial investments, as they diminish the financial attractiveness of the activity for investors. Furthermore, the framework suffers from a lack of a precise definition for eligible digitalization assets, creating ambiguity for DSOs regarding what investments will be adequately remunerated.

The current regulatory framework, despite its formal acknowledgment of digitalization, inadvertently creates a structural disincentive for DSOs to invest optimally in digital solutions. By favoring traditional Capital Expenditure (CAPEX)-based "wire solutions" (e.g., new cables and transformers) over potentially more efficient and flexible Operational Expenditure (OPEX)-driven digital alternatives, the framework creates a financial bias. This structural bias risks bottlenecking Spain's energy transition by impeding the necessary deployment of SG technologies, which are crucial for enabling active network management, integrating DER, and enhancing overall grid flexibility and resilience.

CNMC Circular 6/2019 also suffers from a lack of a precise and comprehensive definition for eligible digitalization assets. This ambiguity creates significant uncertainty for DSOs regarding what investments will be adequately remunerated, leading to a higher risk of stranded investments or inadequate cost recovery. This uncertainty can result in cautious underinvestment or misallocation of resources.

While largely successful in its objective of developing the solar PV in the country, the exemption of capacity study from the distributor that RD 1183/2019 introduced has created significant challenges for DSO regarding network control and planning. DSOs often lack real-time visibility into the actual generation and consumption patterns of decentralized installations. Furthermore, they do not have control over which phase the PV installation is connected to, leading to increasing issues with unbalanced networks. In areas with high PV penetration this situation is increasingly leading to issues such as voltage control, stability or congestion management and difficulties in optimizing network reinforcement investments. While CNMC Circular 1/2024 aims to mitigate these issues through enhanced transparency and "flexible access," its full operationalization is still evolving and faces delays.

The analysis reveals that both European and Spanish regulatory frameworks acknowledge the critical role of electricity grid modernization and digitalization for a successful energy transition. However, the reactive nature of Spanish regulation, where challenges emerge (e.g., grid management issues from decentralized generation) after policies are enacted, and subsequent regulations attempt to mitigate these issues with delays in full operationalization, highlights a critical lack of anticipatory regulation and regulatory agility. This "regulatory lag" hinders the timely deployment of necessary grid solutions and poses a significant systemic risk to achieving climate and energy goals.

2.4 Rethinking CBA for Digitalization

A more holistic evaluation framework is essential to fully capture the true value proposition of digitalization within the energy sector [7]. A comprehensive CBA must extend beyond traditional monetary and technical metrics to encompass both tangible outcomes, such as reduced outage durations and deferred CAPEX, and a broader array of intangible benefits, including enhanced consumer empowerment and significant emissions reductions.

Traditional CBAs often overlook the broader, distributed benefits that digital technologies can deliver across the energy system and society. These include substantial societal and environmental gains enabled by the seamless integration of DER, the facilitation of Dynamic Demand-Side Management (DSM) markets, or the implementation of intelligent tariff structures that promote efficient energy use. To ensure a robust and accurate evaluation of digitalization investments, the CBA framework should specifically incorporate the quantification of avoided network reinforcements, a comprehensive valuation of enhanced reliability and service quality, a thorough assessment of cybersecurity and interoperability risks, and careful consideration of consumer engagement and data governance frameworks [8, 9].

The inadequacy of traditional CBA in accurately valuing digital investments, particularly its failure to capture the full spectrum of intangible and distributed benefits, represents a fundamental flaw in current investment decision-making processes. This implies that without a revised, dynamic CBA framework that can properly account for these broader societal and environmental gains, DSOs will likely continue to under-invest in digital solutions. Such underinvestment could lead to suboptimal grid development, hindering the necessary modernization of LV networks and potentially jeopardizing Spain's ambitious energy transition targets for decarbonization and renewable integration.

Existing guides for SG project appraisal, such as those from the Electric Power Research Institute (EPRI), [10] and the Joint Research Centre (JRC) of the European Commission, [11] provide frameworks for identifying and quantifying both monetary and non-monetary impacts. However, these often acknowledge that not all non-monetary benefits can be adequately monetized or included in a traditional financial viability assessment. This limitation is particularly pertinent for digitalization technologies that yield a wide array of benefits that may not be easily quantified.

The integration of DERs, the enablement of demand response, and the provision of flexibility services are key pillars of the ecological transition. Digitalization technologies, are crucial for facilitating these advancements. Without an updated CBA that can accurately account for the value created by these capabilities the true economic and societal benefits of digitalization may be underestimated. Furthermore, the implementation of digitalization technologies often brings about intangible benefits such as increased customer participation and improved energy security, which are difficult to quantify monetarily using conventional CBA methods. A more holistic evaluation framework, potentially integrating Multi-Criteria Analysis (MCA) with CBA, can address this gap by considering both monetary and non-monetary impacts, as well as multiple stakeholder perspectives. Such a joint approach would provide a more comprehensive assessment of digitalization projects, ensuring that investments align with broader strategic objectives of decarbonization and grid modernization.

Chapter 3. Methodology

This chapter presents a detailed account of the methodologies and reasoning applied throughout the project, including the assumptions adopted and the justification for their selection. It offers a comprehensive explanation of the project's development process and the procedures used to derive key outcomes, aiming to enhance the reader's understanding of the analytical framework and the principles underpinning the conclusions. Additionally, the chapter outlines the configuration and segmentation of the system under study, describing the various components analyzed and tracing the evolution of the work over time.

3.1 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 first phase of the project focuses on leveraging Iberdrola's extensive datasets, organized by SS centers and containing over and under VEs recorded by smart meters and Main Distribution LV Box (MDB). These data is to be used to develop a comprehensive Key Performance Indicator (KPI) that consolidates all available metrics. This KPI will enable the rapid identification of the most vulnerable areas and substations within the LV network.

By equipping decision-makers at i-DE with a tool that highlights problematic substations without the need for field inspections or waiting for failures to occur, the project significantly enhances operational responsiveness. This proactive approach will not only improve asset management and service quality but also strengthen Iberdrola's competitive position relative to other distribution companies.

Furthermore, the analysis uncovers recurring patterns and technical characteristics associated with poor performance, enabling the company to anticipate issues and prioritize interventions that deliver the highest return on investment and customer value.

In its second phase, the project will evaluate multiple use cases for implementing digitalization solutions across various LV networks. Using insights from the initial analysis and the newly developed KPI for network criticality indicator, real-world grid scenarios will be simulated using Iberdrola's internal electrical modeling software PlexiGridSim, shown in Section 3.2.4, evaluating various digital solutions.The performance of different flexibility devices will be assessed through key technical indicators. These results will feed into a structured CBA using the ISGAN CBA tool, [22], explained in Section 3.2.3 ensuring a transparent, repeatable, and scalable evaluation process.

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.

3.2 Technology Description

3.2.1 i-DE Databases

A fundamental resource employed in the development of this project is the set of databases provided by i-DE, part of the Iberdrola Group. These databases contain detailed information about the low-voltage distribution network, including the identification of transformation centers, associated lines, and power distribution box. They also include data on contracted power, the presence and magnitude of distributed generation, and records of voltage and undervoltage events regstered y smart meters: the number of events, their duration, and the number of meters affected. This dataset enables a comprehensive characterization of the SS and their operational conditions.

3.2.2 SQL

To process and analyze the large volumes of data provided by i-DE, the project utilizes SQL (Structured Query Language), a programming language designed for managing and querying relational databases, [53]. SQL allows for the efficient extraction, filtering, and aggregation of data, making it possible to identify trends, correlations, and anomalies within the network. Through SQL queries, it is possible to identify and isolate specific SS, analyze the frequency and severity of VEs, and correlate these with other variables such as generation capacity or network topology. By leveraging SQL, the project ensures that data-driven insights are at the core of its decision-making process, providing a solid foundation for evaluating the effectiveness of digitalization strategies.

3.2.3 ISGAN MC-CBA

Another key resource in the project is the ISGAN MC-CBA tool, developed by the International SG Action Network, [22]. This tool was specifically designed to support the evaluation of SG investments by incorporating a broader set of criteria beyond traditional economic metrics. Unlike conventional cost-benefit analyses that focus solely on financial returns, the ISGAN MC-CBA framework allows for the inclusion of social, environmental, and technical factors. These may include improvements in service quality, reductions in greenhouse gas emissions, increased energy access, and enhanced system resilience. By using this tool, the project can standardize the evaluation of digitalization scenarios and ensure that investment decisions are aligned with long-term sustainability goals. The tool also facilitates the comparison of different technological alternatives under consistent criteria, helping to identify the most balanced and impactful solutions.

3.2.4 PlexigridSim

PlexigridSim, is a proprietary simulation tool developed by PlexiGrid in collaboration with i-DE specifically for studying the application of digitalization solutions in the context of voltage management within electrical networks. The software utilizes a series of network models based on real-world networks, incorporating detailed information on customer hourly consumption, equipment ratings, and network configurations. The databases employed for this analysis contain hourly load curve data from all customer meters over ∼11,000 hours, grouped into MDB.

The tool's automated calculation capabilities allow for the aggregation of all hourly curves from all customers over the calculation period, identifying different representative moments in the system's monotonic load curve. The algorithm selects the most representative cases along the monotonic load curve by detecting changes in the curve's slope, which signify shifts in consumption trends. The tool also allows for the manual modification of the case studies which are utilized in the CBA analysis developed in Section 6. A full explanation on the software workflow, algorithm and equipment modeling techniques is shown in Annex G.

3.3 Project Development

This section outlines the workflow and sequential phases followed throughout the development of the project. It presents the key decisions made at each stage, the rationale behind those decisions, and the main outcomes obtained. Furthermore, it describes the specific methodology implemented in the MC-CBA framework, providing insight into the criteria and structure used for the multidimensional evaluation of digitalization strategies in low-voltage networks. A visual representation of the overall methodology adopted is provided in Figure 5.

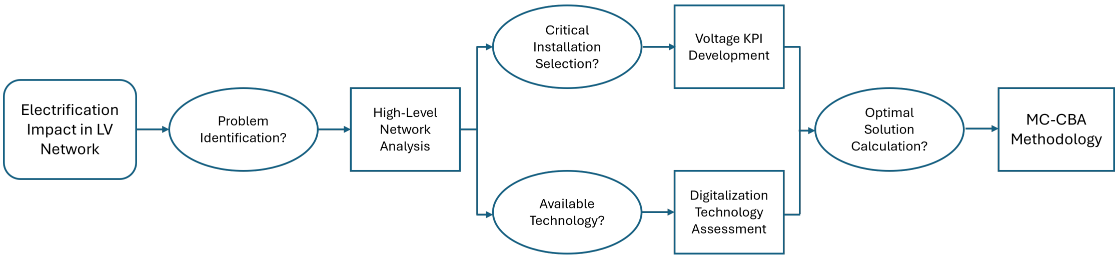


Figure 5: Project Methodology

The initial phase, Network Characterization and Data Analysis performed in Annex C, entailed a comprehensive examination of the LV network utilizing structured SQL datasets provided by i-DE. These datasets encompassed detailed information on SSs, line configurations, and historical voltage measurements. The analysis focused on identifying recurrent patterns and operational vulnerabilities, with particular emphasis on VEs. Statistical techniques revealed significant correlations between line length, DER penetration in both the frequency and severity of VEs. These findings facilitated the profiling of critical SSs and guided the selection of representative use cases for subsequent analysis.

In the second phase, developed in Section 4, a Voltage KPI was developed to quantify the criticality of SSs. Six evaluation metrics were defined to capture the frequency, intensity, and spatial distribution of VEs. These metrics were normalized and weighted using the Entropy Method to ensure analytical objectivity. The resulting KPI, scaled from 0 to 100, was constructed as a weighted aggregate and demonstrated strong alignment with internal prioritization strategies, proving effective in identifying high-impact installations.

The third phase, Assessment of Digitalization Technologies developed in Section 5, focused on evaluating digital solutions applicable to LV networks. A review of real-world implementations by Spain's five major DSOs was conducted to assess the current state of digitalization. Four representative technologies were selected based on their relevance to voltage regulation and operational performance. Each technology was evaluated in terms of its benefits, limitations, and suitability for addressing specific network challenges.

The final phase of the project, detailed in Section 6, consolidates all prior findings into the MC-CBA framework, enabling a multidimensional evaluation of digitalization strategies in LV networks. This methodology integrates electrical, operational, economic, and sustainability-related criteria through three main branches: the Economic Branch, evaluating financial impact, the Smart Grid Branch which considers technical and operational improvements, and the Externality Branch, which assesses environmental impact.

Technologies previously analyzed in the third phase were applied to real-world use cases, selected based on the Voltage KPI obtained in the second phase, and evaluated across these dimensions. The MC-CBA framework facilitated a structured comparison of devices and configurations, offering DSOs a robust tool for identifying optimal investment strategies that align with technical performance, financial viability, and sustainability objectives.

Additionally, a more detailed graphical description of the methodology applied in the MC-CBA framework is presented in Figure 6, highlighting the structure and criteria used in the multidimensional evaluation of digitalization strategies.

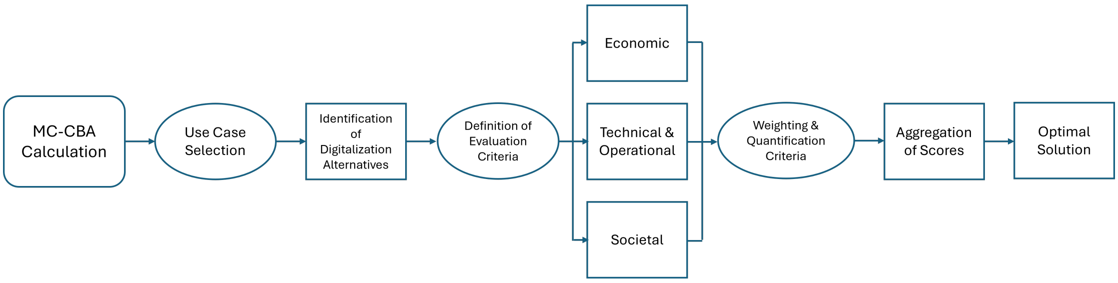


Figure 6: CBA Methodology

Chapter 4. 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. It details the variables considered, the rationale for their inclusion or exclusion, and the algorithm implemented to compute the KPI. The KPI is created with the objective to help utility companies to streamline the selection of critical SS, maximizing the return on investment for digitalization. Furthermore, the results obtained with KPI influences the use-case selection analyzed in Section 6. Finally, the section concludes with an evaluation of the results and their implications for network digitalization planning.

4.1 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. These meters are allocated into specific MDBs, which are conceptually organized into logical groupings, herein referred to as *micro-clusters*, nested within specific SSs. The micro-cluster architecture facilitates the clustering of customer groups based on their electrical proximity, enabling the identification of localized patterns concerning the number, duration, and type of VEs.

The formation of micro-clusters adheres to two primary criteria. Firstly, all MDBs within a given micro-cluster must belong to the same SS and the same electrical line, ensuring electrical coherence. Secondly, each micro-cluster is assigned a master MDB based on a hierarchical rule. For every new SS, if any MDB within possesses local generation, the one with the highest generation capacity is designated as the master for the first micro-cluster. In the absence of local generation, the MDB with the shortest electrical distance to the SS is selected as the master. Once the first master MDB is established, the micro-cluster encompasses all MDBs within an electrical distance of 200 meters from the master, provided they are located on the same electrical line. A new micro-cluster is initiated whenever a new electrical line begins, following the same criterion explained before. In scenarios where a SS has only one line and a limited number of distinct MDBs, all MDBs are included within a single micro-cluster, irrespective of the 200-meter electrical distance criterion.

For a more in-depth explanation of all the parameters located within i-DE's dataset, refer to Annex D.

4.2 Initial Data Evaluation

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. Emphasis is placed on the methodological decisions undertaken during the data preprocessing phase, including the selection of filtering parameters and the rationale for excluding specific data ranges. These foundational steps are critical for ensuring the integrity and consistency of subsequent analyses. Furthermore, this section outlines the key assumptions and initial decisions that guide the overall analytical framework adopted in the study.

4.2.1 Evaluation Metric Definition

Based on the information available in the dataset, the data are aggregated and transformed into six distinct metrics, divided into two main categories, which serve as the basis for evaluating the performance of the network:

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. This approach allows utilities to prioritize digitalization efforts where they will yield the greatest benefits, maximizing improvements in QoS-related and minimizing service interruptions, both System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI).

- $N_{meter\ affected}$ (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 and its societal impact.

- 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, reflecting the aggregated inconvenience.

- 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. A SS with a higher proportion of affected customers relative to its total number of connected meters should be prioritized over others with a lower relative impact, even if the absolute number of affected clients is smaller. They also provide an overview of problems on a per-unit basis, ensuring equitable comparison regardless of the size of the installation.

- 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, allowing for fair comparison across micro-clusters of varying sizes.

- 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. By quantifying the extent of outage dispersion, this measure provides valuable insight into the spatial and systemic characteristics of network reliability.

Furthermore, the analysis also incorporates various differentiating characteristics of SSs explained in Section D, including the specific type of VEs (overvoltage and undervoltage), the presence or absence of local generation within any MDB of the SS, and the specific time periods during which the events occurred (Period 1: 01/04/2024 to 01/09/2024; Period 2: 01/10/2024 to 01/04/2025). This temporal disaggregation allows for the identification of potential seasonal or operational shifts in network performance.

4.2.2 Data Cleansing

During the initial data analysis, a significant disparity was observed where the mean duration of events substantially exceeded the median value. Investigating the causes of the positive skew, it was found that the dataset contained extreme values that were distorting the data interpretation and leading to incorrect assessments. These outliers could be potentially stemming from anomalous meter readings or intermittent communication issues, constantly giving the signal of events taken place.

Figure 7 presents a histogram, plotted on a base-10 logarithmic scale of a 1000 data sample for each metric. It illustrates the distribution of the primary aggregated metrics used in the analysis: total event duration, total number of events, and number of affected clients.

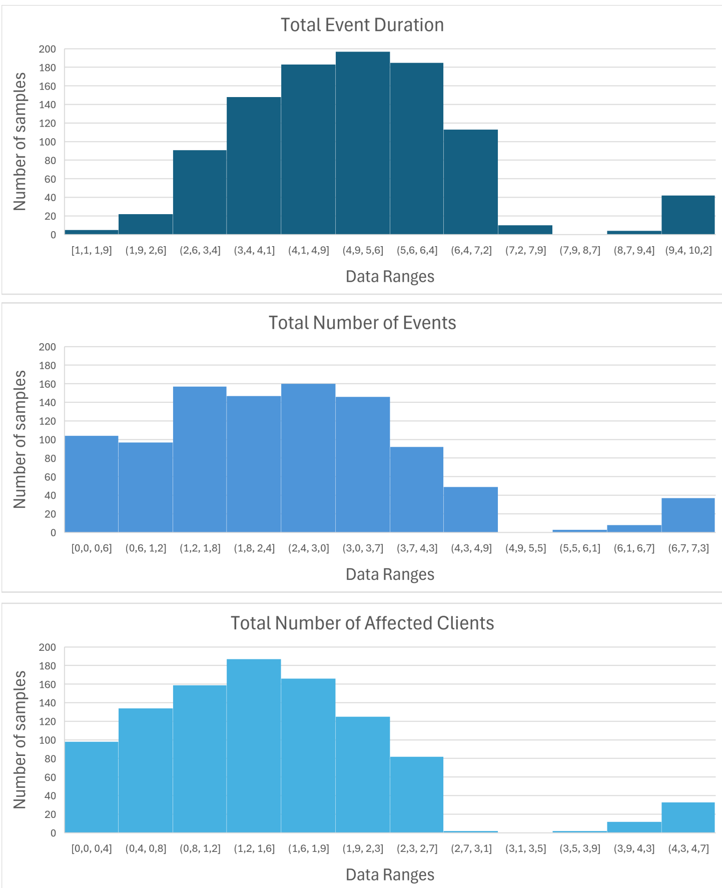


Figure 7: Histogram on Base 10 Logarithmic Scale of Primary Aggregated Metrics

As it is clearly seen in the histograms of Figure 7, all aggregated metrics contain extreme outliers that significantly distort data reading and interpretation. To ensure a representative sample and mitigate the undue influence of such anomalies, the following filtering measures were applied: the top 2% of values for accumulation metrics (total duration, total number of events, and number of affected customers) were systematically removed. Additionally, a minimum threshold of 10% in $r_{meter\ ev}$ within a micro-cluster was established, to reduce instances were a single or small number of meters are heavily affecting the event reading of a micro-cluster. The top 2% threshold was selected as it was seen as the limit between reasonable and unreasonable readings.

Figure 8 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.

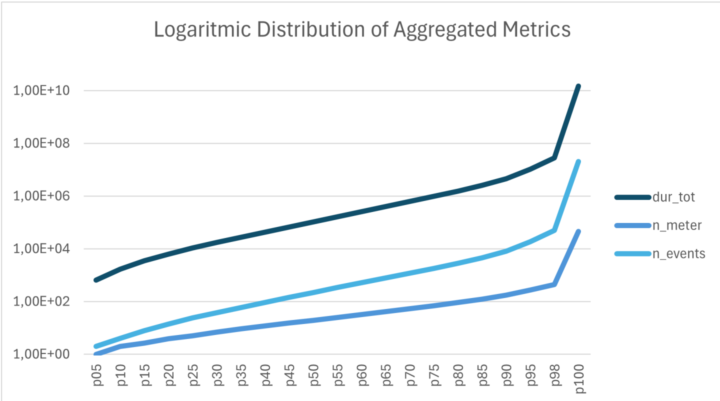


Figure 8: Base 10 Logarithmic Scale Distribution of Aggregated Metrics

These filtering measures were crucial for data cleansing, ensuring that the subsequent analysis was based on reliable and representative event data, thereby excluding spurious readings such as those caused by a malfunctioning meter constantly reporting events.

4.3 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 7 provides an overview of the analyses performed, the underlying rationale, and the key outcomes achieved. For a more detailed discussion and justification of the methodologies and decisions adopted, refer to Annex C.

Table 7: Summary of Network Analysis Performed

Study	Investigation Rationale	Outcome
Electrical Distance to SS	Longer electrical lines tend to have more faults, greater energy losses, and are harder to control. Fault localization and repairs are more complex.	Medium-length lines had the highest number of affected clients. Event frequency and severity (e.g., undervoltages) increased with line length. Overvoltages were more frequent in shorter lines.
Presence of Generation	DERs such as PVs introduce local variability, potentially causing overvoltages and operational challenges if not properly controlled.	Installations with generation showed a higher number of voltage events (+13.88 events on average), with overvoltages being 2.3 times more common than undervoltages.
Generation Capacity	Larger generation capacities can induce reverse power flow and voltage fluctuations, especially in networks not designed for DERs.	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. More lines increase fault propagation and event frequency.	SSs with many lines (≥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 to PV 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.

4.4 Voltage KPI

Building upon the robust network characterization and the invaluable insights derived from the comprehensive VE analysis, this section proposes the conceptual design of a composite indicator, termed the Voltage KPI, or only KPI for simplicity, in this document. This KPI objective's is to be an strategic and objective tool engineered to identify critical micro-clusters that represent optimal targets for strategic investment in digitalization and flexibility solutions within the LV network. The Voltage KPI is designed to provide a quantitative ranking of micro-clusters based on their criticality, with higher numerical values unequivocally indicating a greater and more urgent need for intervention. The results obtained with the KPI are utilized in the selection of the network use-cases analyzed in Section 6.

4.4.1 Development Decisions

The proposed Voltage KPI is constructed using five out of the six metrics defined in Section 4.2.1, 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. Specifically, in cases where a micro-cluster contains only a single meter, any event affecting that meter results in a maximum score of 100%, thereby introducing a bias that overemphasizes the criticality of such installations. Nevertheless, $r_{meter\ ev}$ was subsequently employed as a supplementary indicator following the computation of the KPI, serving to contextualize and validate the identification of the most critical installations.

Following a comprehensive evaluation of alternative methodologies for constructing the KPI using the available data and metrics, it was determined that the most suitable approach would be to formulate the index as a weighted sum of the selected metrics. To mitigate the influence of differing metric scales and ensure comparability, normalization was deemed necessary. Two primary challenges remained: selecting an appropriate normalization technique and determining the optimal weighting scheme for the constituent metrics. Regarding the normalization techniques, two main approaches were selected due to their effectiveness and relative simplicity compared to more complex alternatives, [54]:

- **Min-Max normalization:** rescales data to a fixed range, typically [0, 1], using the formula:

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

  This method preserves the relationships between values but compresses or stretches the data based on the minimum and maximum values. It is commonly used in machine learning algorithms that rely on distance metrics. Its main benefit is simplicity and interpretability, though it is sensitive to outliers, which can distort the scaling.

- **Z-Score standardization:** transforms data to have a mean of 0 and a standard deviation of 1 using the formula:

$$z = \frac{x - \mu}{\sigma} \tag{2}$$

  This method is useful when features have different units or scales, especially in algorithms like logistic regression or PCA. It centers the data and adjusts for variance, making it more robust to outliers compared to min-max normalization. Z-score normalization is ideal when the data distribution is approximately Gaussian and helps ensure that each feature contributes equally to the model.

The determination of metric weights proved more complex. The two main weighting methods were studied, [55]:

- **Subjective weighting** rely on expert judgment to assign importance to indicators. Techniques include expert scoring, ranking, and analytic hierarchy processes. These methods synthesize expert knowledge and experience, making them suitable when data is scarce or qualitative. Their main advantage is the incorporation of domain expertise, but they are prone to bias and inconsistency. The reliability of results depends on expert consensus. Subjective methods are especially useful in complex evaluations where human insight is critical.

- **Objective weighting** use mathematical models to derive weights from data, avoiding human bias. Common techniques include principal component analysis, factor analysis, entropy, and coefficient of variation. These methods quantify the information content or variability of indicators, ensuring consistency and reproducibility. Their main benefit is objectivity, but they may overlook the contextual importance of indicators. However, objective methods may yield inconsistent weights across datasets and ignore expert knowledge, limiting their interpretability in some decision-making contexts.

Initial attempts to resolve this issue through subjective weighting by consulting domain experts revealed significant disagreement, as no single metric was universally regarded as more critical than the others. Given the absence of consensus and its importance in the final weighting, the decision was made to adopt objective weighting methodologies to ensure transparency and reproducibility in the construction of the KPI. Several objective weighting methodologies were evaluated for their applicability to the present case and ease of application. Building upon the prior implementation of min-max normalization, as it is used as the standard normalization protocol within the algorithm, it was concluded that the most appropriate method for deriving objective weights was the Entropy Method.

The Entropy weighting method is an objective technique used to determine the relative importance of indicators in a MC evaluation system. It is based on the principle of information entropy from information theory, which measures the degree of disorder or uncertainty in a system. In the context of index weighting, entropy reflects the variability of an indicator across different observations. The more dispersed the values of an indicator, the more information it conveys, and thus, the higher its assigned weight. This method is particularly useful when expert judgment is unavailable or when a purely data-driven approach is preferred, [56].

The 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:

$$e_i = -k \sum_{j=1}^{n} t_{ij} \ln(t_{ij}), \quad \text{where } t_{ij} = \frac{q_{ij}}{\sum_{j=1}^{n} q_{ij}}, \quad k = \frac{1}{\ln n} \tag{3}$$

This entropy reflects the disorder or uncertainty of each indicator, where a higher entropy implies less useful information.

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

$$u_i = \frac{d_i}{\sum_{i=1}^{m} d_i} \tag{4}$$

By executing the algorithm detailed in Equations 1, 3, and 4, the relative weights of the selected metrics were computed. Based on the available dataset, these weights were disaggregated according to the type of VE, the temporal period in which the event occurred, and the presence or absence of generation capacity within each micro-cluster as explained in Section 4.2.1. The resulting distribution of weights is presented in Table 8.

Voltage Event	Generation	Period	N_events	Dur_events	N_meter	Ev_tot	Dur_tot
Undervoltage	No	1	0.20095	0.20068	0.19957	0.19928	0.19952
		2	0.19957	0.20129	0.19989	0.19955	0.19970
	Yes	1	0.19998	0.20011	0.19980	0.19997	0.20015
		2	0.19944	0.20020	0.20007	0.20011	0.20018
Overvoltage	No	1	0.20061	0.19956	0.20003	0.19997	0.19983
		2	0.20008	0.19950	0.20013	0.20019	0.20011
	Yes	1	0.20027	0.19942	0.20002	0.20025	0.20004
		2	0.19997	0.19918	0.20005	0.20050	0.20030

Table 8: Metric Weight Distribution Categorized by VE, Generation Capability & Period of Occurrence

Analysis of the computed weights revealed a high degree of homogeneity across the eight evaluated categories, with only minimal variations observed. Consequently, it was determined that the weights would be averaged across all categories, resulting in a single representative weight for each metric, independent of the specific characteristics of the data subset.

Another noteworthy finding is that all variables received nearly identical weights, indicating that each contributes a comparable amount of information to the system. This outcome suggests that the variables exhibit similar statistical distributions and variability, with no single metric emerging as significantly more informative than the others. In practical terms, this reflects a balanced dataset in which all variables play an equally important role in the analysis, and none disproportionately influences the KPI.

Further experimentation with alternative metric combinations yielded similar results, reinforcing the conclusion that the variables are strongly correlated. SSs with a high number of events also tend to exhibit a greater number of affected clients, longer total duration, and elevated values in both events per meter and average event duration. Despite the observed redundancy, it was decided to retain all five metrics in the final formulation of the KPI. This decision was based on the rationale that, although the weights and variability are similar, the inclusion of all variables may still capture nuanced combinations of conditions that could be critical for identifying high-impact scenarios.

A final consideration incorporated into the construction of the Voltage KPI is the prioritization of upstream micro-clusters when identifying critical conditions downstream. This design ensures that, upon detection of a problematic micro-cluster, the investment prioritization algorithm naturally selects the first upstream micro-cluster as the optimal target for intervention. If the problematic micro-cluster were to be the first micro-cluster in the line, both problematic and preferred investment micro-clusters would be the same value. This approach is consistent with the empirical findings discussed in Section 5, which emphasize that by allocating digitalization devices at upstream points in the feeder, they are able to yields broader and more impactful improvements across all downstream MDBs. Such upstream interventions contribute to a cascading enhancement in network reliability and overall QoS.

The final Voltage KPI is normalized with the Min-Max algorithm to produce a score ranging from 0 to 100, where a value of 100 denotes the most critical micro-cluster requiring immediate and strategic investment, while a score of 0 corresponds to a micro-cluster exhibiting minimal or negligible VE-related issues.

4.4.2 Results

With the finalization of the Voltage KPI, its results are now available for analysis. Table 9 presents a subset of the top-ranked installations based on the KPI, with SS identifiers anonymized to preserve privacy and confidentiality.

CT	Problematic micro-cluster	Preferred Investment micro-cluster	Generation	KPI
Cod_CT_1	19	4	No	100
Cod_CT_2	5	5	No	98.61
Cod_CT_3	1	10	Yes	98.252
Cod_CT_4	7	7	No	97.578
Cod_CT_5	3	0	No	96.067
Cod_CT_6	12	11	No	95.425
Cod_CT_7	2	0	No	95.216
Cod_CT_8	5	5	Yes	94.467
Cod_CT_9	1	4	Yes	94.412
Cod_CT_10	8	7	No	94.215

Table 9: Extract of KPI Results

The extracted results from the KPI output provide sufficient information to identify and geographically locate the most critical micro-clusters within the system. Additionally, the presence or absence of generation in each micro-cluster is indicated, enabling an assessment of the relationship between DER integration and voltage-related issues.

Analysis of the top 100 KPI-ranked micro-clusters yielded several key findings. First, 52% of these micro-clusters are associated with generation, a figure significantly higher than the overall generation presence of 31.3%, thereby underscoring the voltage disturbances linked to uncontrolled PV installations. Second, the most prevalent VEs type among these micro-clusters was overvoltage, accounting for 62% of all events. Third, the KPI effectively identified the most critical SSs, as a substantial proportion of the top-ranked installations were positioned above the 85th percentile across all five evaluation metrics.

These findings are further illustrated in Figure 16.

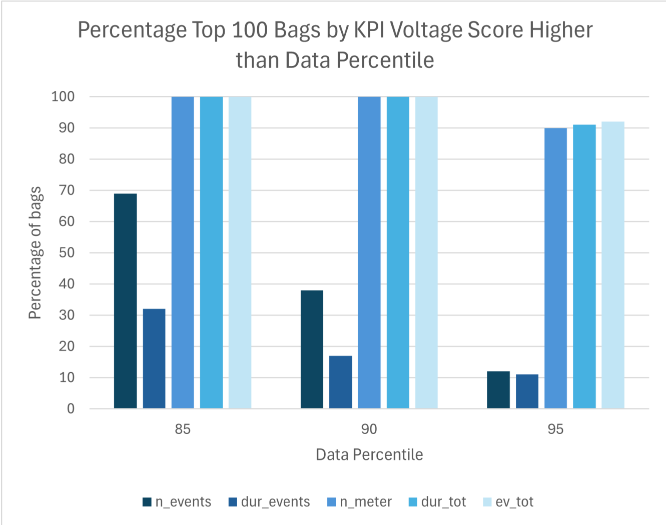


Figure 9: Percentage Top 100 micro-clusters by KPI Voltage Score Higher than Data Percentile

The Voltage KPI demonstrates particular effectiveness in identifying SSs with the highest aggregated metric values. Notably, over 90% of the top 100 ranked micro-clusters fall above the 95th percentile in the aggregated metrics, confirming the KPI's capacity to prioritize installations with the greatest impact on QoS. While its performance is slightly less pronounced when applied to relative metrics, this is consistent with the KPI's primary objective: to identify micro-clusters with the highest number of affected clients in order to maximize improvements in QoS. In this context, the KPI is designed to prioritize aggregated metrics during the initial ranking phase, with relative metrics serving as secondary criteria to differentiate between similarly ranked installations. The results confirm that the KPI fulfills this objective effectively.

The practical applicability of the Voltage KPI is further validated through cross-referencing with ongoing internal initiatives. At present, several projects are underway within the firm to deploy voltage regulation devices across the LV grid, with three SSs identified as primary candidates for intervention. Of these, two SSs were not included in the dataset due to missing event data, likely resulting from computational limitations during the micro-cluster creation process or data corruption. However, the third SS was successfully evaluated and ranked 9th overall in the KPI results, appearing as Cod_CT_9 in Table 9. This alignment between the KPI output and real-world operational priorities underscores the tool's practical relevance and its potential for broader implementation to support data-driven investment planning and QoS improvements in the LV network.

4.5 Conclusion

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 process began with the extraction and preprocessing of data from a structured SQL dataset, followed by the definition of six evaluation metrics designed to capture the frequency, severity, and spatial distribution of VEs. Through normalization and objective weighting using the Entropy Method, the KPI was constructed as a weighted sum and normalized from 0-100 for clearer interpretation.

The results of the KPI analysis demonstrated its effectiveness in identifying high-impact areas. Over 90% of the top 100 ranked micro-clusters were above the 95th percentile in aggregated metrics, confirming the KPI's ability to highlight installations with the greatest potential for QoS improvement. The tool also revealed a strong correlation between DER generation presence and the prevalence of overvoltage events in critical installations. Furthermore, the KPI's real-world applicability was validated through alignment with internal initiatives, including the identification of Cod_CT_9 as a top candidate for voltage regulation. These findings underscore the KPI's potential as a decision-support tool for DSOs, enabling data-driven planning, targeted investment, and proactive grid modernization. With further refinement and integration into operational workflows, the Voltage KPI can serve as a foundational element in the transition toward smarter, more resilient LV networks.

This analysis also raises important considerations regarding the regulation of product quality and the associated incentive frameworks. In the current Spanish regulatory context, there is no specific incentive for DSOs to actively ensure, monitor, or be rewarded/penalized for maintaining voltage within the allowable limits at the point of connection. Despite the existence of technical standards defining acceptable voltage ranges for end users (e.g., UNE-EN 50160, [57]), national regulations such as Royal Decree 1955/2000, [58], Order ECO/797/2002, [59], and associated distribution quality frameworks do not impose binding requirements or economic signals related to voltage compliance.

As a result, voltage quality is often managed reactively rather than proactively, and DSOs lack the regulatory and financial motivation to prioritize digital monitoring or corrective investments in areas with recurring voltage deviations. Addressing this regulatory void would be critical to unlock the full potential of digitalization in supporting both operational efficiency and service quality.

This section provided an overview of the current state of i-DE's LV network, establishing patterns regarding the occurrence of VEs within the grid. Among them, it is demonstrated how longer line lengths correlate with an increased frequency of events, and how generation significantly impacts the VE profile and severity, particularly in high penetration areas. The analysis revealed that a small proportion of large SSs are responsible for the majority of VEs, with the remaining network demonstrating relative stability. This information informs the profiling and selection of use cases in Section 6. However, before proceeding to the use cases, Section 5 explores the current state of digitalized voltage management solutions, which will aid in selecting the most appropriate devices to address network issues building upon the insights gathered throughout the project.

Chapter 5. 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. The discussion highlights how these technologies address existing challenges and unlock significant benefits for DSOs. Furthermore, this section evaluates the technological maturity of these solutions for large-scale implementation. Digitalization elements covers several key areas and fulfill a wide array of functions in the network.

A more in-depth analysis of digitalization solutions in the network is provided in Annex F.

5.1 Strategic Benefits of Digitalization in LV Networks

The push for digitalization of electricity distribution grids in Spain is strongly backed by both European and national initiatives. The Spanish PRTR has earmarked 525 M€ to promote digital solutions aimed at modernizing distribution grids [60, 61]. This funding is 50% co-financed by the European Union through the Next Generation EU program [62].

Although the regulatory framework does not explicitly prioritize investment in either MV or LV networks, the structure and scale of the projects required to secure these funds tend to favor initiatives in the MV domain. This bias arises because larger-scale MV projects offer greater execution certainty, better economies of scale, and clearer eligibility alignment with the funding criteria. As a result, DSOs may be disincentivized from deploying digitalization measures in the LV environment, where investments are typically smaller in scale, more granular, and operationally complex.

This capital injection is part of Component 8 of the PRTR, which focuses on electrical infrastructures, the promotion of SGs, and the deployment of flexibility and storage [61]. The primary objective is to transform distribution grids, traditionally passive, into active and participatory grids, placing the customer at the center of the electrical system [63]. This European and national funding acts as a crucial catalyst for digitalization, mitigating the initial economic barriers that distributors might face. Without this significant capital investment, the pace of transformation in the sector would be considerably slower, which underscores the dependence on public support to face investments of this magnitude and align the efforts of distributors with the country's macroeconomic and environmental objectives. The need for these funds for companies to digitalize their grids is evident, given the scale of the required modernization [60].

Despite the clear financial impetus, the digitalization of the electricity grid faces a series of complex challenges. One of the problems is the difficulty in quantifying the benefits of digitalization, due to its dual nature as both an enabler and a direct provider of advantages [60]. Although digitalization can generate substantial long-term savings, the initial investment in infrastructure and technology remains an obstacle for many companies [60]. Furthermore, the unequal distribution of funding among DSOs can generate disparities in the progress of digitalization.

Another essential component of grid digitalization is the deployment of reliable and scalable telecommunications infrastructure. The ability to establish bidirectional and real-time communication with digital devices across the network is a foundational requirement for enabling advanced monitoring, automation, and control functions. Although this project does not specifically analyze the telecommunications dimension, it must be acknowledged that any systematic digitalization roll-out would need to incorporate communication capabilities as a core deployment constraint. The design and availability of telecoms solutions can significantly influence both the CAPEX and OPEX of digital technologies, and thus should be considered as a strategic factor in planning and cost-benefit assessments.

Additionally, cybersecurity represents a growing concern and a key objective to ensure supply continuity and consumer data privacy [64]. As electricity grids digitalize and become more interconnected, the risk of cyberattacks increases exponentially. A security failure in a SG could compromise the electricity supply on a massive scale. The interconnection of these systems and the management of large volumes of data amplify the cyberattack surface, turning cybersecurity into a systemic risk that demands robust public-private collaboration and an agile regulatory framework.

5.2 Status of Digitalization in Spain

The landscape of digitalization in Spain's main electricity distributors shows a firm commitment to modernizing their grids, albeit with specific approaches and projects that reflect their strategic and operational particularities. In this section the main projects and objectives of the main 5 distributors in Spain, which account for approximately 29 M clients and most of the national territory, are reviewed.

The most relevant project are highlighted in Table 10, with the full information and explanation of each project highlighted in Annex E.

Company	Project Details
Endesa (e-distribución)	
Digitalization Solutions	Grid digitalization initiative (PRTR), 412 M€, [62] SGs Development, >1.2 B€, 2021-2023, [65, 66] Digital Twin of LV grid , [65, 66] e-distribución mobile application, [67]
Advanced Supervision & Telecontrol	Sensorization of distribution centers, [63] MONICA project, [66] Telecontrol in Canary Islands, 32.8 M€, 2024, [68]
AI, IoT & Innovation	Aerial-Core, Smart5Grid, Resisto, RE2GRID, LEO Satellite [65]
Iberdrola (i-DE)	
Digitalization Solutions	Digitalization Investment, 290 M€, 2024, [69] Low Voltage Management Model, [70] i-DE mobile application, [71]
Advanced Supervision & Telecontrol	Advanced Low Voltage Supervision, [70] Grid Digitalization [72] SensoCeT (Intelligent Sensors for Transformation Centers), [70]
AI, IoT & Innovation	Global SGs Innovation Hub (GSGIH), [73] Use of Big Data, [73]
Naturgy (UFD)	
Digitalization Solutions	Grid Digitalization & Improvement, 450 M€, 2023, [74] Grid Reinforcement & Digitalization Plan, 1.33 B€, Until 2028 UFD's Digital Services Platform, [75]
Advanced Supervision & Telecontrol	Sensorization & Telecontrol of grids, [76]
AI, IoT & Innovation	DALI (Drone & AI Line Inspection), [77] TAIS (Telesupervision AI System), [78]
EDP (E-Redes & Viesgo)	
Digitalization Solutions	New Generation Control & Data Acquisition Centers, [79] LV Line Replacement (RZ-type), (100 km replaced) [80] E-Redes mobile application, [81]
Advanced Supervision & Telecontrol	Grid sensorization (IoT), [79]
AI, IoT & Innovation	AI for planning and dispatch management, [79] EDP LABELEC, [82]

Table 10: Summary of Digitalization Projects & strategies in Spain

5.3 Voltage Regulators

Voltage management is one of the most critical challenges in modern LV networks, exacerbated by the integration DER. Voltage regulators offer solutions to mitigate voltage fluctuations and maintain supply quality. There are two types of regulators: passive and active.

Passive regulators are simple and cost-effective devices connected in parallel with the feeder. They are primarily deployed to mitigate localized voltage issues by improving the voltage profile in their area of influence. Their functionality includes partial voltage compensation and phase current balancing, albeit without dynamic adjustment.

Active regulators, as referred to in this project, are conventional On-Load Tap Changer Transformers (OLTC) installed in series with the feeder, enhanced with electronic control that allows progressive voltage adjustment under load conditions. These systems enable real-time voltage regulation per phase by comparing the measured output voltage with a target setpoint and adjusting the tap position accordingly.

A third and more advanced alternative is the deployment of **power electronic-based regulators**. These devices offer hybrid capabilities, combining voltage control downstream with active phase balancing. They can independently increase or decrease voltage per phase and dynamically adjust to the grid's operating conditions via high-frequency modulation techniques, such as PWM. Their dynamic response and multi-functional design make them particularly suitable for areas with high penetration of DERs and asymmetrical loads.

This section focuses on the study of four devices and its utility in LV power network.

5.3.1 On-Load Tap Changer Transformers

OLTC transformers, which in this paper are also referred as i-Trafo for simplicity and internal nomenclature, are essential a novel innovation for dynamic voltage management in SSs in the LV network.

The i-Trafo is a transformer equipped with an OLTC that operates between MV and LV. Its primary function is to regulate voltage fluctuations by automatically changing the transformation ratio, also called tap changing, under load, allowing dynamic voltage adjustment without interrupting electricity supply [83]. This capability is crucial for maintaining voltage within operational and regulatory limits. Additionally, i-Trafos include LV telecontrol, enabling remote management of tap adjustments.

i-Trafos adjust the tap position to compensate for variations in input voltage. If the input voltage is too low, the tap setting is raised, disengaging sections of the primary winding, effectively increasing the secondary voltage to the desired level. Conversely, if the voltage is too high, the tap position is lowered to reduce the secondary voltage [84]. This dynamic control is typically managed by a microprocessor-based control system with programmable settings. Furthermore, the i-Trafo can regulate voltage independently for each phase, which is vital for mitigating phase imbalances prevalent in LV networks with single-phase loads or DERs[85]. The operation of these devices requires ensuring that the load circuit is not interrupted and that no short circuits occur in the windings during tap changes.

i-Trafos are a proposed solution to ensure that voltage levels across the LV network remain within acceptable regulatory and operational limits, preventing issues like overvoltage (due to high DER generation) or undervoltage (due to increased load or line drops), which can compromise power quality and equipment lifespan. Moreover, the dynamic voltage control provided by i-Trafos reduces reactive power flows and associated energy losses, improving overall system efficiency. Their rapid response to voltage variations further enhances the flexibility and adaptability of the LV grid, increasing the DER hosting capacity of the network

i-Trafos, functioning as active voltage regulators, are associated with substantial investment and maintenance costs, which are significantly higher than those of alternative LV solutions. Their physical deployment also presents practical challenges due to their considerable weight and the need for ground-level installation. As a result, their current adoption remains limited; for example, only around 200 units have been installed within the i-DE network, reflecting a slow and selective rollout. While i-Trafos provide advanced voltage regulation capabilities, their high cost and operational demands necessitate a strategic approach to deployment. Specifically, their use should be prioritized in critical locations or in areas facing persistent voltage issues that cannot be effectively mitigated through more economical passive solutions.

5.3.2 Zig-Zag Transformers

A Zig-Zag transformer (ZZT) is a passive device that uses a specialized "interconnected star" winding configuration where each output phase is a vector sum of two phases offset by 120° [86]. Although it is not strictly a digitalized solution it serves as a crucial technology being explored by i-DE and other DSOs to mitigate and solve the challenges caused by the electrification of the economy. In conjunction with other digitalized investments it greatly improves flexibility, operational capabilities and hosting capacity of the network.

Unlike conventional transformers, it typically operates without a separate secondary winding, featuring a core with three limbs, each containing two identical windings wound in opposite directions. The inner coil terminals connect to a common neutral point, while the outer coil of one phase links in series with the inner coil of the neighboring phase. Under normal, balanced conditions, the opposing winding directions lead to the cancellation of magnetic fluxes, resulting in negligible total flux. This design effectively makes the transformer "invisible" during healthy operation.

ZZTss are utilized for their ability to balance imbalanced loads across different phases, [14]. By providing a path for zero-sequence currents, they contribute to stabilizing voltage levels in three-phase systems, thereby reducing mechanical and electrical strain on equipment and enhancing overall system performance and power quality. Additionally, their unique winding design makes them highly effective in suppressing triplen (3rd, 9th, 15th, etc.) harmonic currents, [87]. These harmonics get "trapped" by the transformer, preventing their propagation upstream into the power network.

Furthermore, these transformers play a critical role in limiting the magnitude of fault currents during line-to-ground faults. Their construction inherently provides high impedance to positive- and negative-sequence currents while maintaining low zero-sequence impedance, a characteristic that is ideal for effective fault current management. Additionally, their versatility is noteworthy: they can provide neutral grounding even in the absence of a connected load, which expands their applicability across diverse network configurations. This feature also contributes to preventing overvoltages in the event of neutral loss outages—an especially relevant scenario, as such incidents are among the most likely to cause equipment damage and trigger user complaints.

Despite their significant advantages, ZZTss present certain challenges and operational limitations. A primary concern is their cost; they can be more expensive to construct than conventional star-connected transformers. This is mainly due to the requirement for approximately 15.47% more turns in their windings to achieve the same voltage magnitudes [86]. This increased copper content also contributes to higher active resistance and potentially higher short-circuit losses.

Another key limitation is their short-time rating. Under normal operating conditions, the current through the neutral point of a ZZTs is negligible. Consequently, these transformers are not designed to carry continuous fault loads. This design necessitates that any defective load must be automatically and rapidly disconnected during a fault condition to prevent transformer damage. Research indicates that under some conditions, they may exhibit "overestimated power losses" when operating with small values of current asymmetry [15]. This suggests their efficiency benefits are most pronounced under more severe unbalanced conditions. Furthermore, compared to simpler transformer configurations, the "star-zigzag with zero" scheme has a more complex winding design. This complexity can impact manufacturing costs, operational reliability, and maintenance requirements.

5.3.3 Autotransformers

An Autotransformer (AT) is a distinct type of electrical transformer characterized by a single winding, where specific portions serve dual roles as both primary and secondary sides [88]. The "auto" prefix denotes this singular coil acting alone, not an automated mechanism. Unlike conventional two-winding transformers, ATs lack electrical isolation, as their primary and secondary windings are linked both magnetically and electrically through the shared winding section.

ATs offer several compelling capabilities and advantages within electric networks. Similarly to ZZTs, ATs are not digital investments, however, due to the improved capabilities and operational improvement it offers DSOs, these technologies are studied in this project.

ATs are frequently more compact, lighter, and more cost-effective than conventional dual-winding transformers [88]. This is directly attributed to their single-winding design, which requires less conductor material. They also exhibit improved electrical performance, characterized by lower leakage reactance, reduced losses, and a higher VA rating for a given physical size and mass. The design also requires a more modest excitation current.

A significant capability is their flexibility in voltage regulation, [16, 89]. Voltage adjustment is achieved by connecting the primary voltage across two terminals and taking the secondary voltage from various tap points along the single winding, often sharing a common terminal. For fine control, a continuously variable turns ratio can be achieved using a sliding brush on exposed winding coils. Because a significant portion of the power bypasses the inductive transformation process, less energy is lost as heat, resulting in smaller, lighter, and cheaper designs.

Despite their numerous advantages, ATs come with important challenges. The most significant drawback is the absence of electrical isolation between their primary and secondary circuits, meaning any fault, surge, or voltage spike on the primary side can be directly transferred to the secondary side, posing severe safety hazards or damaging sensitive equipment, [17]. Due to their shared winding structure and lower internal impedance, ATs are prone to higher short-circuit currents, increasing the potential for widespread faults.

Unlike some isolation transformers, they offer no inherent phase shift or assistance in removing minor harmonic distortion, which can be a disadvantage in systems with significant non-linear loads [88]. They are also most efficient and cost-effective when the difference between input and output voltage is relatively small; for large voltage changes, conventional transformers are often more practical.

5.3.4 STATCOM

A Static Synchronous Compensator (STATCOM) is a shunt-connected reactive compensation device that utilizes power electronics to form a voltage-source converter (VSC), operating as either a source or a sink of reactive AC power to an electricity network STATCOMs are categorized as second-generation Flexible AC Transmission Systems (FACTS) devices. FACTS are defined by IEEE as AC transmission systems that incorporate power-electronic-based and other static controllers, primarily enhancing controllability and increasing the power transfer capability of electrical networks [18]. These devices are specifically designed to address challenges in AC power, including dynamic voltage and current variations and control. They play a crucial role in improving overall power quality, enhancing voltage stability, and mitigating undesirable voltage sags and swells [19].

The operational principle of a STATCOM is based on a VSC connected in series with some type of reactance, typically a fixed inductor or a power transformer. The STATCOM controls reactive power flow by adjusting the magnitude difference between the voltage it creates and the system voltage at its point of connection. If the STATCOM's generated voltage magnitude exceeds the system voltage, it supplies capacitive reactive power; conversely, if its voltage magnitude is less, it consumes inductive reactive power. The ability to rapidly and precisely control the magnitude and phase of the injected voltage allows the STATCOM to instantly respond to grid disturbances, providing the exact amount of reactive power needed to maintain voltage stability.

STATCOMs are increasingly vital for modern electric networks, with diverse applications. These devices can be used as mid-point compensation along a transmission line to improve system power flow; by providing current to unbalanced three-phase lines they are able to stabilize voltages. By doing this, they are able to aid or augment DER and BESS, facilitating their seamless integration into the grid. Advanced STATCOMs can even provide grid-forming capability, sustaining stable grid voltage and frequency during disturbances and load changes, critical for future grid architectures [20].

Despite their advanced capabilities, STATCOMs face challenges and operational limitations. Historically, STATCOMs have been costlier than passive devices due to the higher cost of power electronics circuits, limiting their deployment to very specific situations. Furthermore these devices also incur in higher operational losses, making them costlier to operate. Additionally, the initial energization of a STATCOM requires rapid charging of its DC-side energy storage to operating voltages [21].

5.4 Conclusions

Voltage regulation technologies play a pivotal role in managing the increasing complexity of LV networks, particularly in light of the growing integration of DER. Both passive and active voltage regulators contribute to maintaining voltage stability and enhancing power quality; however, their respective functionalities, advantages, and limitations differ significantly depending on the underlying technology.

Active voltage regulators provide dynamic voltage control capabilities and superior operational performance, making them well-suited for environments with high variability and rapid fluctuations in load or generation. Nevertheless, these systems are associated with higher cost, increased maintenance requirements, and greater operational complexity. Conversely, passive voltage regulators, while offering more limited control capabilities, present a cost-effective and robust solution for addressing a wide range of voltage-related issues. Their simplicity and lower maintenance demands make them particularly attractive for deployment in less dynamic segments of the network. Each technology presents distinct advantages and trade-offs, and their applicability must be evaluated in the context of specific network conditions and operational objectives.

This section presents a comprehensive evaluation of advanced voltage regulation technologies, specifically OLTCs, ZZTs, ATs, and STATCOMs. The analysis focuses on their principal characteristics, operational benefits for DSOs, and inherent limitations.

OLTCs, referred to as intelligent transformers or i-Trafos, enable dynamic tap-changing under load conditions, thereby enhancing voltage stability and minimizing energy losses. Despite their technical advantages, their deployment is constrained by elevated capital costs and complex installation requirements.

ZZTs are primarily utilized for phase load balancing and harmonic mitigation. They offer a cost-effective solution under mild unbalanced load conditions; however, their effectiveness diminishes with increasing distance from the source of imbalance and under severe asymmetries.

ATs provide a compact and economically viable means of voltage regulation, particularly suitable for scenarios involving minor voltage differentials. Their high efficiency and reduced footprint make them attractive for specific applications, although their lack of galvanic isolation and susceptibility to fault propagation pose significant operational risks.

STATCOMs, as part of the FACTS family, deliver precise reactive power compensation and exhibit grid-forming capabilities. These features are particularly beneficial for the integration of DERs and BESS. Nevertheless, their high investment and operational costs limit their use to strategically critical nodes within the network.

Collectively, the studied voltage regulation technologies significantly contribute to enhancing the flexibility, efficiency, and DER hosting capacity of LV networks. However, their effective deployment requires a strategic approach based on a thorough evaluation of technical specifications, economic feasibility, and the specific characteristics of each DS. Accordingly, Section 6 presents a comprehensive assessment of the utility of these technologies through real-world use cases. This analysis includes a detailed electrical characterization of representative LV networks, reflecting the critical SSs identified in Section 4. Leveraging the insights gathered throughout the project, a novel CBA framework is applied to these use cases to determine the most optimal solutions for both the DSO and end-users.

Chapter 6. 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 4, ensuring representation of critical scenarios. Following the identification of representative cases, the digital technologies described in Section 5 are strategically implemented to address the identified challenges. Their performance is subsequently evaluated using the ISGAN MC-CBA framework presented in Section 3.2.3, which extends beyond conventional technical and economic parameters to include societal and sustainability dimensions.

The primary objective is to determine the most suitable digital solution for each scenario, leveraging the CBA framework to quantify the added value of digital technologies in enhancing the performance, resilience, and sustainability of the LV network.

6.1 CBA Framework

The MC-CBA framework applied in this project follow the methodology developed by ISGAN in [22] following the criteria proposed by the JRC in [11] to support decision-making in SG investment planning. The framework is developed to integrate both monetary and non-monetary criteria into a unified evaluation structure. Unlike traditional CBA, which focuses solely on economic indicators, MC-CBA incorporates qualitative and quantitative dimensions, enabling a more holistic assessment of SG projects. This approach is particularly relevant in the energy sector, where societal, environmental, and technical impacts often cannot be fully captured through financial metrics alone. The methodology begins with the identification of relevant alternatives. Each alternative is then evaluated across a set of criteria, which are structured hierarchically to reflect their relative importance and interdependencies.

In the MC-CBA framework, criteria are organized into three main categories following a hierarchical structure:

- **Economic Branch:** focuses on the direct financial impacts of SG projects, providing a quantitative foundation for comparing investment alternatives. This branch evaluates criteria such as capital expenditures CAPEX, OPEX, avoided costs (e.g., outage-related penalties or infrastructure upgrades), and potential revenue streams. These monetary values are assessed using standard economic tools such as Net Present Value (NPV), Internal Rate of Return (IRR) or Cost Benefit Ratio (CBR).
- **Technical or Smart Grids Branch:** This branch evaluates the technical and operational performance of proposed investments in relation to grid modernization, considering criteria such as system reliability, flexibility, controllability, and the integration of DER. It aims to quantify performance improvements not always reflected in traditional economic metrics. By incorporating digitalization, network utilization and capacity can be increased, reducing the need for conventional reinforcement investments and associated costs. Enhanced monitoring further enables accurate assessment of the network's operational state, supporting informed reinforcement decisions when necessary. Together, these measures ensure

that modernization initiatives not only address immediate operational challenges but also contribute to long-term grid resilience, adaptability, and efficiency.

- **Externalities Branch:** designed to capture the broader societal and environmental impacts of SG investments that are not directly reflected in market transactions. This includes criteria such as emissions reduction, air quality improvement, noise reduction, land use, and social acceptance. The utility of this branch lies in its ability to internalize the external costs and benefits associated with energy infrastructure projects, thereby promoting more sustainable and socially responsible decision-making.

Each main category may encompass several sub-criteria, which are individually assessed and subsequently aggregated. These individual scores are normalized and weighted based on their relative importance, facilitating a direct comparison with monetary indicators. The integration of both monetary and non-monetary criteria is carried out through a MC decision analysis process, which consolidates the weighted scores into a single composite performance index for each alternative. This comprehensive index enables decision-makers to rank projects not only in terms of economic efficiency but also according to their broader contributions to sustainability and system resilience. By adopting this structured and transparent approach, the framework enhances the accountability of the decision-making process and allows stakeholders to clearly understand the rationale behind project selection and prioritization.

Figure 10 provides a visual representation of the hierarchical structure of the CBA framework, illustrating the progression from the three primary branches to the specific study criteria and, ultimately, to the final evaluation metrics that quantify the impact of the digital solutions.

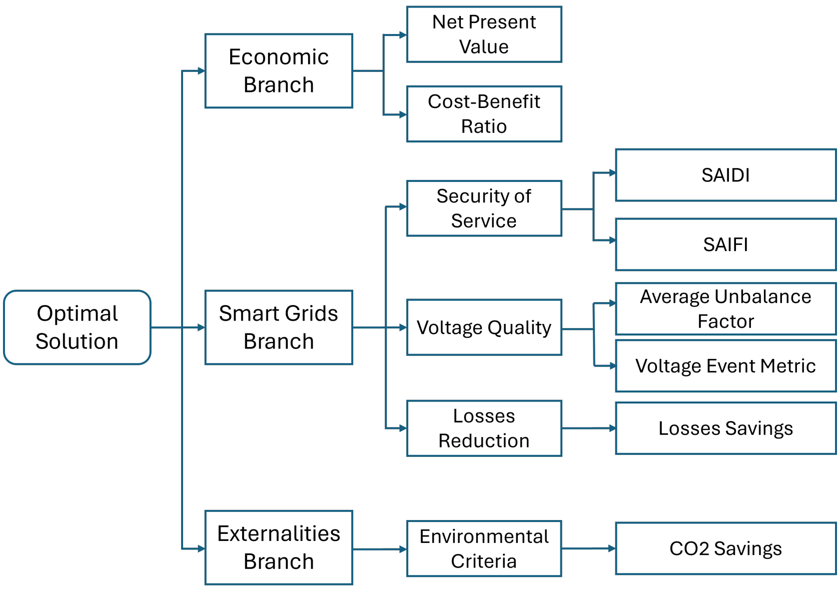


Figure 10: Example Load Curve Case Selection

6.2 Evaluation Metrics & Hypothesis

The PlexigridSim software performs a sequence of analytical steps, including the identification of representative use cases and the proposal of targeted solutions based on the specific voltage disturbances observed in each scenario. Additionally, it offers customization tools that allow the user to define device ratings and assess performance parameters. A comprehensive analysis of the initial software-generated metrics, the case selection algorithm, and the device rating definitions is presented in Annex H.

However, following a critical evaluation of these KPIs, the objectives of the project and the MC-CBA framework, the original outputs were revised and adapted. This section outlines the adjustments made to the software-derived metrics, providing the rationale behind each modification and its intended analytical contribution.

To enhance the comparative evaluation of the proposed alternatives, all metrics discussed in this section are assessed as variations relative to a baseline scenario. This reference case corresponds to the initial base configuration or Case 1, assuming no intervention (i.e. business-as-usual). It serves as a benchmark for quantifying the added value and practical applicability of each digital solution. A positive variation in a given metric indicates an improvement in the corresponding variable, with higher values reflecting greater benefits. Conversely, a negative variation denotes a deterioration in performance. For consistency in the temporal analysis, a **12-year** equipment lifespan is assumed, which defines the evaluation period for all proposed solutions.

6.2.1 Smart Grid Branch

For the final CBA, the SG branch is divided into three main criteria:

- **Voltage Quality (VQ):** Assesses the operational performance in the networks voltage values and evaluates the QoS delivered to end users. It quantifies the extent of voltage disturbances across the LV network. It is subdivided into two metrics:
  - **AUF:** Serves as an evaluation of the average voltage unbalance of the three phases in the network. Voltage unbalance results in unequal current distribution, increasing power losses and causing overheating in equipment. It also leads to voltage deviations at customer connection points, potentially pushing voltages outside the acceptable range. It is kept unchanged from the initial output of the PlexigridSim tool. Its calculation formula is shown in Equation 5.

$$AUF = 100 \times \frac{V_{max} - V_{min}}{V_{avg}} \tag{5}$$

    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 and the extent of problems across the network and clients affected. It is constructed by aggregating the PUL and POL metrics from the PlexigridSim tool into a single representing the total percentage of buses experiencing VE. It is evaluated as shown in 6.

$$VEM = \frac{1}{n}\sum_{i=1}^{n} \delta_i \times 100\%, \quad \text{where} \quad \delta_i = \begin{cases} 1, & \text{if } V_i < 215\,\text{V or } V_i > 245\,\text{V} \\ 0, & \text{else} \end{cases} \tag{6}$$

    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):** Evaluates the system's ability to ensure a continuous, stable, and reliable supply of electricity by minimizing interruptions. As the extreme situations chosen as use cases have a minimum occurrence of 3% throughout the 11,000 hours of simulation (which means $T \geq 330h$), one of the hypotheses used is that these situations occur for a number of days equivalent to the percentage of time equal to or worse than the selected simulation. This means that for 3% of the days, these situations occur for a considerable amount of time, indicating they are steady-state rather than transient voltage deviation events. For this reason, it has been decided that the regulator has protections in the SS that protect against these voltage deviation events and that it disconnects the buses that are permanently experiencing heavily deviated voltages. It is measured utilizing two metrics:

  - **SAIDI:** is a key metric used by electric utilities to measure the average total duration of power outages experienced by customers over a specific period, in this case a year. It has been considered that the utility will disconnect buses outside the ±10% range for 25% of the study period as a result of the VE. It is calculated as shown in 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:** complements SAIDI by measuring 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 ±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.

  It is important to note that this study applies SAIDI and SAIFI indices to the LV grid, despite their predominant use in most national regulations for assessing MV and HV reliability.

- **Losses Reduction (LR):** This criterion evaluates the minimization in power losses for the network with the introduction of the digitalization devices. A reduction in power losses in a distribution network means that less electrical energy is wasted as heat or other forms of dissipation while being transmitted from substations to end users. This is highly desirable because it directly improves the efficiency and cost-effectiveness of the power system. It is quantified by a single metric:

  - **Losses Savings (LS):** Energy losses are quantified as the difference between the power measured at the SS transformer and the aggregate power across all system buses. Given that the analysis focuses on a critical scenario at a specific point in time, an estimation methodology is employed to extrapolate annual energy losses. Since such critical conditions occur only during a limited portion of the year, a broader analysis is conducted using the PlexigridSim simulation tool to model less severe, yet representative, operational scenarios.

By analyzing the losses associated with these additional cases, a proportional reduction coefficient is derived, reflecting the relationship between the losses in the initial critical case and those in subsequent scenarios. This coefficient, combined with the number of hours and demand levels corresponding to each scenario, enables the extrapolation of energy losses over the entire year. The resulting values are then annualized to estimate total yearly losses and, consequently, the potential annual energy savings. In addition, an annual system demand growth rate of 3% is assumed, with energy losses projected to increase at the same rate. It is calculated as shown in Equation 9 and Equation 10.

First, the initial power loss calculation is obtained with 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 LS_0 is the initial power loss calculation at year 0, P_{SS} is the power measured at the substation transformer, $\sum_{i=1}^{n} P_{\text{bus}_i}$ is the aggregate power measured across all n system buses, α_s is the loss factor associated with representative scenario s, obtained through simulation, h_s is the number of representative hours corresponding to scenario s and S represents the total number of representative scenarios considered. Finally the temporal aggregation of power losses throught the project lifespan is obtained with Equation 10.

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

Where LS_0 is the inital power loss calculation, g is the estimated growth rate for power consumption and losses, defined as 3%, LS_t is the adjusted LS_0 power calculation at year t and LS is the aggregate of all adjusted LS_t metrics throughout the project lifespan T of 12 years.

It is important to emphasize that the metrics NAVE and PAVE, as generated by the software tool, have been intentionally excluded from the present analysis. This decision is based in the specific objective of the study, which is not to assess the average voltage deviations across all buses outside the acceptable range. Relying on such average-based metrics could be misleading, as networks exhibiting relatively low average deviations may still conceal severe voltage anomalies due to the presence of numerous minor deviations. Instead, the analysis is designed to focus on the most critical voltage deviations and the most significantly affected buses. This targeted approach ensures that the evaluation highlights the most severe and operationally relevant conditions within the network, thereby providing insights that are more aligned with the practical challenges encountered in system operation and planning.

6.2.2 Externalities Branch

The final externalities branch is comprised of only one criteria:

- **Environmental Criteria (EC):** it is essential for aligning the electricity sector with global sustainability objectives. Reducing emissions within the network not only contributes to mitigating environmental degradation but also promotes public health. As electricity increasingly becomes the backbone of sectors such as transportation and industry, its decarbonization emerges as a critical component in meeting both national and international climate targets. Ultimately, integrating environmental considerations ensures that the evolution of the electricity sector is guided not solely by demand, but by a commitment to responsible and sustainable development. It is quantified using a single metric:

- **CO_2 Savings:** CO_2 is one of the most significant greenhouse gases contributing to climate change, and its reduction is essential to mitigate environmental degradation and ecosystem disruption. In this analysis, the CO_2 savings result from reduced network losses, assessed using the LS metric obtained in the SG Branch. The emission factor used for this estimation is 110 CO_2g/kWh, based on historical data for Spain and the recent evolution of this parameter [90]. It is assumed that this emission factor remains constant throughout the analysis period. This value is applied to calculate the annual CO_2 emissions avoided due to loss reduction, thereby quantifying the environmental benefits of the proposed digitalization measures and their contribution to broader emission reduction and sustainability objectives. Its calculation method is highlighted in 11

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

Where LS_t is the metric Loss Saving metric calculated in the SG Branch Section 6.2.1 in year t, E_t is the estimated emissions factor at year t and T is the total number of years of the project, in this case, 12 years.

6.2.3 Economic Branch

From a financial perspective, several assumptions have been made to support the calculation of the metrics included in the analysis.

On the cost side, only CAPEX and OPEX associated with the deployment of new devices in the network are considered. The CAPEX is derived from the Cost variable provided by the PlexigridSim application and corresponds to the total cost of all installed devices. OPEX is estimated based on the failure rates of the various types of equipment. The failure rate is defined as the expected number of device failures per year that necessitate repair or replacement. Each failure is assumed to result in the complete replacement of the device, and thus the OPEX is calculated as the product of the CAPEX for a new device and its corresponding failure rate. Routine maintenance and additional repair costs are not included in the OPEX estimation.

Both the failure rates and CAPEX values are based on internal estimates developed by i-DE, informed by practical experience gained through the deployment of pilot projects within the network. Since iCOBT have not been used in pilot Tests at i-DE, their failure rate assigned has been similar to iEBT devices. A summary of the assumed failure rates and CAPEX values is provided in Table 11.

Table 11: Device Cost and Reliability Data

Device	CAPEX(€)	Failure Rate (replacements/year)	OPEX (€/year)
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

Several considerations have been made regarding the failure rates of the different devices analyzed. Among them, the ZIGZAG device is assigned the lowest failure rate. As a passive component, it exhibits minimal susceptibility to failure and requires relatively limited maintenance. The next device in terms of reliability is the iTRAFO. Its failure rate has been estimated based on operational data from multiple units already deployed within iDE's network. Although the iTRAFO demonstrates a higher failure rate than conventional transformers, primarily due to the presence of an on-load tap changer, it remains significantly more robust than devices incorporating power electronics. The highest failure rates are attributed to the iCOBT and iEBT devices. The iCOBT, being an active device that integrates power electronic components, is inherently more prone to failure. Similarly, the iEBT, which also relies on power electronics for voltage regulation, exhibits a comparable failure profile. These elevated failure rates reflect the increased complexity and operational demands associated with power electronic systems.

Positive cash flows, or revenues, are derived from the reduction in network energy losses, as quantified using the methodology outlined in the technical metrics section. A monetary value of 0.1 €/kWh saved in Year 0 has been assigned. This valuation is based on the estimated price at which energy could be sold to residential end consumers, incorporating the average pool price over the period 2023–2025 [91], along with a commercialization margin. This approach is intended to reflect the opportunity cost associated with the inability to sell the energy that would otherwise be lost within the network.

Additional benefits are derived from the improvement in Iberdrola's QoS, specifically through the reduction of the SAIDI. It is estimated that a one-hour reduction in the global SAIDI corresponds to an additional remuneration of approximately 840.000 €. Notably, this income is recurrent, which enhances its attractiveness compared to the standalone monetary value. Given that i-DE serves approximately 11.4 million residential customers, the estimated SAIDI reduction achieved through the implementation of digitalization solutions is used to calculate the associated financial benefit. A linear relationship is assumed between the magnitude of SAIDI improvement and the corresponding remuneration, allowing for an estimation of the quality-related benefits attributable to each network.

In addition, the reduction in CO_2 emissions resulting from decreased energy losses will be assessed and monetized. The quantification of avoided emissions is carried out using the CO_2 Savings metric developed within the Externalities Branch of the framework. To assign an economic value to these savings, an estimate is derived based on the average between the spot market price of CO_2 emission credits and the price of one-year forward contracts, as referenced in [92]. For the purposes of this analysis, the selected valuation is set at 70€/ton in Year 0.

To account for the time value of money, a discount rate, equivalent to a common DSO's Weighted Average Cost of Capital (WACC), of 7% is assumed. This figure is based on internal assessments and publicly available estimates [93]. Although not exact, this rate is considered reasonable, as it exceeds the 6.46% remuneration proposed by the regulatory authority for the upcoming period [94], thereby ensuring that the investment remains financially viable for the company. The price of electricity and the QoS benefits are expected to grow by 3% , while the price of CO_2 emissions is projected to increase by 5% per year. The evaluation period spans the full 12-year life cycle of the digitalization assets, during which the investment is assessed comprehensively. These assumptions form the basis for the temporal valuation of the proposed implementation, enabling a long-term financial and environmental impact analysis.

Table 12 shows a summary of all the inputs and hypothesis utilized in the revenues estimation for the economic value metric calculation.

Table 12: Summary of Economic Inputs and Temporal Valuation Assumptions

Economic Inputs	**Annual Evolution**
Initial Electricity Price: 0.1 €/kWh, [91]	Evaluation Period: 12 years
Initial CO_2 Price: 70 €/ton [92]	WACC: 7%, [93]
QoS Benefit: 870.000 € per hour of SAIDI reduction	Electricity Price Growth: 5%
	CO_2 Price Growth: 5%
Customer Base: 11.4 M	QoS Benefit Growth: 3%
	OPEX Growth: 5%

Having analyzed the assumptions made, two metrics are calculated to estimate the monetary impact of the project:

- **NPV:** is a fundamental financial metric utilized to determine the economic viability of investment projects. This metric serves as a key indicator of business performance, enabling a comprehensive economic evaluation of each proposed alternative. The NPV is computed as shown in Equation 12.

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

  Where R_t denotes the revenues or benefits at time t, C_t represents the costs at time t, WACC is the discount rate reflecting the project's cost of capital, and T is the total duration of the evaluation period.

- **CBR:** is employed to assess the proportional relationship between the total costs incurred by a project and the benefits it generates throughout its useful life. A CBR value less than 1 indicates that the benefits exceed the costs, suggesting that the project is economically viable. Conversely, a value greater than 1 implies that the costs surpass the expected revenues, rendering the project financially unfeasible. A value equal to 1 denotes a break-even scenario, where benefits and costs are equivalent. The CBR 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 $PV_t[Benefits]$ is the present value of the benefits obtained by the project at year t, $PV_t[Costs]$ the present value of the cost at year t and T is the total number of years of the project, 12 years.

All these metrics will serve to evaluate the utility of digitalization solutions and allow for a holistic assessment of the benefits they present for utilities in different use cases.

6.2.4 Weights of Terminal Criteria

The MC-CBA framework requires the evaluator to assign weights to each branch of the decision tree, reflecting the relative importance of each dimension to the stakeholders involved in the project. Within this structure, *local weights* represent the relative importance of criteria within a specific branch, while *global weights* are calculated by multiplying the local weights by the weight assigned to their respective branches. This dual-layered weighting approach ensures that both intra-branch and inter-branch priorities are appropriately considered.

In this project, due to the multifaceted nature of the analysis, each branch is considered equally important, and thus each is assigned a branch weight of 0.3333. Following the recommendations of the JRC [11], criteria at the same hierarchical level are assigned equal weights. The Economic Branch includes two criteria: NPV and CBR, each with a local weight of 0.5, resulting in global weights of 0.1667. The SG Branch comprises three criteria: VQ and SoS, each with two final metrics, and LR with one metric. By assigning equal weights within the hierarchy, each VQ and SoS metric receives a global weight of 0.0556, while the LR metric is assigned 0.1111. The Externalities Branch, containing a single criterion, CO_2 Savings, receives the full global weight of 0.3333.

Table 13 provides a summary of all the global weight of the terminal criteria utilized in the project.

Table 13: 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

6.3 Case Studies

This section outlines the specific LV networks selected for analysis and the corresponding use cases employed to evaluate the proposed digitalization solutions. All networks considered are three-phase LV systems operating at standard voltage levels of 400 V line-to-line and 230 V line-to-neutral. As is typical in distribution systems, the networks exhibit a radial topology and operate under radial configuration principles. Their sole connection to upstream voltage levels is established through a 20/0.4 kV transformer located at the SS, which serves as the interface between the medium-voltage MV and LV domains.

The electrical results and graphical analyses related to the operational performance of the digital solutions, as well as their comparison with the base case, are presented in Annex I.

6.3.1 Network 3

Network 3 (N3) is a medium-size, residential LV system comprising four feeders and a total of 246 buses, of which 94 are equipped with MDB that connect end-user clients. This network exhibits a high penetration of PV DER, and in the selected case study, it presents a generation surplus of 220 kW due to excess renewable production under a scenario of low demand and high generation, leading to reverse power flow conditions. While the upstream effects of this surplus are acknowledged, the study of the effects fall outside the scope of this project. The voltage profile of the network can be seen in Section I.1.

N3 has been selected as a representative case for evaluating the impact of high DER integration in residential networks lacking adequate supervision, phase balancing, and distribution planning. The system is significantly unbalanced and exhibits both undervoltage and overvoltage conditions, making it a relevant candidate for assessing the effectiveness of digitalization for both unbalance and voltage regulations solutions.

The network topology is illustrated in Figure 11, and the numerical results of the evaluation metrics are summarized in Table 14.

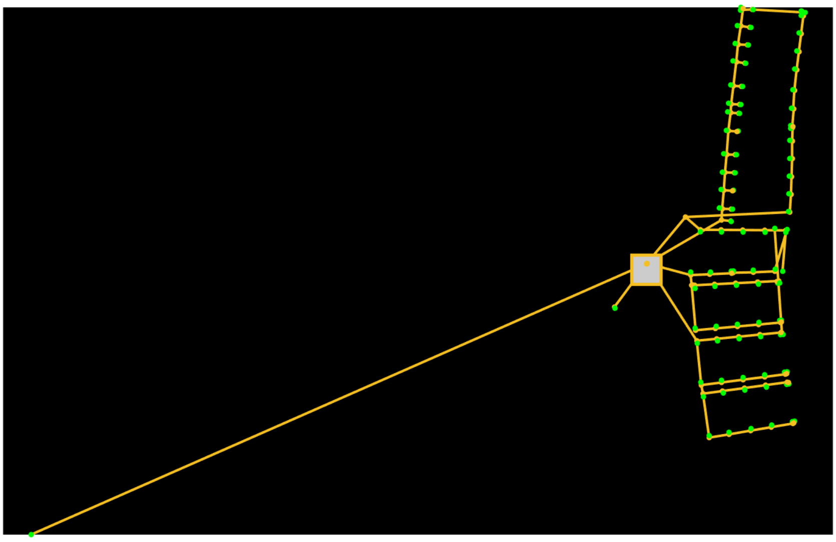


Figure 11: Network 3 Topology

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

Table 14: N3 Decision Variables Numerical Value

Scenario 3.2 clearly emerges as the most favorable alternative from an economic standpoint, exhibiting the highest NPV and the only CBR below 1. It is the sole scenario with a positive NPV, indicating economic feasibility. One of the main reason for the positive economic return would be that this solution offers the smallest CAPEX and OPEX among all evaluated solutions. Furthermore, 3.2 slightly outperforms 3.4 in terms of AUF, LS, and CO_2 savings the most significant VE in this scenario are caused by unbalance conditions.

Scenarios 3.2, 3.4, and 3.5 demonstrate identical performance with respect to SAIDI and SAIFI, by maintaining voltages within the acceptable range. However, 3.5 achieves the best results in VEM across all scenarios analyzed, due to the iTrafo's superior characteristics. In contrast, 3.3 ranks lowest in both economic and technical dimensions, as its characteristics do not align with the networks problems, making it an easily dismissible option.

The final assessment and comparative scoring of all alternatives are presented in Table 15.

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

Table 15: N3 Overall & Partial Scores

Following a comprehensive assessment of the metric values employed in the analysis, an optimal alternative was promptly identified. However, the execution of the algorithm validated that Case 3.2 represents the most advantageous solution among the scenarios evaluated, consistently ranking as the top-performing option across all three branches. This configuration entails the deployment of twelve ZIGZAG devices, strategically installed at the most vulnerable nodes within the LV network. The allocation of these devices and voltage profile is shown in Section I.1.

Despite the relatively high number of devices, this solution achieves the lowest CAPEX and OPEX by a considerable margin, highlighting its cost-efficiency and operational value. By addressing phase unbalance, it effectively mitigates voltage deviations, reduces power losses, and improves key reliability indicators such as SAIDI and SAIFI.

These results underscore the critical importance of load balancing in LV networks and demonstrate how the integration of cost-effective technologies can significantly enhance network reliability, operational performance, and economic return. Additionally, this approach contributes to a much improved QoS for end-users.

6.3.2 Network 5

N5 represents a large-scale LV network comprising 317 buses and a high customer density, including 193 MDBs with end-users. The scenario analyzed assumes significant penetration of EVs and HPs, under an evening peak demand condition driven by both thermal and mobility needs. The hypothesis further assumes the absence of intelligent EV charging strategies and a high simultaneity factor across the network. This use case was selected to illustrate the voltage challenges that can arise from elevated and uncoordinated demand-side DER integration. Although the distributed demand is relatively well-dispersed and phase unbalance is moderate, the voltage profiles across the network are notably poor. Widespread undervoltage conditions are observed across all phases and throughout the system. These findings are detailed in Section I.2. The topology of the network is presented in Figure 12.

The initial baseline metrics for this case are presented in Table 16.

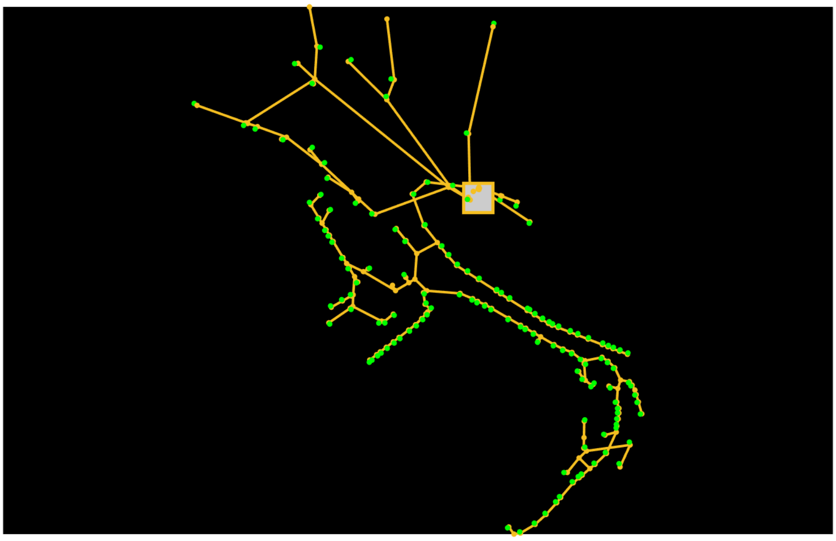


Figure 12: Network 5 Topology

Case	NPV (k€)	CBR	SAIDI (min/y)	SAIFI (occ/y)	AUF (%)	VEM (%)	LS (MWh)	CO_2 Savings (ton/y)
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

Table 16: N5 Decision Variables Numerical Value

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.

The final scores, derived through the application of the MC-CBA methodology, are presented in Table 17.

Case	Overall Score	Partial Score Economic Branch	Partial Score Smart Grid Branch	Partial Score Externality Branch
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

Table 17: N5 Overall & Partial Scores

The results clearly identify Case 5.5 as the most advantageous among the evaluated alternatives, demonstrating superior performance across all assessment domains and achieving a significantly higher overall score. This solution involves the deployment of both an iCOBT and an iTRAFO.

The implementation of the iCOBT presents a compelling use case for the application of STATCOMs in LV networks. These devices are particularly effective in scenarios where voltage unbalance issues are concentrated along extended feeders with a high number of customers connected to the SS through a single line. In such configurations, the iCOBT's advanced unbalance mitigation capabilities outperform those of multiple ZIGZAG devices, which are more suitable for smaller localized disturbances.

Similarly, while the iTRAFO offers robust operational performance, its high cost and inherent limitation, namely, the simultaneous adjustment of all three phases via a common tap, restrict its ability to address both overvoltage and undervoltage conditions independently. Nevertheless, in large-scale networks experiencing widespread voltage deviations in a single direction, the iTRAFO emerges as the most effective and reliable solution.

Although the combined deployment of iCOBT and iTRAFO entails the highest CAPEX and OPEX among the analyzed alternatives, their superior operational characteristics yield the most favorable outcomes for both utilities and end-users, offering the highest return on investment.

6.3.3 Network 8

This case study focuses on a medium-sized LV network comprising 199 buses, of which 115 are equipped with MDBs serving end-users. A notable characteristic of this network is the considerable distance between the buses and the SS, which increases susceptibility to energy losses and widespread VE.

The selected use case aims to illustrate the impact of significant phase unbalance on system performance. It demonstrates how such conditions can propagate throughout the network even under moderate loading, without the need for peak demand scenarios to trigger severe voltage deviations. This scenario exhibits the highest AUF among all analyzed cases, accompanied by the widest voltage deviations, as shown in Section I.3.

The network features substantial localized single-phase demand and generation-side DER concentrated in a limited number of downstream nodes. This configuration results in extensive upstream voltage issues. The case underscores the importance of effective planning and phase load balancing to maintain voltage stability within acceptable limits. The performance metrics for this scenario are summarized in Table 18.

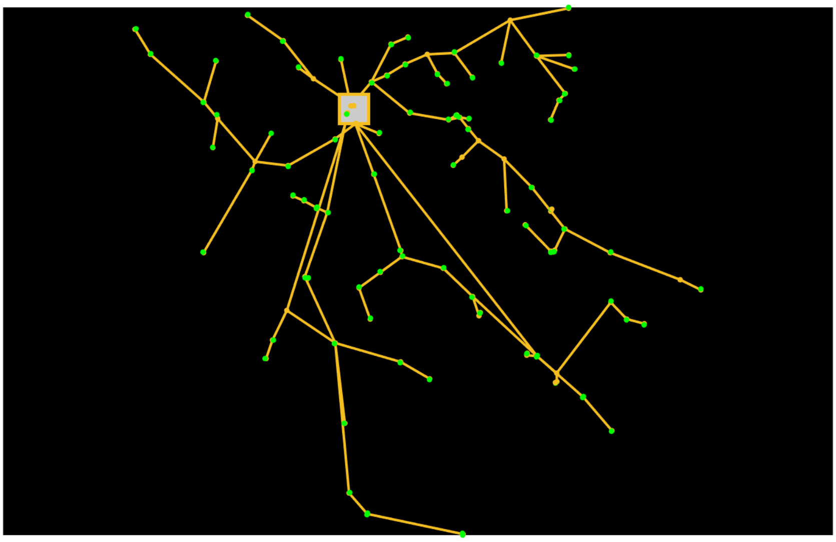


Figure 13: Network 8 Topology

Case	NPV (k€)	CBR	SAIDI (min/y)	SAIFI (occ/y)	AUF (%)	VEM (%)	LS (MWh)	CO_2 Savings (ton)
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 18: N8 Decision Variables Numerical Value

This analysis presents two alternatives, Cases 8.2 and 8.4, with positive NPV values and CBRs below unity, indicating the presence of multiple economically viable solutions. Among them, Case 8.2 demonstrates a superior return due to its smaller CAPEX requirement. However, when considering operational and externality-related metrics, Case 8.4 consistently outperforms Case 8.2 across all operational evaluated indicators.

It is worth highlighting that Case 8.5 demonstrates a technical performance closely aligned with that of Case 8.4, exhibiting the highest AUF and VEM values among all alternatives. Although it presents slightly lower LS and CO_2 savings compared to Case 8.4, its overall performance remains highly competitive, showcasing the iTrafo's capabilities to solve VE. However, its much higher CAPEX and OPEX limits its economic return for the utility.

In contrast to the N5 and N3 case studies, no clearly optimal solution is identifiable prior to the application of the MC-CBA algorithm.

The final results are summarized in Table 19.

Case	Overall Score	Partial Score Economic Branch	Partial Score Smart Grid Branch	Partial Score Externality Branch
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 19: N8 Overall & Partial Scores

An analysis of the results indicates that Case 8.4 is the most favorable alternative, outperforming Cases 8.5 and 8.2. It achieves the highest scores in both the SG and Externalities categories, and ranks second in the Economic branch. Notably, although Case 8.5 is not economically viable, its strong technical and operational performance allows it to be ranked above the most profitable alternative. This outcome underscores the importance of considering multidimensional evaluation criteria beyond purely economic return.

The optimal configuration in Case 8.4 consists of a single iEBT and six ZIGZAG devices. The allocation of the devices can be shown in Section I.3. In this context, the iEBT proves more advantageous than the iTRAFO due to its significantly lower cost and its ability to independently regulate each phase, offering greater operational flexibility. iEBTs are particularly well-suited for scenarios involving both overvoltage and undervoltage issues concentrated along a single feeder, rather than widespread voltage deviations.

The inclusion of ZIGZAG devices further enhances system performance by mitigating voltage unbalance. Strategically deployed along feeders with localized single-phase loads, these devices substantially improve the effectiveness of voltage regulation and represent a promising solution for broader implementation in LV networks.

6.4 Results & Discussion

As observed in the graphs for each case, a different solution is obtained, highlighting the distinct utilities of digitalization equipment and how certain equipment makes more sense than others in specific situations. It is evident that although these solutions are expensive, they resolve a significant number of problems related to voltage management and quality incentives. These solutions not only solve problems for the distribution company but also represent a significant advancement in service quality for customers, generating value in terms of the utility and lifespan of their electronic equipment, preventing service interruptions, and ensuring optimal operation.

In general, the experiments reveal several key conclusions regarding the performance and applicability of different digital solutions.

ZIGZAG transformers emerge as highly effective devices. They resolve the vast majority of unbalance problems at a moderate cost. As passive equipment, they exhibit a limited failure rate, making them compact and suitable for installation in numerous network locations with minimal space requirements. They provide a robust solution for issues arising from high single-phase loads, such as PV panels or EVs, effectively addressing all types of unbalance problems and resolving issues both downstream and upstream in the system. Their utility and low cost make them highly versatile and complementary to other digital solutions. They can be deployed in large, medium, or small SS due to their cost-effectiveness, and their development represents a quality solution for voltage problems induced by unbalances from single-phase loads.

iCOBTs (STATCOM) currently provide limited value for the money for DSOs. Although they perform effectively in resolving major voltage or reactive power balance problems in MV and HV in very large and interconnected networks, their application is limited in small, LV networks with multiple localized problems across different radial feeders. While capable of resolving unbalance problems similarly to ZIGZAG equipment and offering greater dynamism, their high cost for a single application limits their viability.

Deploying multiple ZIGZAG devices is often more beneficial than a single iCOBT due to the former's lower cost and the distributed nature of problems in network topologies. Furthermore, iCOBTs exhibit a significantly higher failure rate than ZIGZAGs due to the complexity of their power electronics. However, these devices have use cases where their required performance characteristics is preferred to other options, such as highlighted in Section 6.3.2. Additionally iCOBT technology cannot be ignored as an alternative, given that world digitalization will grow and both cost and reliability will improve.

The iEBT (LV regulator based on ATs) is also quite interesting for solving voltage problems in LV. Its ability to operate each phase independently provides superior unbalance control compared to the iTRAFO and can resolve voltage issues in both directions or of varying magnitudes. However, its utility is most pronounced when problems are concentrated within a single, long feeder serving numerous customers. These devices are not designed to resolve network-wide voltage problems, which limits their broad application. Nevertheless, for concentrated problems or situations involving both undervoltage and overvoltage within the same SS, the iEBT offers a more effective and adaptable solution than the iTRAFO.

The iTRAFO (OLTC Transformer) is by far the most expensive element among LV digitalization solutions. For widespread voltage problems throughout the network in a single direction, it offers the best solution in terms of technical parameters and performance. It is capable of solving higher and more generalized voltage problems than the iEBT, and its automatic tap changing functionality makes it significantly more dynamic for addressing voltage fluctuations in a variable and volatile environment compared to a traditional transformer. However, they represent a very expensive solution for voltage problems. Consequently, in situations of low criticality or with limited problems, they may not yield a positive or adequate return on initial cost and present a high failure rate. They are the most suitable solution for large SS experiencing a large number of problems, which effectively limits their application to systems serving a substantial number of customers.

The application of the MC-CBA framework has proven essential for evaluating the viability of LV digitalization technologies. By incorporating real-world project lifespan, CAPEX, OPEX, failure rates, and WACC, the analysis ensures alignment with industry conditions. This structured approach supports investment decisions and regulatory alignment by quantifying trade-offs across evaluation criteria.

The construction of evaluation metrics within the MC-CBA framework was based on clearly defined hypotheses to ensure analytical consistency and transparency. The SG branch incorporated three core criteria, VQ, SoS, and LR, each supported by specific metrics designed to quantify the technical impact of the evaluated technologies. The Externalities branch focused on EC and the broader sustainability implications, measured through CO_2 savings. The Economic branch assessed financial viability using NPV and CBR, integrating monetized values derived from the

LR criterion in the SG branch and the CO_2 savings from the Externalities branch. The weighting methodology applied equal importance across the three branches and proportional weighting within each branch, ensuring a balanced representation of stakeholder priorities.

The MC-CBA framework enables a systematic, data-driven evaluation of digital solutions for LV grid modernization. It identified optimal configurations that balance technical performance, economic feasibility, and environmental impact. For DSOs, it provides a decision-support tool to prioritize investments; for regulators, it offers a replicable methodology to assess proposals against policy objectives such as decarbonization and QoS. Ultimately, the framework bridges operational needs with strategic planning, supporting the efficient and sustainable evolution of the electricity distribution sector.

Chapter 7. Conclusions

The primary objective of this project was to promote the digitalization of LV networks and the integration of advanced devices that facilitate the operation of increasingly complex systems. Traditionally overlooked by both regulators and utilities, LV networks are now facing new challenges due to the widespread integration of DER and the emergence of a diversified energy mix.

In response to this context, the project begins with a detailed analysis of the current state of the LV network using i-DE's internal databases. This analysis aims to identify the most pressing issues affecting the network and to characterize the SSs that exhibit the most critical operational behavior. From this, a set of key attributes is proposed to guide regulators in the early identification of problematic network segments. Building on these insights, a voltage KPI is developed to enable utilities to pinpoint specific SSs with voltage-related issues, offering a practical and scalable tool for network monitoring and prioritization.

Following the identification of critical areas, the project proceeds with an in-depth evaluation of digitalization technologies applicable to LV networks. This includes a review of the current state of digitalization in Spain, supported by real-world projects from the five major DSOs, and a comparative analysis of representative technologies. Each technology is assessed in terms of its benefits, limitations, and suitability for addressing specific network challenges.

The final phase integrates all findings into a comprehensive MC-CBA framework, combining electrical, operational, economic, and externality-related criteria. This methodology enables a holistic evaluation of digitalization alternatives, providing DSOs with a systematic decision-making tool that quantifies traditionally intangible variables. By applying this framework to real-world use cases, the project demonstrates how digital devices can enhance network resilience and performance. Ultimately, the project achieves its goal of facilitating and encouraging the adoption of digital technologies in LV networks.

The project demonstrates the benefits of various digital solutions through grid simulation, evidencing improvements in network indices and confirming digitalization as a viable alternative to costly and time-consuming grid reinforcement. An effective DSO strategy should integrate smart grid deployment with traditional MV/LV reinforcement measures to achieve operational efficiency while maintaining a long-term strategic vision.

7.1 Achievement of Objectives

This section revisits the initial objectives established at the outset of the project, which served as the evaluation criteria for determining its overall success. Each objective is examined in light of the final outcomes, assessing the extent to which it has been fulfilled. The analysis provides a structured comparison between the intended goals and the actual achievements, offering a clear perspective on the project's effectiveness.

7.1.1 Voltage KPI Development

One of the core objectives of the project was to **develop a KPI capable of quantifying the criticality of SSs to support DSOs in making informed investment decisions**. This goal was successfully achieved through the creation of the Voltage KPI in Section 4. The KPI is developed founded on a detailed analysis of the LV network using i-DE's SQL databases regarding SS VE.

The evaluation methodology was structured around six metrics designed to quantify the frequency, severity, and spatial distribution of VEs. These metrics were subsequently normalized and weighted using the Entropy Method, an objective approach for determining the relative importance of each variable. The resulting KPI, scaled from 0 to 100, proved to be both intuitive and effective in identifying high-impact areas. Notably, over 90% of the top 100 ranked micro-clusters were positioned above the 95th percentile across the aggregated metrics. Its practical relevance was further validated through alignment with internal initiatives, for instance, both the KPI and Iberdrola's internal assessments independently identified Cod_CT_9 as a priority candidate for the deployment of voltage regulation devices.

In addition, the KPI enabled a more comprehensive understanding of LV network behavior. It highlighted the role of extended line lengths and high DER concentrations in exacerbating VE severity. The analysis reaffirmed the strong correlation between DER penetration and the occurrence of overvoltage conditions, further validating the tool's diagnostic capabilities. Moreover, the results indicated that a small number of large SSs account for the majority of VEs, offering a clear and actionable basis for prioritization of installations and a clear guideline of the most critical SS that required investments in digitalization. These insights directly informed the selection of representative use cases and guided the subsequent evaluation of digitalization technologies.

Overall, the development and application of the voltage KPI not only achieved its intended purpose but also established a foundation for a data-driven and systematic approach to LV grid modernization.

7.1.2 Analysis of Digitalization Technologies

Another major objective of this work is the **analysis of current digitalization technologies in the market** and studying their use cases and applications. This has been thoroughly addressed through the assessment of key innovations in LV networks, with a specific focus on voltage regulation devices in Section 5. Technologies such as OLTC and ZZTs , AT, and STATCOMs have been examined in detail. These digital assets enable DSOs to enhance real-time observability, reduce fault durations via automation, and maintain voltage stability under increasing DER penetration.

The analysis revealed that while OLTCs enhance voltage stability through dynamic tap-changing, their deployment is limited by cost and installation complexity. ZZTs and ATs offer efficient solutions for load balancing and minor voltage corrections, though they present trade-offs in terms of limited downstream effect or fault isolation, respectively. STATCOMs, with their precise reactive power compensation and grid-forming capabilities, are ideal for DER integration but are economically viable only at extremely critical cases.

Their evaluation, aligned with real-world use cases and supported by the Voltage KPI and network profiling provided in Section 4, culminated in a comprehensive MC-CBA presented in Section 6. This framework enabled a holistic assessment of each technology's utility, ensuring that DSOs can make informed, context-aware investment decisions. Thus, the project successfully fulfilled its objective by not only analyzing the state of digitalization technologies but also demonstrating their practical application and strategic value in modern LV grid management.

7.1.3 Operational & Economic Evaluation of Digitalization Technologies

Following the preliminary assessment of digitalization technologies and the examination of their functional characteristics, operational utility, and inherent limitations, a **comprehensive technical and economical analysis of digitalization investments is conducted** in Section 6. This evaluation was grounded in real-world industry parameters, incorporating estimated CAPEX, OPEX, asset lifespan, and WACC to ensure the relevance and applicability of the findings within a practical deployment context.

Among the technologies evaluated, ZZTs emerged as the most cost-effective and technically robust solution for mitigating voltage unbalance, particularly in LV networks characterized by high levels of single-phase DER penetration. Their low CAPEX, minimal failure rate, and ease of deployment across a wide range of SS sizes render them a highly versatile option. Furthermore, their compatibility with other digitalization initiatives enhances their value as a foundational component in broader modernization strategies. In contrast, STATCOMs, while offering superior technical performance and dynamic voltage regulation capabilities, were deemed economically unfeasible for widespread deployment in LV networks. Their high cost and limited applicability to localized voltage issues constrain their utility, making them most suitable for long radial feeders where their advanced operational characteristics can be fully leveraged.

The iEBT demonstrated strong performance in mitigating both overvoltage and undervoltage conditions in specific LV feeders, particularly where voltage deviations are concentrated along a single radial feeder. Its capability to regulate each phase independently offers a key operational advantage over the iTRAFO, which, despite its superior technical performance for managing widespread voltage issues, is constrained by its uniform three-phase tap-changing mechanism and significantly higher CAPEX. Consequently, while the iTRAFO remains the optimal solution for large-scale, unidirectional voltage deviations across extensive networks, its cost-effectiveness diminishes in localized or less critical scenarios. In such cases, the iEBT presents a more viable alternative.

Overall, the evaluation aligned closely with the project's initial goal by identifying optimal digitalization strategies that balance technical effectiveness with economic feasibility, thereby supporting data-driven decision-making for LV grid modernization and successfully meeting its initial objective.

7.1.4 Comprehensive CBA of Digital Investments

The application of the MC-CBA framework has effectively fulfilled the project's primary objective: to **conduct a comprehensive, multidimensional evaluation of digital investments in LV networks**. By integrating economic, technical, and environmental dimensions, the methodology offers a holistic perspective on the value and impact of digitalization strategies.

The integration of real-world parameters ensures that the analysis remains firmly grounded in industry practice, thereby enhancing its practical relevance and credibility. The MC-CBA framework's tripartite structure, comprising the SG, Externalities, and Economic branches, facilitates a comprehensive and balanced evaluation across all critical performance domains. Technical performance is assessed in the SG Branch through criteria such as VQ, SoS, and LR, which capture voltage deviations, network unbalance, interruption indices, and power loss reduction. Environmental and social sustainability is addressed in the Externalities branch via EC, quantified through CO_2 Savings. Financial viability is evaluated in the Economic branch using NPV and CBR, incorporating monetized impacts from both technical and environmental dimensions.

A defining feature of the MC-CBA framework is its weighting strategy, which applies equal importance to each of the three branches while assigning proportional weights to the metrics within them. This approach ensures that the diverse priorities of stakeholders are fairly represented in the final assessment. As a result, the framework not only serves as a robust decision-support tool for DSOs but also offers a replicable and policy-aligned methodology for regulatory bodies.

Through the development and application of the MC-CBA framework, the principal objective of the project is successfully achieved, providing a structured methodology for evaluating digital investments in LV networks. Its alignment with broader strategic goals, such as decarbonization, enhanced grid resilience, and improved QoS, reinforces its relevance as a long-term planning and investment tool.

7.2 Future Work

Following the identification of critical SSs through the application of the Voltage KPI, the next phase of the research should involve a more detailed and dynamic technical assessment of these prioritized installations. One potential development involves conducting a time-dependent analysis of network behavior, with a particular focus on load balancing and peak demand patterns within the identified segments. The aim is to uncover significant load asymmetries that may be contributing to persistent voltage deviations, such as unbalanced phase loading or excessive reactive power flows. This dynamic perspective would provide deeper insights into the operational challenges of the LV network and support the formulation of more effective mitigation strategies.

Additionally, a detailed technical evaluation of the existing infrastructure and current devices installed is essential. This should include an examination of conductor types, cross-sectional areas, age of installed infrastructure and current-carrying capacities. The goal is to identify potential bottlenecks or segments of the network operating near or beyond their thermal limits, which could result in elevated voltage drops or accelerated asset degradation. Such insights would be instrumental in informing targeted reinforcement strategies and optimizing future investment planning.

Another promising avenue for future research involves the practical implementation of the MC-CBA methodology in the evaluation and deployment of digitalization solutions within real-world LV networks. Rather than limiting the analysis to theoretical models or simulation environments, this approach would extend the methodology to actual pilot projects, thereby validating its applicability under operational conditions.

This transition from simulation to field application would necessitate the refinement and contextual calibration of input variables to reflect real network behavior more accurately. Additionally, it would require active engagement with relevant stakeholders and technology providers to ensure a shared understanding of the methodology's structure, utility, and decision-making potential. Familiarization with the MC-CBA framework would empower stakeholders to systematically assess the trade-offs between technical performance, economic viability, and externalities, thereby facilitating more informed and transparent investment decisions in the digitalization of LV infrastructure.

This analysis is conducted in a highly dynamic context, characterized by both the electrification of the domestic economy and the ongoing evolution of digitalization. While there is no "crystal ball" to predict the future, it is certain that every DSO must continuously monitor developments in the manner outlined in your study, adapting to changes and making the best decisions at each stage. Your work establishes a systematic framework for such analysis, which is highly valuable and necessary—for DSOs, for regulators, and for ensuring transparency within the sector.

ANNEX A. Aligment with Sustainability Development Goals

A.1 SDG 9: Industry, Innovation, and Infrastructure

The project directly supports SDG 9 by enhancing the resilience and efficiency of low-voltage electrical infrastructure through digitalization, [95]. As energy systems become more decentralized and complex due to the integration of renewable sources, traditional grid management methods are no longer sufficient. This project aims to increase awareness to both regulators and grid operators, of the potential of advanced digital devices which would enable smarter, more adaptive infrastructure, providing real-time visibility and control over power flows. These innovations reduce the need for costly physical upgrades and instead rely on data-driven solutions to optimize performance, making the grid more robust and future-ready.

A.2 SDG 11: Sustainable Cities and Communities

Urban areas are at the forefront of the energy transition, and this project contributes to SDG 11 by supporting the development of smarter, more sustainable cities, [9]. By improving the management of distributed energy resources and electrified transport systems, the digitalization of low-voltage networks ensures that urban energy systems are more inclusive, reliable, and efficient. The project helps reduce energy inequality by ensuring all citizens, regardless of location, have access to clean, high-quality electricity. It also supports urban resilience by enabling faster responses to grid disturbances and better integration of local renewable generation.

A.3 SDG 13: Climate Action

In alignment with SDG 13, the project plays a key role in mitigating climate change by facilitating the integration of low-carbon technologies, [9]. Electrification of transport and heating, combined with renewable energy generation, is essential for reducing greenhouse gas emissions. However, these changes place new demands on the grid. By using digital solutions to manage variable power flows and optimize energy use, the project reduces the need for fossil-fuel-based backup systems and enhances the overall sustainability of the energy system. This approach supports a transition to a net-zero carbon economy while maintaining grid stability and affordability.

ANNEX B. Global Energy Transition & Electrification

The global energy landscape is currently undergoing a profound and unprecedented transformation, driven by a dual imperative: the urgent need to decarbonize energy systems and the increasing electrification of key economic sectors. There is a global consensus on accelerating the transition away from fossil fuels towards clean, renewable energy sources, with a parallel focus on electrifying sectors traditionally reliant on direct fossil fuel combustion, such as transport, heating, and industrial processes.

For this reason, in recent years, renewable generation capacity has increased exponentially with 2023 alone, reaching a record 560 GW of new additions, with solar PV and wind energy leading the expansion [96]. This surge has increased renewables' share of global electricity generation to 30%, with projections indicating it will exceed 50% by 2030, [96]. A key factor underpinning this accelerated deployment is the drastic reduction in the cost with Levelized Cost Of Electricity (LCOE) for utility-scale solar PV and onshore wind falling by 89% and 70% respectively, [97].

On the demand-side of electrification, the transport sector and heating sectors are also undergoing a particularly rapid transformation, driven by the exponential growth of EV and HPs. Global EV sales continue to surge, with leading projections indicating that EVs could constitute over half of all passenger vehicle sales by 2030 in many major markets [98]. Concurrently, HPs are rapidly gaining traction as a highly energy-efficient alternative to conventional heating and cooling systems in buildings. The spatial and temporal , particularly during evening residential peak hours, poses significant challenges to LV distribution grids, potentially leading to transformer overloading, voltage drops, and increased technical losses if not managed intelligently [99, 100].

Furthermore, the expansion of the digital economy has led to a dramatic increase in the electricity consumption of data centers and other digital infrastructure. Data centers are highly electricity-intensive facilities, requiring substantial power for computing, cooling, and auxiliary systems, operating continuously on a 24/7 basis [101]. Beyond these, various emerging electrified industrial processes are contributing to this trend. Industries like steel, cement, and chemicals, traditionally heavy emitters, are exploring electric arc furnaces, industrial HPs for process heat, and other electrified technologies [102].

The combined effects of increased renewable generation and the extensive electrification of various economic sectors are set to drive an unprecedented surge in global electricity demand with estimations that it will nearly double by 2050, [96]. To accommodate this escalating demand and integrate the expanding renewable capacity, investments in electricity grid infrastruct are indispensable. The IEA estimates that grid investment must increase by an at least 70%, reaching over 600 B$ annually by the early 2030s [96]. This scale of investment reflects the need for not only expanding grid capacity but also for modernizing existing infrastructure.

Digitalization is foundational to achieving the real-time visibility and control necessary to manage peak loads, optimize grid performance, and seamlessly integrate highly variable renewable generation [103]. Without these systemic upgrades and a concerted effort from all stakeholders, the ambitious clean energy transition risks being severely bottlenecked by outdated and insufficient grid infrastructure.

B.1 The Spanish Energy Landscape: Policy and Objectives

Spain's energy policy is firmly guided by two key national strategic frameworks: the Proyecto Estratégico para la Recuperación y Transformación Económica de Energías Renovables, Hidrógeno Renovable y Almacenamiento (PERTE ERHA) [104] and the updated Plan Nacional Integrado de Energía y Clima (PNIEC) 2023-2030 [105]. These comprehensive roadmaps are meticulously aligned with the European Green Deal and the "Fit for 55" package, [106], which outline ambitious objectives for decarbonization, energy efficiency and innovation in the Spanish energy sector [107]. Regarding the strategy and the development plan of the electric network, the 2021-2026 Transmission Network Development plan, with an extended outlook to 2030, is the cornerstone of Spain's strategy to modernize its electricity grid and navigate the energy transition, [107].

The main objectives set out by the Spanish Government and presented in [105, 107, 104] are summarized in Table 20.

Table 20: Spain's PNIEC 2023-2030 Key Energy Targets

Target Category	2030 Target
GHG Emissions Reduction	32% vs 1990
Renewables in Final Energy Consumption	48%
Energy Efficiency Improvement	43% in final energy terms
Renewable Electricity in Total Generation	81% share
Energy Independence	50% reduction in external energy
Total Installed Electricity Capacity	214 GW
Renewable Installed Capacity	160 GW
Wind Generation Capacity	62 GW (3 GW offshore)
Solar PV Capacity	76 GW (19 GW self-consumption)
Energy Storage Capacity	22.5 GW
Green Hydrogen Electrolyzer Capacity	12 GW
Self-consumption Share of Electricity Demand	11%

Although Spain's targets demonstrate a strong national commitment to decarbonization and position the country as a leader in the energy transition, recent events, such as the Iberian blackout in April 2025, provide a critical real-world illustration of the challenges inherent in grid stability in systems with high renewable penetration [108, 109]. The blackout, which occurred when renewable sources accounted for 78% of generation, highlighted a significant deficiency in ancillary services, particularly frequency regulation and inertia, traditionally provided by conventional synchronous generators. This experience underscores that the successful realization of Spain's ambitious targets is not solely dependent on achieving installed renewable capacity goals. In addition, it requires the rapid deployment of grid-forming technologies (e.g., advanced inverters capable of providing synthetic inertia) and the implementation of highly flexible grid management solutions to ensure system stability and resilience in a predominantly renewable energy environment.

B.2 Impact of Electrification on Low Voltage Networks

The critical need for a smarter, more adaptable grid brings the focus to the distribution level, where the rapid electrification of energy consumption is fundamentally altering its operational dynamics. Traditionally passive and designed for unidirectional power flow from the substation to the consumer, these networks are now facing unprecedented technical challenges that threaten power quality, reliability, and asset integrity. This section provides a state of the art analysis of these critical impacts.

B.2.1 Voltage Management Challenges

Voltage management in LV networks has become a significant challenge due to the bidirectional and variable nature of power flows introduced by distributed generation and new high-power loads [110, 111].The simultaneous integration of both generation and demand-side technologies creates two opposing yet equally problematic voltage deviation scenarios:

- **Undervoltage**, due to the widespread adoption of EVs, particularly when charging is uncoordinated and concentrated in residential areas, imposes substantial and often simultaneous load increases on LV feeders [112]. Similarly, the growing deployment of HP, can lead to high localized consumption in winter months, [113]. When multiple EV chargers or HPs are connected to the same feeder, especially near its end, the aggregated current draw can result in excessive voltage drops along the line and at the Point of Common Coupling (PCC). Such undervoltage conditions may degrade the performance of sensitive electronic equipment. Due to reduced voltage levels, to deliver the same power requires higher current , which not only stresses the protection systems but also increases the risk of thermal overloading and potential damage to both customer and grid-side equipment.
- **Overvoltage** due to high energy injection to the grid: Conversely, high penetration of generation technologies, such as rooftop solar PV systems, especially during periods of high irradiance and low local demand (e.g., midday on weekends), injects significant amounts of power into the LV network. If the local load is insufficient to absorb this power, the excess energy flows back towards the substation, causing voltage levels along the feeder to rise above statutory limits [110, 23]. This overvoltage can lead to premature degradation of electrical equipment, malfunction of sensitive appliances, and can force PV inverters to curtail their output (PV curtailment) to prevent damage or maintain grid code compliance, thereby wasting clean energy and reducing economic returns for prosumers.
- **Phase unbalance:** Another significant challenge for DSOs is the increasing phase unbalance caused by the proliferation of high-power single-phase devices in LV networks. In accordance with current regulatory frameworks, loads and generation units below 15 kW are typically connected to the grid via single-phase configurations. This includes a large share of residential PV self-consumption systems and most home-base EV chargers, which often rely on single-phase inverters. The growing penetration of these asymmetrically connected devices exacerbates phase loading discrepancies, leading to voltage unbalance, increased neutral conductor currents, and elevated system losses. Voltage unbalance not only affects the efficiency and lifespan of electrical equipment but can also interfere with the reliable operation of protection systems.

B.2.2 Capacity Constraints

The significant increase in electricity demand from EVs and HPs, combined with reverse power flows from distributed PV, is pushing LV network assets beyond their thermal design limits, leading to capacity constraints and accelerating asset degradation. [23, 114].

Distribution transformers are among the most critical and costly assets in the LV network, and they are particularly vulnerable to the stresses introduced by the electrification of energy demand. Traditionally, these transformers were sized based on historical peak load data; however, the growing penetration of DER is causing these historical baselines to be exceeded, [115]. Frequent overloading can lead to the overheating of transformer windings, accelerating the degradation of insulation materials. This thermal stress reduces the operational lifespan of the asset, increases the probability of premature failure, and ultimately results in higher maintenance costs, unplanned replacements, and service interruptions, [114].

Additionally, the conductors in LV feeders are also increasingly operating close to their thermal limitations. Increased current flows from both new loads and power injected from DERs can cause conductors to overheat, leading to increased resistive losses (I^2R), reduced efficiency, and potential damage to insulation material [116]. Overheating can also cause sag in overhead lines and weaken connections, increasing the risk of faults and localized outages. The issue is exacerbated in older networks where cables may already be operating closer to their limits.

The persistent thermal stress on transformers and cables directly translates to accelerated aging and increased failure rate. The rate of insulation degradation in transformers and cables is highly sensitive to temperature. Operating assets above their rated temperature significantly reduces their expected lifespan [116]. This creates a hidden cost for DSOs, as assets that were expected to last for decades may require replacement much sooner. Furthermore, as insulation degrades, the risk of dielectric breakdown and subsequent failure increases dramatically. The increased stress on network assets directly correlates with increased safety concerns, as overheating equipment can pose safety risks, including fire hazards, if not properly managed.

B.2.3 Power Quality & Protection Coordination

The increasing proliferation of power electronic-interfaced devices in LV networks significantly impacts power quality and introduces complex challenges for traditional protection schemes [117].

Modern electrified loads and generators predominantly utilize power electronic converters to interface with the grid. While essential for their operation, these converters are non-linear loads and sources, leading to which are capable of heavily distorting and compromising the stability of the network, [118]. The presence of harmonics results in overall voltage and current waveforms that deviate from ideal sinusoids, quantified by Total Harmonic Distortion (THD). Maintaining THD within acceptable limits (e.g., IEEE 519) [119] is crucial for grid health and compatibility.

Furthermore, in many LV networks, particularly in residential areas, loads are predominantly single-phase and often unevenly distributed across the three phases. The addition of new high-power single-phase loads like residential EV chargers and HPs, along with single-phase PV installations, exacerbates load imbalance [120]. Unevenly distributed single-phase loads, especially with the influx of new electrified devices, cause voltage and power imbalances at consumer premises. This means different phases experience unequal voltage drops, which can severely impact three-phase equipment and damage the neutral conductor.

Beyond power and voltage quality, the presence of DER fundamentally challenges established protection coordination strategies in LV networks. Traditionally, protection devices like fuses and circuit breakers are designed for radial grids where fault currents flow unidirectionally from the substation [117, 121]. However, with DER, a fault on a feeder can receive current contributions from both the upstream substation and the DER themselves, creating bidirectional fault currents, complicating fault detection. It can lead to "blinding of protection," where the fault current seen by an upstream device is reduced, potentially preventing it from operating or causing dangerous delays. Conversely, "sympathetic tripping" can occur, where a DG system injects current during a fault on an adjacent feeder, causing unrelated protection devices to trip unnecessarily, leading to wider outages. The dynamic environment caused by poorly supervised DER may also disrupt the coordination and selectivity between different protective devices, resulting in incorrect isolation of faulty sections and prolonged service interruptions.

Further compounding these protection challenges are islanding detection and the fault current characteristics of inverter-based DERs, [122]. Islanding, where a section of the grid remains energized by DERs after disconnecting from the main grid, poses serious safety risks to utility workers and can damage equipment; accurately and quickly detecting this condition remains a complex task. Additionally, unlike conventional synchronous generators, inverter-based DERs typically limit their fault current contribution to protect their sensitive power electronics [117]. This means they produce much lower fault current levels, making it difficult for traditional overcurrent protection devices to reliably detect and clear faults, especially those occurring at a distance from the substation.

B.2.4 Limitations of Traditional Solutions

Historically, DSOs have relied on a limited set of conventional techniques to manage voltage and capacity constraints in LV networks, mainly traditional infrastructure upgrades such as increasing conductor cross-sections, shortening feeder lengths, or installing new transformers. While effective, these solutions are capital-intensive, time-consuming (due to planning, permitting, and construction), and inherently static. They do not offer the dynamic flexibility required to respond to the fluctuating nature of modern loads and generation and can lead to over-dimensioned assets that are underutilized for much of their lifespan [123]. In some instances, operators have installed fixed capacitors or reactances in the network. These devices can be installed to provide reactive power support. Altough effective, they offer only fixed compensation and are not adaptive to the dynamic voltage needs of a highly variable LV network, potentially leading to over- or under-compensation under different operating conditions [124].

Traditional feeder capacity assessments primarily consider unidirectional peak load. However, the presence of DERs introduces bidirectional power flow, complicating capacity calculations. While PV injection can locally reduce net demand on a feeder, it can also lead to reverse power flow into the upstream network, potentially overloading upstream transformers or even MV feeders if not properly managed [23]. This change in paradigm requires DSOs to reconsider capacity not just based on "forward" load, but also "reverse" power flow capabilities. Another major concern would be that the effective hosting capacity of a feeder is no longer static but dynamically influenced by time of day, weather conditions, load profiles, and the operational status of DERs. Static planning approaches are insufficient to capture this complexity [125]. Without the required tools to accurately asses the dynamic capacity limits, DSOs risk either under-investing, leading to reliability issues, or over-investing in costly and unnecessary reinforcements.

The increasing electrification of the economy is leading to higher loading levels in MV feeders, particularly in rural areas where infrastructure was originally designed for lower demand. In many of these cases, the installation of new loads or generation requires the uprating of the primary fuse at the feeder head. However, increasing the fuse rating can reduce the overall selectivity and protection coverage, especially in long radial lines, leaving downstream segments partially or completely unprotected.

To mitigate this issue, network operators may need to either reinforce conductor cross-sections or install intermediate protection devices, options that introduce further complexity in coordination schemes and may require remote supervision or automation for effective fault management. In rural grids, alternative supply paths are often unavailable or prohibitively expensive. In this context, the transition towards digital protection systems provides greater flexibility, visibility, and adaptive coordination capabilities, thus enhancing safety and operational reliability under evolving grid conditions.

The transition to a decentralized, renewable-dominated grid exposes inherent vulnerabilities in the traditional grid architecture. This implies that "smart" solutions are not just about improving efficiency but are becoming fundamental for maintaining the basic functionality and reliability of the grid. The network's ability to maintain stable voltage and frequency, along with acceptable power quality, is increasingly challenged by the dynamic and often unpredictable nature of DERs.

ANNEX C. High-level Network Analysis

C.1 Distance to Secondary Substation

The first parameter evaluated would be the electrical distance from the SS to the master MDB. It is selected because line length plays a pivotal role in network performance. Longer electrical lines inherently exhibit a higher probability of faults, due to the presence of a higher number of clients connected to it with increased chance of outages effecting other users, increased energy losses due to resistance, and greater energy flow, making their control and operation inherently more challenging. Furthermore, fault localization and subsequent repair are typically more complex and time-consuming on extended lines.

The lines were classified in 4 categories based on their length:

- **Short:** Below 200 meters.
- **Medium:** Between 200 and 500 meters.
- **Long:** Between 500 and 1000 meters.
- **Very Long:** Above 1000 meters.

Analysis of the dataset revealed that the majority of lines were of short length, with a progressive decline in frequency as line length increased. Instances of LV lines exceeding 1000 meters were found to be exceptionally uncommon, thereby suggesting a predominantly compact configuration of the LV network. Notably, this spatial distribution did not correspond to the distribution of affected clients. The highest number of affected clients was associated with lines of medium length, rather than with the shortest segments. Moreover, the ratio of affected clients to the total number of lines was observed to be lowest among the shortest lines, thereby underscoring the operational and reliability challenges posed by longer line segments.

The findings discussed herein are visually represented in Figure 14.

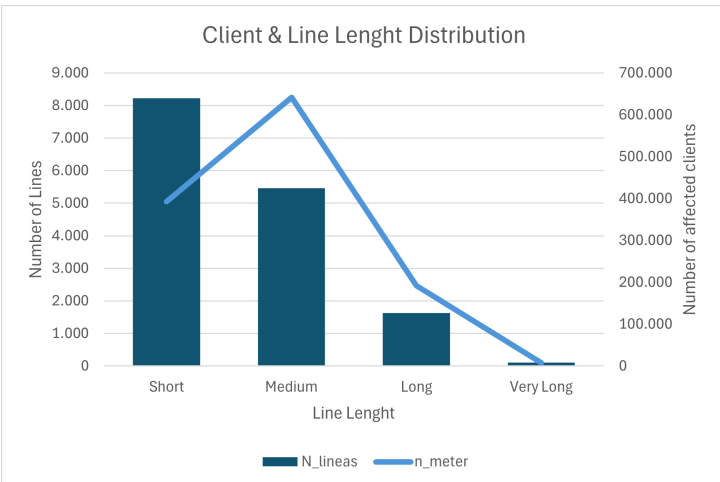


Figure 14: Number of Affected Clients & Line Distribution based on Line Length

The analysis clearly demonstrates a positive correlation between line length and both the number of recorded events (N_{events}) and the event-to-meter ratio ($r_{meter\ ev}$). Specifically, N_{events} increases from approximately 30 in short lines to values exceeding 80 in very long lines, while $r_{meter\ ev}$ rises from 75% to over 90% across the same range. Interestingly, overvoltage events were observed to occur more frequently in short lines. This phenomenon may be attributed to the lower impedance of shorter conductors, which limits their capacity to buffer voltage fluctuations, particularly in the presence of reactive power flows or PV generation. In contrast, the incidence of undervoltage is much more prevalent in very long lines, likely due to cumulative voltage drops along extended feeders. This effect could be further amplified under peak load conditions and by the integration of demand-side DERs. With respect to event duration (Dur_{events}), the data indicate a relatively stable trend across varying line lengths, although a slight increase in duration is noted for undervoltage events.

The results discussed in this section are illustrated in Figure 15.

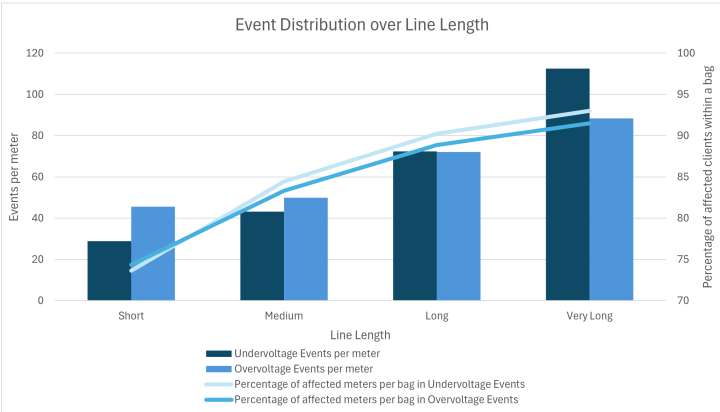


Figure 15: Events Distribution and Prevalence based on Line Length

C.2 Presence of Generation

With respect to the presence of generation capacity, it was determined that only 6.94% of all MDBs were equipped with generation capabilities. Nevertheless, due to the clustering methodology employed in the formation of micro-clusters, a substantially higher proportion, 31.30%, contained at least one MDB with generation. This discrepancy underscores the broader influence that proximate generation sources can exert on neighboring clients and installations. Several notable patterns emerged in association with these generation-equipped installations, offering further insight into their systemic impact.

A critical observation from the analysis is that meters associated with installations possessing local generation capacity exhibited, on average, 13.88 more recorded events (N_{events}) than those without such capacity. This means that clients connected to these installations experienced over 14 additional overvoltage events compared to those that experienced undervoltage events. Furthermore, all other evaluated metrics were significantly elevated in installations with generation, reinforcing the conclusion that the presence of generation increases the likelihood of VE detection. This finding underscores the operational challenges associated with integrating Distributed Energy Resources (DERs) into existing distribution networks, particularly in the absence of adequate control mechanisms. At the aggregate level, overvoltage events emerged as the predominant disturbance type, occurring at a frequency 2.3 times greater than that of undervoltage events.

The results highlighted in this paragraphs are represented in Figure 15.

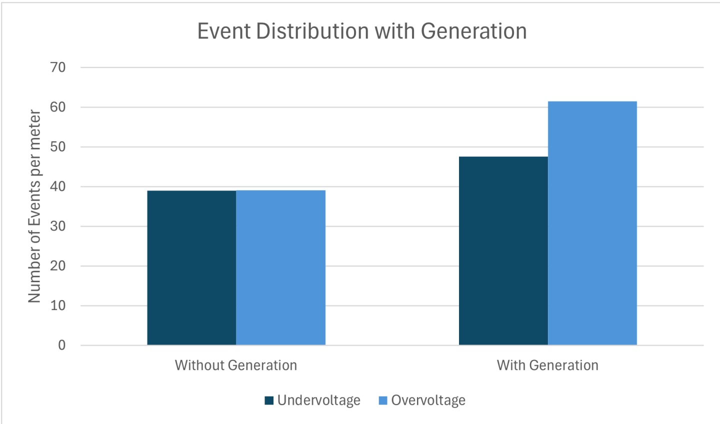


Figure 16: Events Distribution and Prevalence based onthe Presence of Generation

A key insight from the event characterization analysis is that the average duration of undervoltage events consistently exceeds that of overvoltage events across all classifications, irrespective of the presence of generation or the temporal period considered. Specifically, undervoltage events exhibit durations within the range of [560–600] seconds, whereas overvoltage events are typically confined to a shorter duration range of [450–480] seconds. This disparity underscores the inherent variability associated with DER generation, particularly PV installations, whose fluctuating output profiles contribute to transient voltage excursions. In contrast, undervoltage events are more frequently attributed to sustained overload conditions on the demand side, which tend to persist over longer intervals. This distinction highlights the differing operational dynamics and mitigation challenges posed by each event type.

Figure 18 showcases the average event duration against the presence of generation and the two analyzed periods.

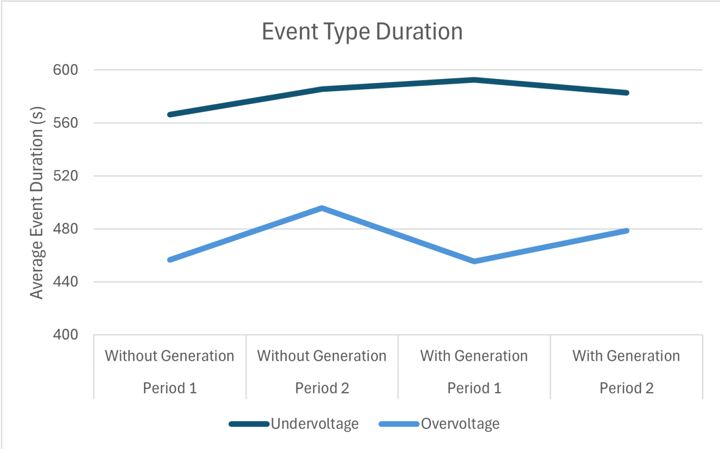


Figure 17: Average Event Duration

C.3 Characterization of MDBs with Generation

Further granular analysis of MDBs with generation revealed nuanced patterns. The following classification was made to differentiate micro-clusters with varying generating power.

- **Low Power:** for micro-clusters below 25kW.
- **Medium Power:** between 25 and 100 kW.
- **High Power:** between 100kW and 200 kW.
- **Very High Power:** above 200kW.

As anticipated, the majority of micro-clusters were found to possess less than 25 kW of installed power, accounting for 40% of the total. These micro-clusters correspond to scenarios characterized by minimal DER penetration, where only a small proportion of customers have adopted PV installations, typically indicative of the early stages of DER integration. Micro-clusters classified as medium power represent a transitional state between the current configuration of the grid and its anticipated future, with approximately 34% of customers exhibiting this generation capacity. Notably, a substantial portion of the network, exceeding 25%, comprises micro-clusters with generation levels above 100 kW, reflecting significant advancements in grid modernization and the integration of DER.

In micro-clusters characterized by low generation capacity, undervoltage and overvoltage events exhibited comparable significance, both in terms of aggregate frequency and the number of affected meters. However, as generation capacity increased (above medium power) a strong correlation was observed between higher generation levels and the emergence of extreme values in both the duration and frequency of VEs. This escalation was accompanied by a widening disparity between overvoltage and undervoltage events, with a pronounced increase in the incidence of overvoltage events. As the amount of power injected into the network by DER increases, whether through the deployment of large individual units or the dense concentration of smaller units within a confined area, the predominance of overvoltage events becomes increasingly evident. This trend presents significant operational challenges for grid operators, as high penetration of PV systems can exacerbate operational challenges, potentially contributing to reverse power flow conditions that are not adequately mitigated by existing grid infrastructure or control strategies.

The issues discussed above are visually represented in Figure 18.

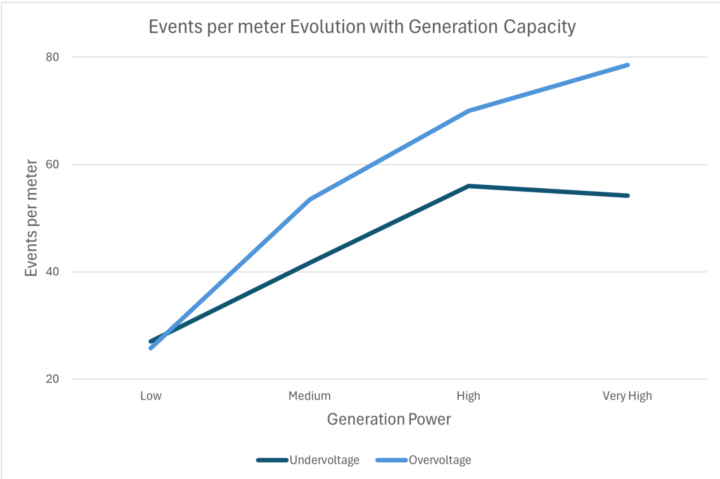


Figure 18: Events per meter Evolution with Generation Capacity

C.4 Number of Meters & Line and Events

The analysis revealed that the number of MDBS per SS and per line is relatively homogeneous across different categories of VEs. However, overvoltage events consistently involved a greater number of customers compared to undervoltage events, indicating a broader impact on QoS when overvoltages occur. A key finding was that the average duration of events tended to decrease as the number of lines and meters increased. This trend may be attributed to operational prioritization by the utility, wherein incidents affecting a larger customer base are addressed more rapidly through expedited resource allocation, resulting in shorter resolution times. Conversely, a higher number of lines was positively correlated with an increased number of events, suggesting that disturbances affecting upstream MDBs within a feeder propagate downstream. This cascading effect underscores the strategic importance of prioritizing investments in upstream MDBs, those located closer to the SS, in order to maximize the positive impact on the entire feeder and mitigate widespread service disruptions.

Furthermore, the network characterization indicated that most SSs are connected to a relatively small number of meters, although a minority of SSs serve a disproportionately high number of connections, reflecting heterogeneous load densities across the network. The majority of SSs were identified as small-scale installations with a single line, representing approximately 40% of all SSs. However, these installations accounted for only 7% of the total number of events and their cumulative duration. In contrast, only 13% of SSs were found to have five or more lines, yet these accounted for 40% of all recorded events. This disparity highlights the structural differences within the dataset: while most SSs are small and affect a limited number of clients, a small subset of large SSs serves a substantial portion of the customer base and experiences the majority of VEs. These events are often the result of cumulative disturbances and the propagation of outages, leading to voltage oscillations and diminished QoS.

The issues discussed in this section are illustrated in Figure 19.

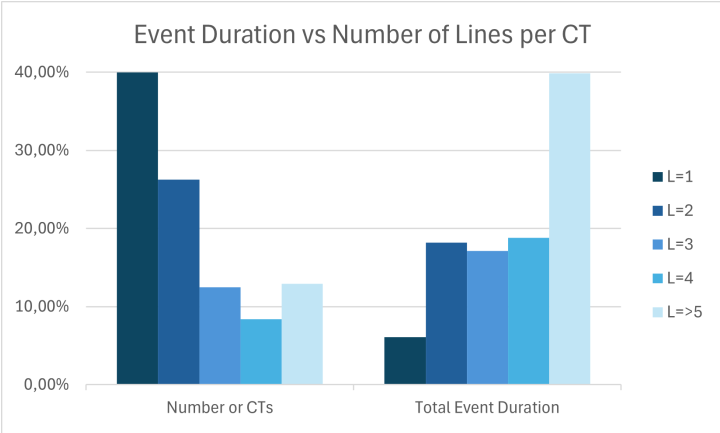


Figure 19: Events per meter Evolution with Generation Capacity

C.5 Temporal Distribution of Events

Despite the aggregation of data on a monthly basis, the analysis of the one-year dataset did not reveal any discernible or consistent temporal trends in the occurrence of VEs. No seasonal or monthly patterns were identified. Due to the computational intensity of the algorithm used for classifying events and meters into micro-clusters, it was not feasible to extend the analysis to a longer temporal horizon within the available time frame. It is plausible that such temporal patterns, potentially influenced by seasonal load variations, meteorological conditions, or the diurnal cycles of renewable energy generation, may become evident in a more extensive dataset spanning multiple years and with a more granular approach. Accordingly, further research utilizing a multi-year dataset is recommended to investigate the presence of any underlying temporal correlations.

ANNEX D. Characterization of i-DE's Dataset

The database employed for this analysis provides detailed information for each installation. Key identifiers include the SS code (COD_INSTAL), which uniquely identifies the secondary substation, and the line code (COD_LINEA_BT), which pinpoints the specific electrical line connected to that SS where the Main LV Distribution Box (MDB) is located. Each line is allocated an specific number within each SS, (NUM_LINEA_BT). The line length (meters) from the SS to the MDB is also recorded (CAN_DIST). Each micro-cluster within a SS is assigned a unique micro-cluster identifier (ID_BOLSA), resetting to 0 with every new SS. The MDB is also identified by a unique code (COD_CGP), with an additional column indicating if it is the master MDB for the micro-cluster, (CGP_MAESTRA) with the MDB code if the MDB is the master and a null value if it is not. Information regarding local generation capacity is captured in kW (MAX_VAL_AE). A null or 0 value in this field denotes the absence of local generation capacity. Furthermore the total number of smart meters connected to a specific MDB is also recorded, (CAN_METER) providing a measure of the customer base served by that point.

Data concerning VEs are aggregated on a monthly basis. For each month, the dataset includes the month of occurrence (MONTH), the cumulative duration (minutes) of all events recorded within that month (EVENT_DUR), and the total count of all recorded events (EVENT_COUNT). The total number of unique customers impacted by any VE during the month is also quantified (METER_COUNT), directly reflecting the scale of service disruption. Events are categorized by in two main categories as either overvoltage or undervoltage (EVENT_TYPE). It is important to note that the severity or importance of the event is not categorized in the dataset besides the event duration time. **Duration time, number of events and affected customers** are the main metrics used in this project to quantify the criticality of installations.

Table 21 shows the an example window with the initial untreated data.

Table 21: Initial Window with Untreated Data

COD_INSTAL	COD_LINEA_BT	ID_BOLSA	COD_MDB	CGP_MAESTRA
Cod_CT_1	Cod_LBT_1	7	Cod_CGP_1	Cod_CGP_1
Cod_CT_2	Cod_LBT_2	4	Cod_CGP_2	-
Cod_CT_3	Cod_LBT_3	0	Cod_CGP_3	-
Cod_CT_4	Cod_LBT_4	1	Cod_CGP_4	Cod_CGP_4
Cod_CT_5	Cod_LBT_5	1	Cod_CGP_5	-

CAN_DIST	NUM_LINEA_BT	MAX_VAL_AE	CAN_METER	MONTH
172,46	9	0	25	01/02/2025
566,08	6	0	2	01/11/2024
112,52	3	0	10	01/12/2024
592,12	1	3,481	1	01/05/2024
387,8	2	0	1	01/03/2025

EVENT_DUR	EVENT_COUNT	METER_COUNT	EVENT_TYPE
124575	50	2	Undervoltage
27290	70	1	Overvoltage
8010	40	2	Overvoltage
274685	376	1	Overvoltage
126078	757	1	Overvoltage

ANNEX E. Status of Digitalization in Spain

The landscape of digitalization in Spain's main electricity distributors shows a firm commitment to modernizing their grids, albeit with specific approaches and projects that reflect their strategic and operational particularities. In this section the main projects and objectives of the main 5 distributors in Spain, which account for approximately 29 Mclients and most of the national territory, are reviewed.

E.1 Endesa (e-distribución)

Endesa, through its grid subsidiary e-distribución, is accelerating the digitalization of its electrical infrastructure. The company has presented projects worth 412 M€within the framework of the grid digitalization initiative of the PRTR, with 50% co-financing from the Next Generation EU Funds [62]. e-distribución's total investment for the 2021-2023 triennium amounts to 2.6 B€, of which over 1.2 B€will be allocated to improving the electrical grid and supply quality for its 12.3 Mcustomers.

Investment is concentrated on the development of SGs. This includes the deployment of 3D modeling devices, virtual and augmented reality of grid infrastructure, using aerial and terrestrial mapping. A central element of its strategy is the creation of a digital twin of the distribution grid, an exact virtual replica that is constantly updated in real-time with IoT data. [65, 66].

The use of AI and drones is prominent in their projects. "Aerial-Core" focuses on developing an integrated aerial cognitive drone with capabilities in operation, manipulation of grid elements with a robotic arm, with the objective of decreasing direct human interaction. "Smart5Grid" aims to delimit safe zones volumetrically, monitoring field technicians with a private 5G network. The "Resisto" project enhances electrical grid resilience in Doñana National Park using sensors, prevention algorithms, and autonomous drones to minimize the impact of meteorological phenomena.

Investments are also allocated to the sensorization of distribution centers, with equipment in MV and LV transformers [63]. Regarding telecontrol, e-distribución has implemented over 2,500 remote controls in the Canary Islands, with the expectation of reaching 2,729 telecontrolled MV installations by the end of 2024. This 32.8 Meuro investment over the last five years has resulted in a 49% reduction in incident response time in the islands, surpassing the national average of 43% [68].

For data analysis and applications, the MONICA project, co-financed by the European Regional Development Fund (ERDF), has monitored over 10 Mdaily data points on grid operation. This has enabled 50 actions to improve supply quality and laid the groundwork for preventive and predictive maintenance that anticipates potential failures [66]. The e-distribución mobile application offers customers the ability to provide readings, consult contract requests, manage connections, report fraud, review consumption history, and access an outage map [67].

E.2 Iberdrola (i-DE)

Iberdrola, through its distributor i-DE, has positioned innovation and digitalization as strategic pillars. The company aims to be a pioneer in flexibility and consolidate itself as an active DSO, participating in various European projects to incentivize flexibility services [73, 70]. Its Global SGs Innovation Hub (GSGIH) has been established as a reference center for innovation applied to grids, with the objective of improving customer service and expanding the SG and digitalization model.

Iberdrola has made significant investments in digitalization. By 2022, it had allocated over 100€Mto innovation projects for the digitalization of its electrical grids, with 32 M€specifically for initiatives in Spain through i-DE [69]. In 2024, digitalization investment for all its activities amounted to 290 M€. At the group level, Iberdrola made total investments of 17 B€in 2024, with 9.2 B€in ongoing projects expected to be launched in 2025 and 2026.

i-DE is actively extending digitalization to the LV grid through the "Low Voltage Management Model" project [70]. This project is structured into three key areas:

1. **Advanced Low Voltage Supervision:** Involves the deployment of digital equipment to obtain phase-level information for voltage and current in each LV line.

2. **Low Voltage Information System (e-LVIS):** This control system, with workstations in Operation Centers and mobile device access, enables local an improved LV network operation and maintenance.

3. **Improved Low Voltage Management:** Focuses on integrating new digitalized information into existing processes, enabling active and predictive network maintenance and the optimization of customer voltages.

The digitalization of Iberdrola's grid has equipped centers with new equipment to monitor installation conditions and critical components, such as MV cells, LV panels, and digital equipment [72]. The "SensoCeT" project (Intelligent Sensors for Transformation Centers) aims to optimize operations by incorporating digitalization and predictive maintenance technologies in distribution network Transformation Centers (CT) [70]. Transport electrification, through EVs, is considered the most effective way to decarbonize this sector [126]. The "Low Voltage Management Model" project is the basis for future services that will include monitoring and management of EV charging, distributed generation, and self-consumption.

i-DE uses Big Data to offer personalized solutions and promote energy transition, facilitating the connection of more renewable energies to the grid [73]. The i-DE mobile application allows users to view and download their daily, weekly, and monthly consumption, perform power measurements, check the status of their Power Control Switch (ICP) and reconnect it in case of overload, report potential fraud, and receive information on outages or scheduled cuts [71].

E.3 Naturgy (UFD)

UFD invested 450 M€in 2023 for the digitalization and improvement of its grid in Spain, representing a 59% increase over the previous year [74]. Over the last five years, UFD's investment to improve the quality of its services has exceeded 1.48 B€, resulting in a 27% improvement in QoS. For 2024 onward, the distributor plans to focus on innovation in the digitalization of its transformation grids. Additionally, UFD plans to invest 1.33 B€until 2028 to reinforce and digitalize its electrical grid in Spain, with an allocation of 317 M€in 2025 alone.

A prominent project is DALI (Drone & AI Line Inspection), in which UFD has partnered with eSmart Systems to fully automate the inspection of its overhead HV and MV lines using drones and AI [77]. eSmart Systems' "Grid Vision®" software uses 30 AI models trained with over 6 Mglobal images, allowing for safer, more precise, and cost-efficient inspections, as well as reducing the environmental footprint by eliminating unnecessary travel.

Another relevant project is TAIS (Telesupervision AI System), through which UFD plans to intensify the adoption of AI in all its operations and processes. TAIS uses AI algorithms for supervising activities and operations in UFD's facilities, enabling more effective and proactive supervision [78]. Naturgy seeks to digitalize the value chain at all voltage levels of its electrical grid, contributing to greater efficiency and flexibility to integrate DERs. UFD's improvement measures have also focused on advancing tele-metering and remote management of supply points, as well as telecontrol and sensorization of grids [76].

Regarding data analysis and recollection, meter data is transmitted via PLC technology to the concentrator in the transformation center, and from there wirelessly to the distributor's systems. Furthermore, UFD's Digital Services Platform is a comprehensive space where users can perform all their transactions from any device. This platform offers detailed information on daily, monthly, or hourly electricity consumption, allows checking meter status and reactivating the ICP if inactive [75]. Additionally, UFD has launched a comparison tool to help customers understand their consumption peaks by time slots and adjust them to their contracted power, which can lead to savings on their bill.

E.4 EDP (E-Redes & Viesgo)

EDP's electricity distribution business in Spain has undergone significant consolidation with the acquisition of Viesgo in 2020 for 2.7 B€, after obtaining all regulatory permits [127]. This operation allowed EDP to control almost 100% of distribution in Asturias and consolidate a network of 1.3 M supply points and 52,177 kilometers of grid. As a result, Viesgo's digitalization initiatives in electricity distribution are now integrated under the EDP umbrella, primarily through its subsidiary E-Redes.

The EDP Group considers the digitalization of the electrical grid a strategic pillar for facing the energy transition, aiming to equip grids with greater intelligence and flexibility [79]. E-Redes is implementing a new generation of control and data acquisition centers. It uses AI for planning and dispatch management, which increases efficiency in field operations. This AI capability at the core of its operations underscores progress towards more predictive and optimized grid management.

The company focuses on remote management and automated control solutions, complemented by grid sensorization (IoT) for maintenance optimization and early fault detection [79]. EDP LABELEC, EDP's innovation laboratory, has a high-tech infrastructure that emulates a real electrical grid, including up to four LV grids with 400 smart metering devices. This unique environment allows testing equipment for functionality, performance, and interoperability [82]. E-Redes is a pioneer in the use of interlocks between MV installations using the IEC61850 protocol to accelerate protections, which improves efficiency and reduces response times.

In an effort to improve safety and reduce environmental impact, E-Redes has replaced approximately 100 kilometers of bare LV overhead lines with RZ-type insulated conductors, minimizing the risk of fires and bird impacts. Additionally, the EDP Group has demonstrated its expertise in managing LV and MV grids by sending electrical distribution material to Ukraine for the reconstruction of its affected grids [80]. The E-Redes mobile application allows customers to manage their data, control their electricity consumption and power, send requests or complaints, consult their reading history, report breakdowns or fraud, and check for scheduled outages that affect them [81].

ANNEX F. Main Digitalization Technologies

F.1 Voltage Regulators

Comprise all devices which are capable for maintaining voltage levels within acceptable limits. These regulators come in two main types: active and passive, [13]. Active devices, such as static VAR compensators (SVCs) and dynamic voltage restorers, provide real-time, adaptive voltage support by injecting or absorbing reactive power based on grid conditions. Passive solutions, like shunt reactors or capacitor banks, offer fixed compensation to stabilize voltage. Both types help mitigate voltage sags, swells, and imbalances caused by variable loads or intermittent generation. Both have their merits and challenges. On the one hand, passive solutions are cheaper and easier to operate, however they lack responsiveness to rapid fluctuations. On the other hand, active solutions while more flexible, can introduce harmonic distortion if not properly filtered and need precise coordination requirements. These devices are explained in detail in Section 5.3.

F.2 Automation Devices

Automatization offers significant benefits by enhancing grid resilience, operational efficiency, and service reliability. Devices such as intelligent switches, reclosers, automated MDBs, and OLTC transformers enable real-time, autonomous control of the grid, reducing the need for manual intervention. These technologies quickly detect and isolate faults, restore service automatically, and maintain optimal voltage levels, which minimizes outage durations and improves power quality. For customers, this means fewer and shorter power interruptions, more stable electricity supply, and better protection for sensitive equipment. Utilities benefit from lower operational costs, improved safety, and greater flexibility in integrating renewable energy sources, [128]. However, challenges include the significant CAPEX associated with their deployment and the need for sophisticated communication infrastructure.

F.2.1 Intelligent Breakers and Reclosers

Intelligent LV breakers and reclosers (RECBT) are advanced switching devices designed to autonomously isolate faults and restore service in LV networks. Equipped with remote operation capabilities, they can be controlled from a central control center, eliminating the need for field crews to manually operate switches [129]. Traditionally installed at various points in the grid, a novel development is their integration into LV secondary distribution swithcboards (MDBs). This advancement enables DSOs to remotely manage assets and restore service to customers without dispatching maintenance teams. RECBTs combine advanced digital protection features with programmable logic for accurate fault detection and response. Their telecontrol functionality further enhances grid efficiency by enabling continuous remote monitoring and operation, reducing manual interventions and improving reliability.

The primary function of a RECBT is to detect fault currents and interrupt the circuit, with the capability to automatically restore service following momentary disturbances. Upon detection of a fault, the RECBT promptly disconnects the power supply and subsequently tests the line. If the fault is determined to be transient in nature, such as those caused by windblown branches or lightning strikes, the device automatically recloses and restores service. However, if the fault persists after a pre-defined number of reclose attempts (typically three), the RECBT enters a "lockout" state, maintaining the circuit open to indicate a permanent fault. In such cases, manual intervention by a maintenance crew is required to resolve the issue and reset the device. This self-healing functionality significantly reduces the faulted area, thereby enabling DSOs to more rapidly locate and address the issue. As a result, both the duration and frequency of service interruptions experienced by customers are minimized [130].

The deployment of RECBT technology represents a strategic initiative aimed at extending the advantages of advanced automation, previously limited to MV and HV networks, into the LV grid through the facilitation of meshed network configurations. Traditionally, LV distribution systems have operated in a radial topology, characterized by unidirectional power flow originating from the SS toward end-users. In contrast, meshed LV networks enable multiple power flow pathways, thereby enhancing operational resilience and flexibility. These characteristics are particularly critical for the efficient integration of high penetrations of DERs and for the effective management of bidirectional power flows within increasingly complex distribution systems.

The implementation of complex automated switching systems, faces several challenges. There is a lack of standardized industrial practices, which can lead to diverse design and operational philosophies [131]. The potential lack of alignment between different engineering disciplines (protection, power systems, automation) during design and programming can also introduce errors. Furthermore, the limited availability of complete systems for thorough testing and commissioning can hinder problem identification before large-scale deployment. Integration with legacy systems and existing communication protocols also represents a difficulty, as new digital technologies must be compatible or at least coexist with already installed infrastructure.

F.3 Sensorization & Advanced Supervision

These devices in the electric network comprise advanced sensors, smart meters, and integrated monitoring platforms that collect real-time data on voltage, current, power quality, and equipment status, [132]. These technologies, DSOs with unprecedented visibility into the operational state of the LV grid. By continuously monitoring grid parameters, DSOs can detect anomalies early, prevent outages, and balance loads more effectively. However, the deployment of these systems introduces challenges, including the management of vast data volumes, ensuring data accuracy and consistency, and implementing robust cybersecurity to protect sensitive infrastructure information.

Real-time data collection and processing are fundamental to the digitalization of the electrical grid, as effective and proactive network management depends on adequate system visibility. In this context, Advanced Low Voltage Supervision (SABT) emerges as a key technology for the detailed monitoring of LV switchboards and lines, [133]. The increased visibility of SABT allows for accurate diagnosis of network conditions. Furthermore, SABT supports LV telecontrol, enabling remote operation of specific network elements. Its scalability makes it suitable for a wide range of deployment scenarios, from small-scale applications to complex automation systems, positioning it as a flexible and powerful tool for advancing LV grid digitalization.

SABT offers real-time, high-resolution monitoring of key electrical parameters across individual feeders and bus bars, allows DOS unprecedented levels of visibility into their network. Some models even incorporate oscilloscope capabilities for detailed waveform analysis. SABT systems are capable of correctly detecting pre-fault indicators, such as hot spot detection, [134], severely limiting its impact on equipment and personnel improving safety and allowing for proactive maintenance strategies. They continuously assess power quality, monitoring phenomena such as flicker and voltage sags/swells, and ensuring compliance with international standards like EN 50160, [57].

In terms of energy management, SABT enables detailed tracking of consumption and flow on each line, which supports energy balancing and the identification of both technical and non-technical losses. Additionally, these systems support remote telecontrol of certain network elements and feature configurable alarms to alert operators of abnormal conditions in real time. Finally, SABT generates large volumes of operational and event data, which can be harnessed through advanced analytics, such as Big Data techniques or AI/ML tools to support informed decision-making and enhance grid efficiency and resilience.

The implementation and operation of SABT, while highly beneficial, are not without challenges. Increased connectivity and interactive devices generate a massive volume and variety of information that must be processed. Effective data management requires clear rules for information exchange and data processing. A shared responsibility model for public clouds and mechanisms for data protection, such as anonymization and aggregation, need to be established. New use cases, such as flexibility markets, further increase the complexity of information management.

Integration and interoperability are significant challenges. While SCADA integration is a benefit, interoperability requires compatibility between diverse devices and systems from multiple vendors, crucial to avoid vendor lock-in and foster competition. Cybersecurity is another fundamental concern. The increase in network "observability" drastically expands the exposed surface of the DSO, increasing the likelihood of critical assets being compromised. Integrating new equipment with traditional or "legacy" systems poses a challenge, as many old communication protocols used in electrical networks are obsolete in terms of cybersecurity. Coordinating the strict cybersecurity requirements of OT with the often more flexible requirements of IT is crucial to prevent cascading effects during incidents.

F.4 Protection Schemes

The increasing complexity and decentralization of power systems necessitate advanced protection schemes. Digital protection relays offer faster, more selective, and highly configurable protection compared to traditional electromechanical devices [135]. These relays can detect and isolate faults with millisecond precision, support remote configuration, and integrate seamlessly with DA systems. Advanced FCLs are another key technology, designed to limit the magnitude of fault currents, thereby protecting equipment and improving system stability. These devices are especially valuable in networks with high penetration of DER, where fault levels can exceed traditional design limits. However, with more complex devices, coordination of protection settings becomes increasingly complex to operate and configure [136].

Historically, protection in LV networks has relied on simple devices, primarily fuses. The capabilities of fuses are severely limited in the context of modern grid challenges. Fuses possess fixed time-current characteristics, rendering them unable to adapt to dynamic changes in fault current levels or network topology introduced by distributed generation [121]. Achieving optimal coordination and selectivity with fuses across complex LV networks is challenging, often leading to over-tripping and affecting larger areas than necessary during a fault. Furthermore, fuses are single-use devices that require manual replacement after each operation, resulting in prolonged outages and significant manual intervention. Traditional fuses are designed for unidirectional power flow and struggle to operate effectively with the complex and variable fault current contributions from multiple DER. Finally, certain inverter-based DG technologies contribute limited fault currents, making them difficult to detect reliably with traditional overcurrent-based fuse protection.

Digitalized protection schemes for LV networks offer several significant advantages. These systems provide precise and faster fault detection and isolation compared to electromechanical relays and fuses, minimizing equipment damage and improving grid stability. Modern digital protection systems can dynamically adjust their settings, such as tripping curves and thresholds, in real-time based on changes in network topology, operating conditions (e.g., grid-connected versus islanded microgrid mode), or variations in distributed generation output [117]. Directional fault detection is essential for bidirectional power flows, as digital protection can determine the direction of fault currents, ensuring selective isolation of only the faulty section, regardless of the fault current source [23]. Digitalized systems also utilize sophisticated algorithms and sensors to detect complex fault types, including high-impedance faults, intermittent faults, and those with low fault current contributions that are challenging for traditional methods. Similar to intelligent switches, digital protection systems can be remotely operated for reclosing and other operational maneuvers, reducing manual interventions. Future LV switchboards in transformation centers are envisioned to integrate advanced digital protection functionalities with real-time monitoring (like SABT), enabling a unified approach to protection and supervision. These integrate sensors and communication for comprehensive protection, monitoring, and control.

To fully realize the benefits of digitalized protection in the future grid, several changes are necessary from today's perspective. A fundamental shift is required from a simple, unidirectional, and static protection approach to a dynamic, adaptive, and bidirectional one, necessitating a rethinking of protection coordination for complex power flows. Reliable, high-speed, and secure communication links are fundamental to enable real-time data exchange between intelligent protection devices for adaptive coordination and self-healing functions [137]. The increased connectivity and intelligence of protection systems drastically expand the grid's attack surface, thus implementing stringent cybersecurity protocols, from device-level security to network segmentation and AI-driven threat detection, is paramount to protect critical infrastructure from cyber threats [32]. Developing and adhering to open standards, such as IEC 61850, is crucial to ensure seamless interoperability between various digital protection devices from different vendors, avoiding vendor lock-in and facilitating large-scale deployment. The complexity of digital protection systems requires new testing and commissioning methodologies, including real-time simulation and hardware-in-the-loop testing, to ensure their reliable operation in diverse scenarios. Supportive regulatory frameworks and strategic investments are also needed to incentivize DSOs to deploy these advanced, albeit often more costly, digital protection solutions.

ANNEX G. PlexigridSim Tool for Automated LV Network Simulation

The Plexigrid tool offers automated simulation and electrical calculation capabilities for LV networks, facilitating the digitalization and optimisation of electrical grids. This is particularly relevant in the context of i-DE's network operations. The tool's core functionality revolves around multifase analysis to address common distribution network challenges.

G.1 General Application Workflow & Algorithm

The general workflow of the Plexigrid application involves several key stages, starting with data input and progressing through automated simulation methodologies, critical test case selection, power flow solving, device placement, aggregated solution generation, and result exportation.

The simulation primarily requires the distribution network topology database and PQ (active and reactive power) profiles for the desired simulation period. The network topology is defined by the connections of switches and line segments linking the transformer's secondary to the network buses. The network is organised into multiple feeders, each representing a tree-like connection of buses that may include multiple laterals.

Customer loads are aggregated into load nodes whose PQ profiles are stored in CSV files, with each file containing multiple rows across two columns: the first for active power demand (kW) and the second for reactive power demand (kVAR). Positive values indicate power demand, while negative values represent power injection from generation. Each row corresponds to a specific time instant within the simulation period. The set of data used includes one year load profiles for each node. This amount covers all year seasons

Once inputs are defined, the automated methodology proceeds through a series of steps. Initially, phase balancing of demand at each connection point is an optional first stage, with results potentially saved for subsequent use. The second step may involve updating the phase assignment of demand based on the new energy injection location derived from the phase balancer.

Subsequently, the tool selects critical test cases to represent the network during the analysis. This selection is fully automated, based on the load duration curve. Ten representative points from the load duration curve are chosen to derive a linear equivalent. This approach significantly reduces simulation time while still addressing the primary test conditions. The power deviation for the load duration curve (Δp) is calculated as:

$$\Delta p = \frac{P_{agg,max} - P_{agg,min}}{\text{test\_count\_max}} \tag{14}$$

where $P_{agg,max}$ is the maximum aggregated active power demand, $P_{agg,min}$ is the minimum aggregated active power demand, and test_count_max is the maximum number of test cases. Similarly, for the unbalanced power percentage curve, the unbalanced power deviation (Δp_u) is calculated as:

$$\Delta p_u = \frac{P_{uagg,max} - P_{uagg,min}}{\text{test\_count\_max}} \tag{15}$$

where $P_{uagg,max}$ is the maximum power unbalance and $P_{uagg,min}$ is the minimum power unbalance.

Test cases are prioritized based on their duration time weight relative to the total reading time, and cases with a duration time percentage below the minimum tolerance are discarded. For each defined critical test case, the power flow solver evaluates the case under different conditions. Initially, the case is solved without modifications or devices to establish the original situation, assessing for two primary issues: unbalance and voltage limit violations. Unbalance detection relies on the AUF KPI for both the network and individual feeders. The AUF formula is shown in Equation 5. where V_{max} is the maximum voltage, V_{min} is the minimum voltage, and V_{avg} is the average voltage. If unbalances are detected, ZIGZAG reactors and iCOBT devices can be added for mitigation.

Voltage violation detection utilizes several KPIs: PUL, representing the percentage of undervoltage relative to the limit at the network or selected feeder's MDB; POL, indicating the percentage of overvoltage; NAVE, which is the average voltage deviation from the nominal value under undervoltage conditions; and PAVE, the average voltage deviation from the nominal value under overvoltage conditions. In instances of voltage violations, devices such as iTRAFO (OLTC Transformer) and iEBT (LV AT) can be utilized.

The placement of devices is contingent on the location of the MDB experiencing the most critical system violation. A maximum number of devices permitted for installation is considered a constraint. For ZIGZAG reactors, the MDB bus under the most critical condition is the appropriate location. For iCOBT and iEBT, the upstream line associated with the MDB bus under the most critical condition is preferred, specifically the midline between the MDB bus and the transformer's secondary side.

Upon resolution of all test cases, an aggregated solution is generated from the combined individual solutions, selecting common devices among them to achieve minimal violation under the constraint of maximum allowable cost. The aggregated solution is then exported as a zip file with a specific naming convention: `fix_{device name}_{device name}.zip`. Base case scenarios and solutions for all selected test cases are also exported as a zip file.

G.2 Equipment Modelling

The Plexigrid tool's database comprises eight tables: five for devices (CBT, iCOBT, iEBT, iTRAFO, ZIGZAG), two for line impedance and demand, and one for simulation configuration. The four primary equipment types and their modelling approaches are detailed below.

CBT (Fuse): The CBT is designed to ensure the protection of electrical components during fault conditions by assessing whether the area under its protection is adequately secured. The model evaluates protection based on the fuse's current-time curve and expected response time. It considers both three-phase and single-phase-to-neutral faults. It calculates the total short-circuit impedance (Z_{sc}) and fault current (I_{fault}), then determines the response time (T) from the CBT's current-time curve. Finally, it compares T with the expected time (T_c) to ascertain if the CBT responds within the expected range ("pass" or "fail").

Short-circuit impedance during a three-phase fault is given by

$$Z_{sc3} = Z_{s,ph} + Z_{ph} \tag{16}$$

For a single-phase-to-neutral fault, the short-circuit impedance is

$$Z_{sc1n} = Z_{s\_ph} + Z_{ph} + Z_n \tag{17}$$

Fault current is calculated as

$$I_{fault} = a\frac{V_{ph}}{Z_{sc}} \tag{18}$$

The response time is

$$T = f(TI_{curve}, I_{fault}) \tag{19}$$

Input parameters include system source voltage (V_1), line parameters (Z_1, Z_2), source impedance (Z_s), (T_c), CBT T-I curve (TI_{curve}), and fault type. This device is primarily used for fault protection and device sensitivity evaluation.

iCOBT: The iCOBT is engineered to balance phases by levelling the load and mitigating phase unbalance in the distribution system. It models a simplified shunt device that injects current to compensate for unbalance, calculating the apparent power injected at the PCC. It determines the average apparent power and the shunt apparent power that the iCOBT must inject. If the current injection exceeds a user-defined limit, the injected current is recalculated to remain within the limit.

The power injected by iCOBT is represented as:

$$\begin{bmatrix} P_{sha} + jQ_{sha} \\ P_{shb} + jQ_{shc} \\ P_{shc} + jQ_{shc} \end{bmatrix} = \begin{bmatrix} P_{avg} + jQ_{avg} \\ P_{avg} + jQ_{avg} \\ P_{avg} + jQ_{avg} \end{bmatrix} - \begin{bmatrix} P_a + jQ_a \\ P_b + jQ_b \\ P_c + jQ_c \end{bmatrix} = P_{sh} + jQ_{sh} \tag{20}$$

The injected current from iCOBT is

$$I_{sh,abc} = \left(\frac{P_{sh} + jQ_{sh}}{V_{sh,abcn}} \right) \tag{21}$$

Input parameters include maximum injected current limit, option to allow reactive power injection, system source voltage (V_s or V_1), source parameter (Z_s), line parameters (Z_1, Z_2), and customer demand (P, Q). Its preferred use is phase unbalance mitigation and load levelling.

iEBT: The iEBT is designed to stabilize the voltage across all three phases using ATs. It operates as a simplified AT with taps that automatically vary the number of turns to maintain the voltage at the nominal reference value. It calculates the required tap position based on the measured voltage signal at the target bus and the nominal reference voltage. The effective winding ratio per phase is

$$a = 1 \pm \text{Tap No} \times \Delta v_t \tag{22}$$

The output voltage per phase is:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} \frac{1}{a_{Ra}} & 0 & 0 \\ 0 & \frac{1}{a_{Rb}} & 0 \\ 0 & 0 & \frac{1}{a_{Rc}} \end{bmatrix} \begin{bmatrix} V_{An} \\ V_{Bn} \\ V_{Cn} \end{bmatrix} \tag{23}$$

The output current per phase is:

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} a_{Ra} & 0 & 0 \\ 0 & a_{Rb} & 0 \\ 0 & 0 & a_{Rc} \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \tag{24}$$

Input parameters include the number of turns (HV/LV side), resistance and reactance per AT phase, total number of taps, voltage step percentage, system source voltage (V_s), line parameters (Z_1, Z_2), customer demand (P, Q), and an optional manual tap position. Its preferred use is three-phase voltage stabilization.

One key difference with respect to the iTRAFO is that the in-line autotransformer can regulate each phase independently, as its regulator is electronic. In contrast, the iTRAFO, as implied by its designation OLTC, operates through on-load tap changing, utilizing the conventional tap positions of a traditional transformer.

iTRAFO: The iTRAFO is designed to regulate voltage at the monitored bus by adjusting the number of turns in the transformer's primary winding without interrupting power flow. It operates as a simplified on-load tap changer. The current model utilizes a delta-wye transformer with the tap changer on the primary side. The decision for the optimal tap position involves testing all possible positions, as tap movement across each phase is synchronised. The tap ratio at any position is $a = 1 \pm \text{Tap No.} \times \Delta v_t$.

The output voltage is

$$V_2 = \frac{1}{a} \times \frac{N_2}{N_1} \times V_1 - Z_T \left(a \frac{N_1}{N_2} I_1 \right) \tag{25}$$

The output current is

$$I_2 = a \times \frac{N_1}{N_2} \times I_1 \tag{26}$$

Input parameters include short-circuit impedance percentage ($Z_{sc}\%$), resistance-to-reactance ratio (R/X), transformer size (MVA), maximum number of taps up and down, voltage step percentage, transformer primary and secondary side voltages (V_H, V_{ct}), LV side base voltage (V_b), system source voltage (V_s), line parameters (Z_1, Z_2), customer demand (P, Q), and an optional manual tap position. Its preferred use is voltage regulation at the monitored bus.

ZIGZAG: ZZTs are specialized grounding devices used in three-phase power systems to provide a stable neutral point, suppress zero-sequence currents, and mitigate triplen harmonics (e.g., 3rd, 9th, 15th). Their unique winding configuration—interconnecting windings from different phases—creates a low-impedance path for zero-sequence currents while presenting high impedance to positive and negative sequence components. During unbalanced load or fault conditions, the transformer allows zero-sequence currents to flow to ground, stabilizing the system and protecting equipment. The core modeling relies on symmetrical component transformation:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_{An} \\ V_{Bn} \\ V_{Cn} \end{bmatrix} \quad \text{where } a = e^{j120^\circ} \tag{27}$$

The zero-sequence admittance is:

$$Y_{z0} = \frac{1}{Z_{z0}}, \quad \mathbf{Y}_{012} = \begin{bmatrix} Y_{z0} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{28}$$

Phase currents are recovered via inverse transformation, and the neutral current is:

$$I_n = -(I_a + I_b + I_c) \tag{29}$$

The input parameters required for the ZZT model are the short circuit impedance percentage of the ZZT (SC Z0% or Zsc%), the reactance to resistance ratio (X/R), the rated capacity of the transformer (SC kVA), the system source voltage (V_s or V_1), the impedance of the source (Z_s), the impedance of the lines (Z_1, Z_2), and the active and reactive power demand of the customer (P, Q).

G.3 Database for Calculation

The database is crucial for configuring parameters of all devices, line impedances, network demand, and simulation settings. It consists of eight tables:

- `cbt`: Parameters for the CBT (fuse) protection device.
- `iCOBT`: Parameters for the iCOBT device.
- `iEBT`: Parameters for the iEBT device.
- `iTRAFO`: Parameters for the iTRAFO on-load tap changer.
- `zigzag`: Parameters for the ZIGZAG reactor.
- `line_z`: Allows updating of network line impedance parameters.
- `power`: Establishes customer demand data (active and reactive power per phase).
- `sim`: Configures the simulation to be executed (number of iterations, error tolerance, voltage deviation limits).

The distribution network topology is defined by switch connections and line segments linking the transformer's secondary to the network buses, with the network organised into multiple feeders.

G.4 Utility in i-DE Context and Grid Digitalization

The Plexigrid tool integrates seamlessly with i-DE's new planning tool, ensuring full compatibility between both systems. While the current tool proposes improvements through device deployment in critical cases, the planning tool applies clustering techniques to classify customers and estimate the most critical scenarios, referred to as ADMD (After Diversity Maximum Demand). The critical cases generated by the planning tool follow the same format as those in this project, enabling direct import and analysis. Consequently, if a critical case identified by the planning tool cannot be addressed through additional network capacity, a solution based on the automation tool can be implemented.

This capability is essential for advancing network digitalization, supporting more efficient management, proactive issue detection, and optimized resource allocation. The advantages, as described above, include: (1) a balancing proposal tool, (2) annual selection of ten representative cases for analysis, thereby avoiding computations for all 365*24 scenarios, and (3) mathematical modelling of the solution, in contrast to the simplified modelling approach required in other contexts.

ANNEX H. Case Study Initial Metric Definition & Selection

The selection of use cases is conducted through the automated process integrated within the PlexigridSim software, as described in Section 3.2.4 and ANNEX G. This process identifies the base case for the application of digital solutions by analyzing network behavior across the study period. From the full set of scenarios, the algorithm selects the most representative situations based on voltage profiles and operational characteristics. Subsequently, the algorithm determines the most suitable digitalization strategies to address the identified network issues.

Figure 20 presents an example case selection along the load curve of one analyzed network. It illustrates how the methodology identifies representative scenarios based on network behavior, thereby validating the robustness of the automated selection process.

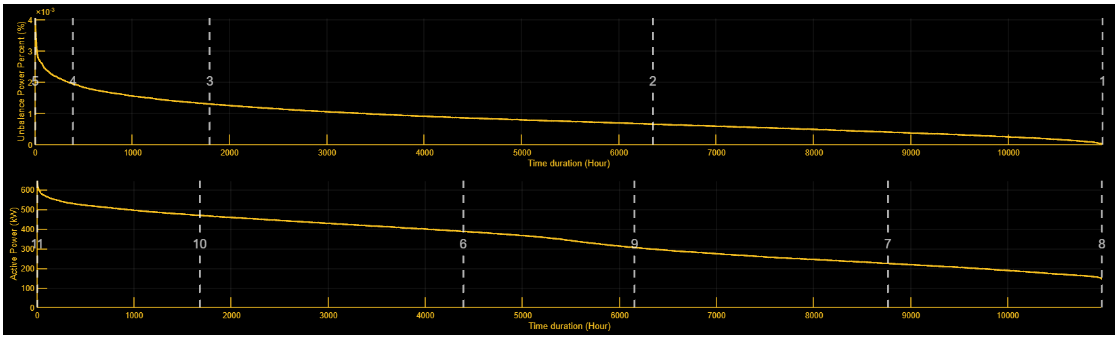


Figure 20: Example Load Curve Case Selection

Among the representative scenarios, the software tool presents a set of KPIs to analyze the performance of both the initial state of the network and the improvements achieved through the implementation of various digital solutions. These metrics are:

- **Cost:** total CAPEX of digitalization solutions. It helps consider the necessary investment to achieve the simulated solution. It also includes the replacement of fuses connected to the feeders of the grid, whose operational characteristics are not evaluated in this project.
- **AUF:** (Average Unbalance Factor) is a metric used to quantify the degree of phase unbalance in a three-phase power network. It represents the average deviation of the voltage magnitudes of each phase from the ideal balanced condition, where all three phases should have equal voltage magnitudes and be 120 degrees apart in phase angle. Unbalance condition is particularly important in LV distribution networks, where unbalanced loading is common due to uneven distribution of single-phase loads.
- **PUL & POL:** (Percentage of Under/Over Limit) indicates the proportion of buses within the network experiencing undervoltage or overvoltage issues. It reflects the number of clients affected by VE across the system, highlighting the extent of voltage quality problems within the network. The metric identifies every bus operating outside the ±15V or [215V-245V] range from the established 230V phase-neutral system voltage.

- **NAVE & PAVE:** (Negative/Positive Average Voltage Error) represent the average deviation of problematic buses from the 230V rated value. Indicates the mean severity and extent of voltage issues in the grid among the buses that suffer VE.

Each metric is conducted for the entire network and for each feeder of the SS; however, for this study, only the global performance of solution application across the entire network is considered. The system also provides all load flows, three-phase voltage and consumption results at all system buses, current intensities through buses, transformer metrics, and details of all applied digitalization solutions.

Once the system's load flows are executed and the baseline case is established, the system applies the digitalization solutions. Initially, it attempts to resolve the unbalance issues using a ZZT (**ZIGZAG**) and an active regulator or STATCOM (**iCOBT**) at buses exhibiting the highest AUF, to determine if solving the unbalance condition with these devices can resolve voltage issues. If the voltage issues are resolved with only these devices, the algorithm does not apply any more alternatives and moves on to the next case along the load curve. These two simulations will always be designated as Case 2 and Case 3, respectively, for each use case.

If voltage metrics remain outside the specified limits even with the integration of the unbalance solving devices in the network, an LV stabilizer that utilizes ATs (**iEBT**) is applied as Case 4, and an OLTC transformer (**iTRAFO**) as Case 5, to directly address voltage problems, as these are devices specifically designed for this purpose. These solutions are not mutually exclusive; instead, the unbalance solution with the best technical improvement metrics will be complemented by the two voltage solutions. For this reason, every case analyzed is either only the ZIGZAG or iCOBT or one or the other in combination with the iEBT or iTRAFO.

Table 22 provides a summary of the digitalization devices present in each case.

Table 22: Digitalization Solutions per Use Case

Case Number	Digitalization Solution
Case 1	Base
Case 2	ZIGZAG
Case 3	iCOBT
Case 4	iEBT
Case 5	iTRAFO

An additional criterion employed in the selection of case study scenarios involves the establishment of a minimum occurrence threshold of 3% for the identified critical situations. This threshold serves to ensure that the selected scenarios reflect recurring peak or stress conditions, rather than isolated or transient events. The objective is to capture scenarios that, although not frequent, exhibit consistent presence and operational relevance, thereby enabling the demonstration of how digital solutions can effectively address recurrent challenges. Furthermore, beyond the predefined critical situations, the system incorporates functionality that allows for the modification of customer consumption data. This feature introduces a degree of flexibility, facilitating the exploration of tailored use cases that align with specific operational requirements and represent critical conditions within the system.

In Figure 21 an example LV network is presented, showcasing its voltage profile and highlighting the locations of operational violations across the grid topology. The representation spans the various buses of the network, providing a clear visualization of the initial data window utilized in the analysis.

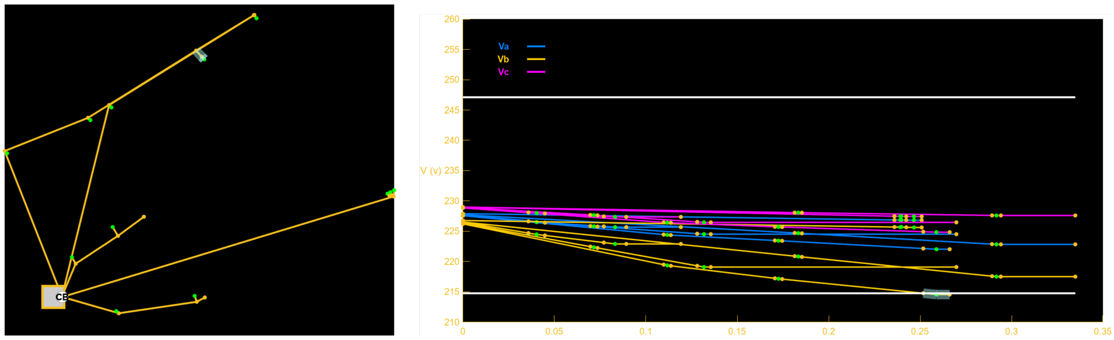


Figure 21: Example Load Curve Case Selection

H.1 Devices Ratings

The tool enables the customization of equipment parameters to align with the specific requirements of the LV network under study. Accordingly, the ratings of the components implemented in the system for the evaluation of digitalization solutions were adjusted to reflect the standard devices that i-DE plans to deploy in its real-world network. For consistency and comparability, all device ratings remain constant across the different use cases, thereby ensuring that the assessment focuses on standard technology performance. The technical specifications of the devices used are presented in Table 23:

Table 23: Equipment Parameters and Values

Equipment	Parameter	Value
ZIGZAG	Short Circuit Power	300 kVA
	Percent Short Circuit Impedance	2%
	Ratio of Resistance to Reactance	1
iCOBT	3-phase Max Current	300A
	Neutral Conductor Max Current	300A
iEBT	Rated Voltage	400/400V
	Short Circuit Power	100 kVA
	Percent Short Circuit Impedance	2%
	Ratio of Resistance to Reactance	0
	Tap Range	[-8, +7]
	Percentage of rated voltage per tap step	0.6667%
iTRAFO	Rated Voltage	20/0.4 kV
	Short Circuit Power	400 MVA
	Percent Short Circuit Impedance	8%
	Ratio of Resistance to Reactance	0
	Tap Range	[-8, +7]
	Percentage of rated voltage per tap step	0.6667%

ANNEX I. Case Study Voltage Profile & Digital Solution Allocation

This section presents the graphical outputs and voltage profiles obtained from the PlexigridSim software, illustrating the operational performance of the implemented digital solutions across the network for the three networks studied and their specific uses cases studied in the project.

The initial set of figures illustrates the network topology, with segments affected by VE highlighted in light blue. This graphical representation serves to convey both the extent and spatial distribution of voltage irregularities within the LV grid. Figure (a) corresponds to the baseline scenario, whereas Figure (b) reflects the network's performance following the implementation of the optimal digitalization strategy. The deployment of digital devices in the optimized scenario adheres to the coding scheme outlined in Table 24. It is important to note that the iTRAFO device is not explicitly depicted in the figures, as its integration involves the replacement of the conventional transformer with an OLTC unit, thereby not altering the visual topology of the network.

The purpose of this comparison is to provide a visual demonstration of how digitalization technologies can mitigate voltage problems, enhancing the overall QoS and operational stability of the network.

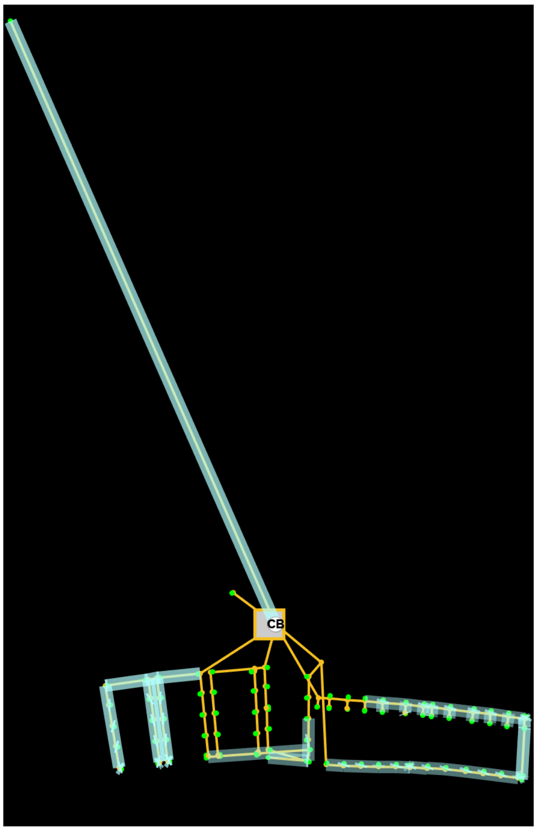
Device	**Code**
Replacement Fuses	CB
ZIGZAG	ZI
iEBT	IE
iCOBT	IC
iTRAFO	–

Table 24: Device and associated codes

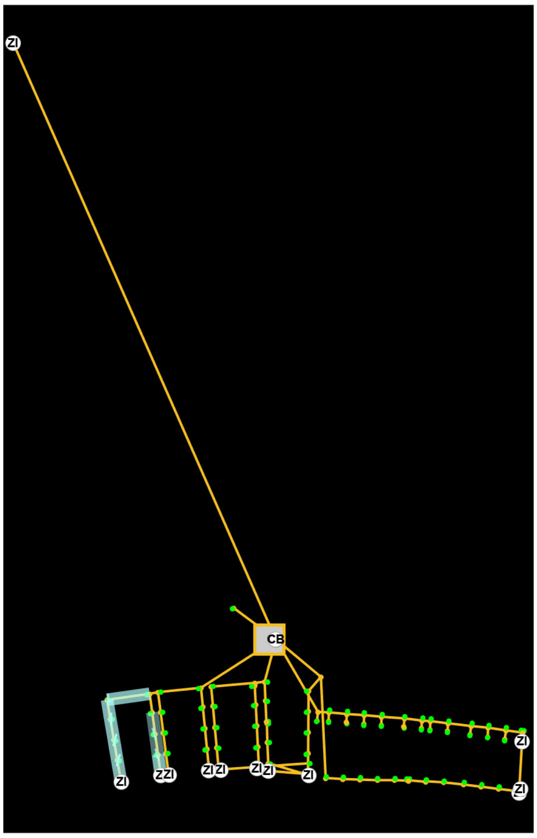
The second set of figures illustrates the voltage profiles across the network buses, providing a detailed view of the three-phase line-to-neutral voltages. Specifically, the voltages of phases A, B, and C are represented in blue, yellow, and pink, respectively. The vertical axis (y-axis) indicates the voltage magnitude in volts, while the horizontal axis (x-axis) represents the electrical distance of each bus from the SS transformer, measured in kilometers. To contextualize the evaluation of voltage quality, the upper and lower voltage thresholds defined by the PUL and POL metrics, 215 V and 245 V, respectively, as established in Section 6, are also displayed on the y-axis. Buses and lines exhibiting voltage values outside these acceptable limits are highlighted in light blue, emphasizing areas of concern within the network.

The upper Figure (c) presents the voltage profiles under the base case scenario, while the lower figure Figure (d) displays the performance of the optimal digital solution. In the latter, the placement of digital devices is indicated at the corresponding buses or lines, demonstrating their impact on voltage regulation and overall network performance.

I.1 N3

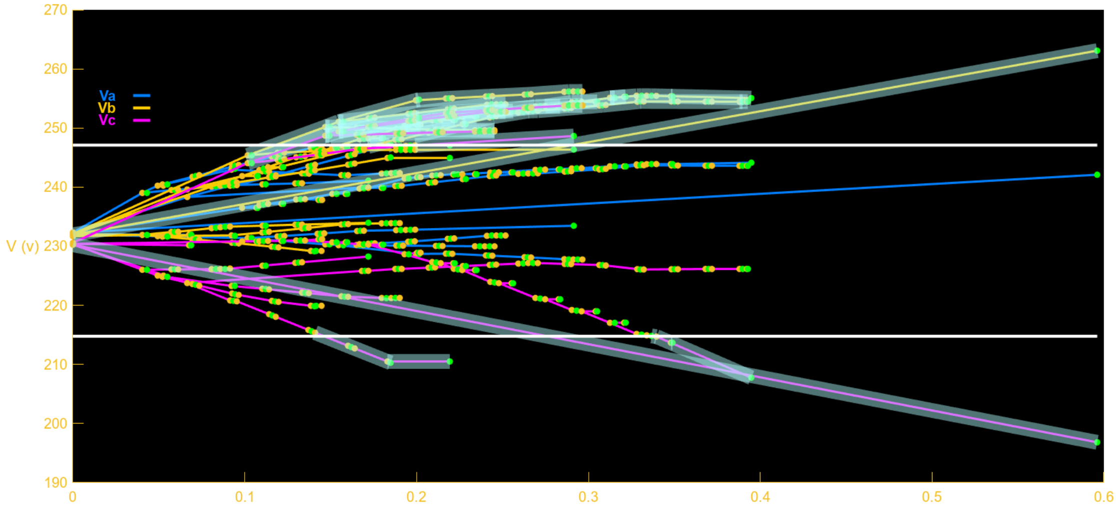


(a) N3 Base Case

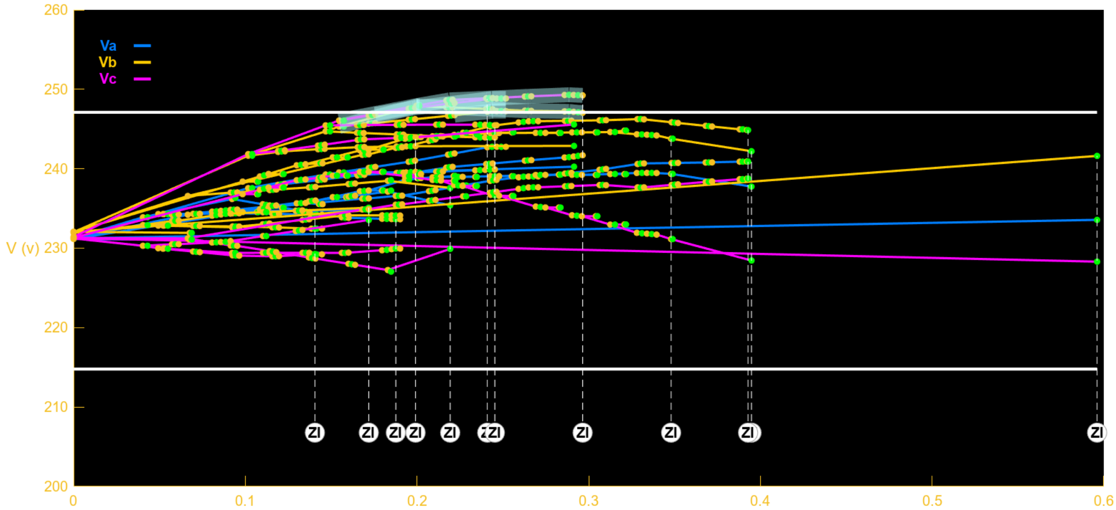


(b) N3 Optimal Case

Figure 22: N3 Voltage Events and Solution Overview



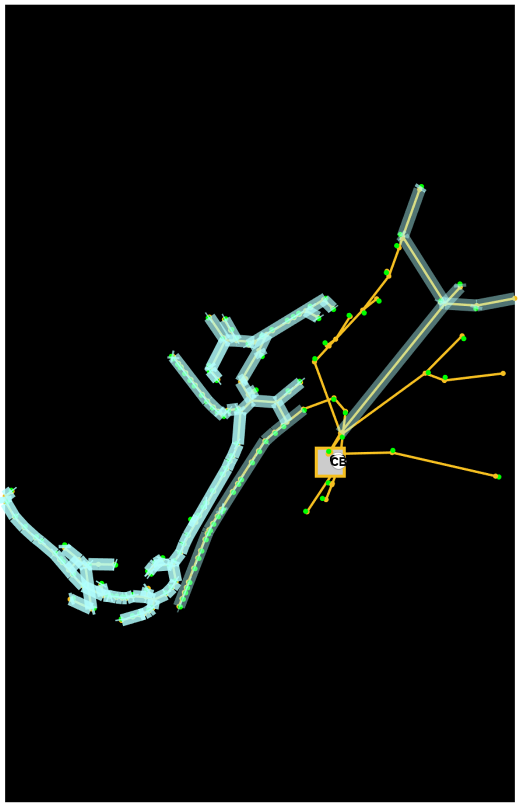
(c) N3 Base Case Voltage Profile



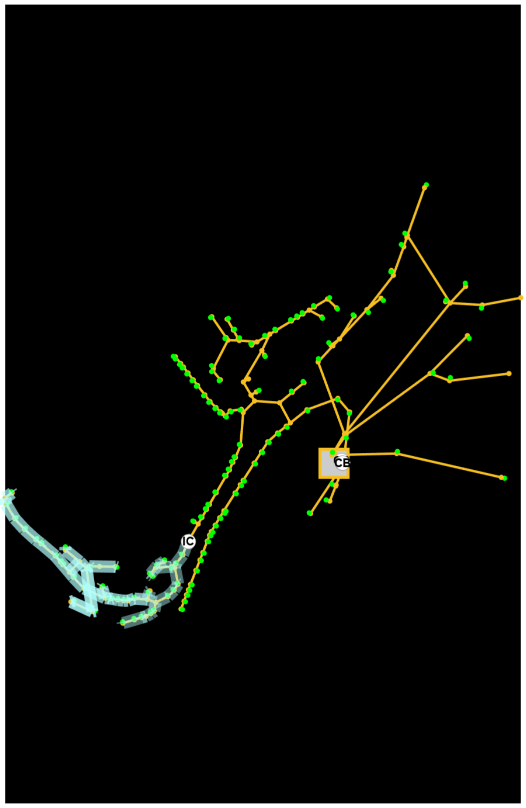
(d) N3 Optimal Solution Voltage Profile

Figure 22: N3 Voltage Events and Solution Overview

I.2 N5

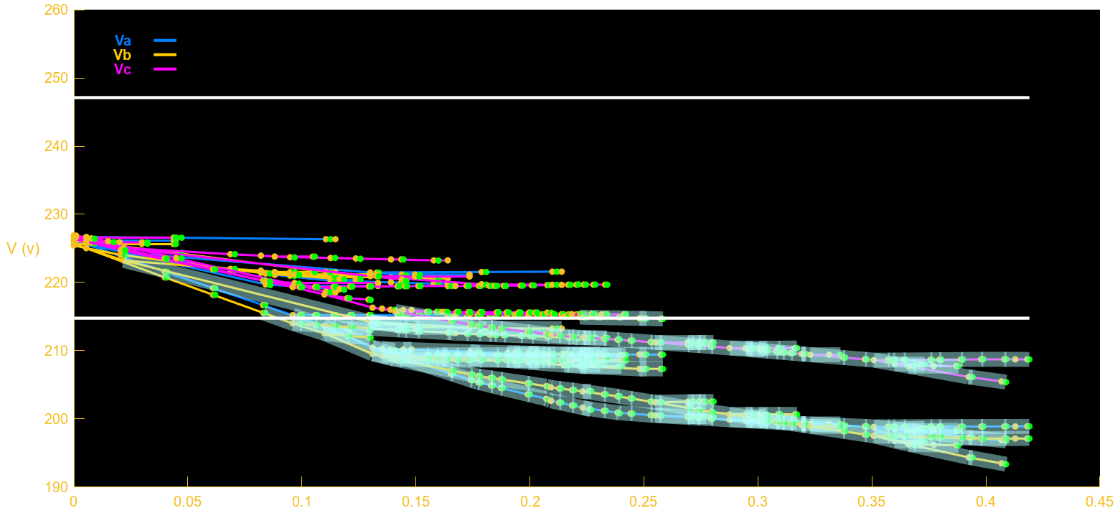


(a) N8 Base Case

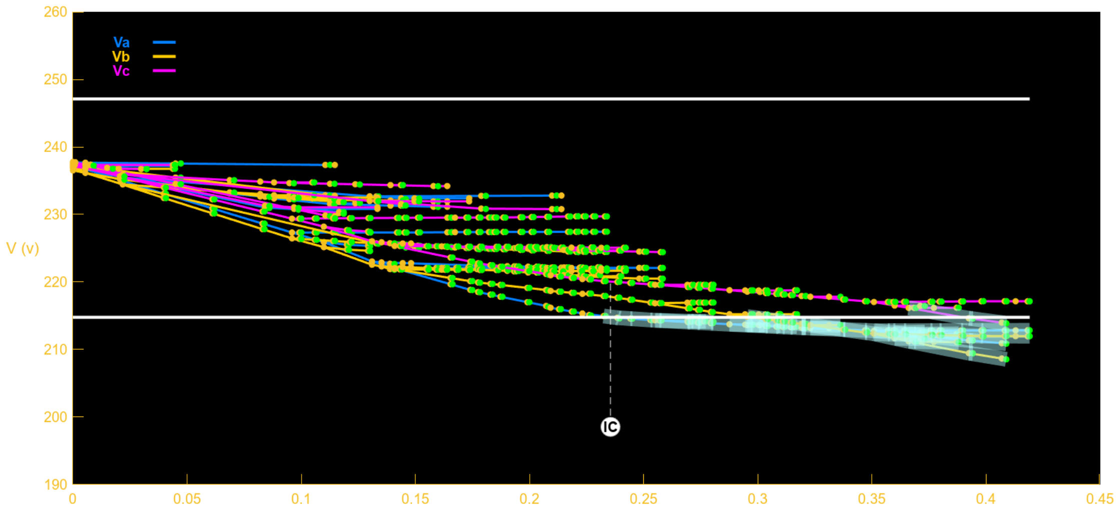


(b) N5 Optimal Case

Figure 23: N5 Voltage Events Distribution & Digital Solution Allocation



(c) N5 Base Case Voltage Profile

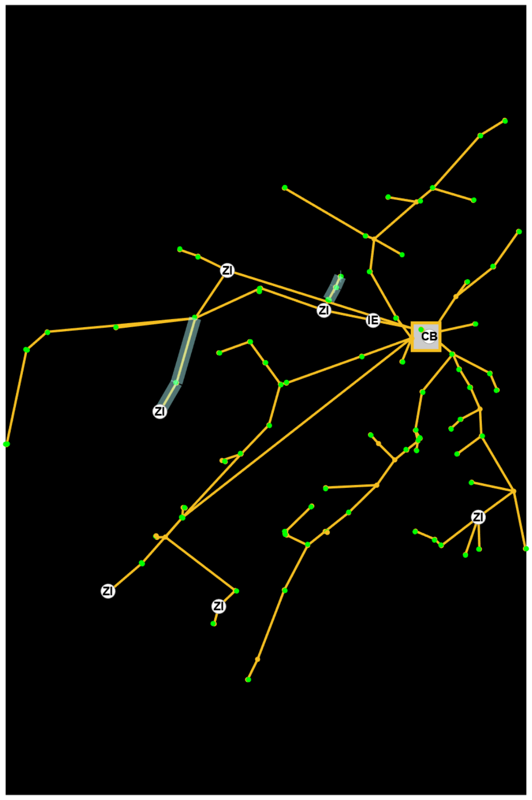


(d) N5 Optimal Solution Voltage Profile

Figure 23: N5 Voltage Profile Comparison

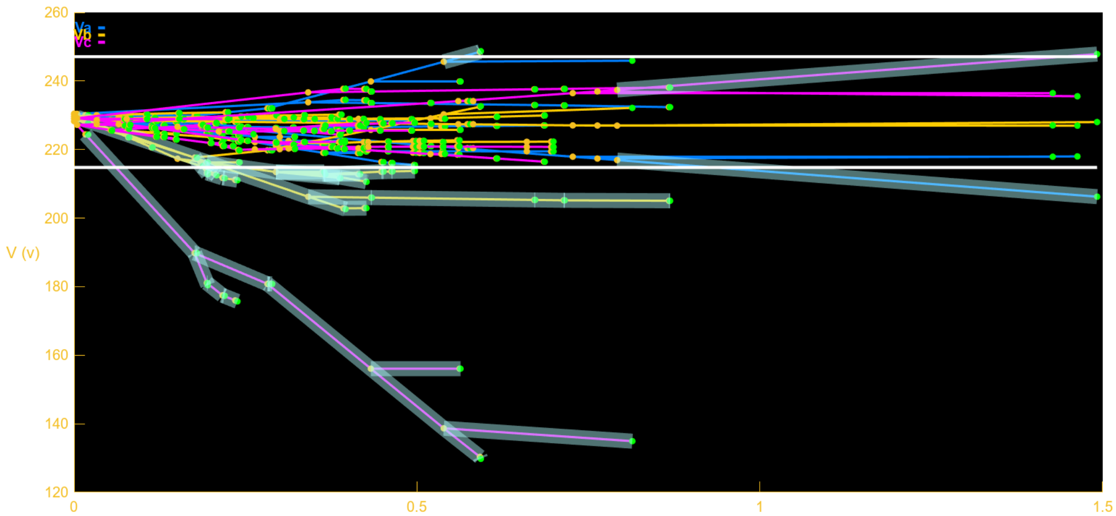
I.3 N8

(a) N8 Base Case

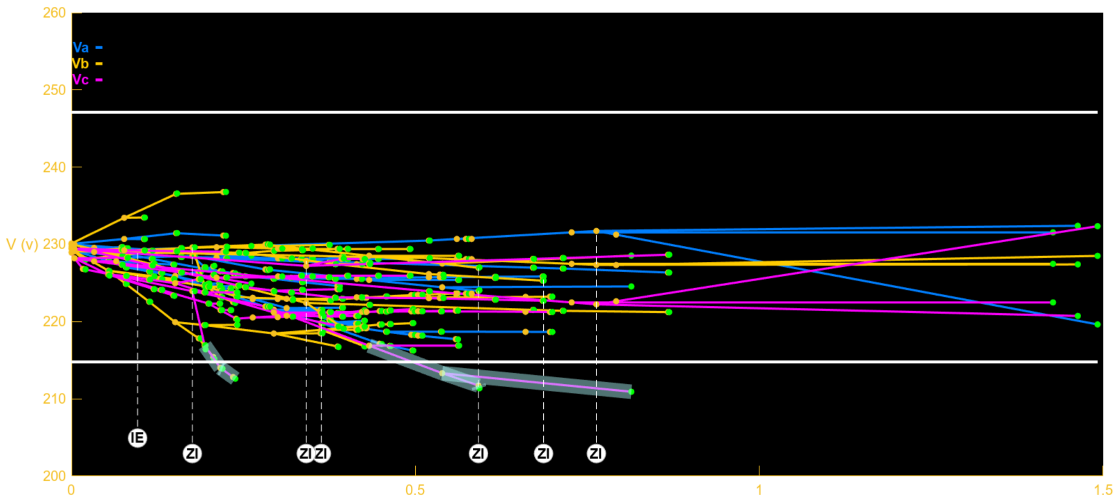


(b) N8 Optimal Case

Figure 24: N8 Voltage Events Distribution & Digital Solution Allocation



(c) N8 Base Case Voltage Profile



(d) N8 Optimal Solution Voltage Profile

Figure 24: N8 Voltage Profile Comparison

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