

# Cable Upgrading Feasibility for Distribution Network Capacity Increase

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## ABSTRACT

Distribution networks globally face critical capacity constraints as urbanization and renewable integration drive load growth beyond the design limits of aging infrastructure, resulting in voltage violations, increased losses, and reliability risks. Confronting this challenge, this study analyzes the feasibility of strategic cable upgrades—specifically, increasing conductor cross-sections and adopting Cross-Linked Polyethylene (XLPE) insulation—as a targeted alternative to complete network reconstruction. To evaluate this solution, the research employs an integrated technical-economic model that combines electrical network simulation with financial analysis. The technical module quantifies performance gains in ampacity, losses, and voltage stability, while the economic module calculates key metrics, including Net Present Value (NPV) and Payback Period.

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## Introduction:

Modern electrical distribution networks are under unprecedented strain. Drivers such as rapid urbanization, rising electrification, and the integration of intermittent renewable energy sources are pushing existing infrastructure toward its operational limits. For utility planners, this presents a critical challenge increasing network capacity and reliability in a manner that is both economically viable and minimally disruptive to service. This study conducts a comprehensive feasibility analysis of a strategic alternative to complete network reconstruction: the systematic upgrade of existing distribution cables.

The investigation focuses on evaluating two primary technical interventions for enhancing cable capacity: increasing the conductor cross-sectional area and adopting advanced insulation materials, notably Cross-Linked Polyethylene (XLPE). A comparative methodology is employed, modeling network performance to quantify key benefits such as enhanced ampacity, reduced technical losses, and improved voltage stability. To ground this analysis in practical reality, the paper presents a detailed case study of a medium-voltage distribution feeder. This case applies the proposed framework, evaluating the upgrade's viability through essential financial metrics, including Net Present Value (NPV) and Payback Period.

The findings demonstrate that targeted cable replacement can be a financially sound investment, effectively deferring more costly network reinforcements while boosting system

reliability. Ultimately, this research provides network planners with a pragmatic, evidence-based pathway, affirming that cable upgrading represents a technically feasible and economically attractive solution for managing gradual load growth when guided by robust feasibility studies.

## 1. Challenges of Existing Distribution Networks Under Increasing Loads

Electrical distribution networks form the critical final link between transmission systems and end consumers, delivering power to residential, commercial, and industrial users. Historically designed for predictable, unidirectional power flows, these networks are increasingly stressed by modern load patterns and energy transitions.

Key drivers exacerbating this pressure include:

**Urbanization and Electrification** Concentrated demand in cities and the shift from fossil fuels to electric vehicles (EVs) and heat pumps significantly increase base and peak loads.

**Distributed Generation** The proliferation of rooftop solar and other renewables introduces bidirectional power flows, voltage fluctuations, and protection coordination challenges.

**Changing Consumption Patterns** The rise of high-power-density applications and digital infrastructure creates new, often coincident, peak demands.

When existing infrastructure operates under sustained or peak loads exceeding its thermal and electrical ratings, several critical issues arise:

1. Voltage Drop excessive loading causes significant voltage reduction along feeders, potentially breaching regulatory limits at distant nodes.
2. Increased Technical Losses (I<sup>2</sup>R Losses) higher currents lead to quadratic ally increasing resistive losses in conductors, reducing system efficiency and raising operational costs.
3. Overheating and Asset Degradation continuous operation near thermal limits accelerates insulation aging in cables and reduces the lifespan of transformers and other equipment.
4. Reduced Reliability and Security the network's margin to handle contingencies, faults, or unexpected load spikes diminishes, increasing the risk of overloads, protective device operations, and extended outages.

Consequently, network planners and utilities face the urgent task of finding cost-effective, timely, and resilient strategies to augment network capacity. While building entirely new infrastructure is one option, upgrading existing components—particularly cables—presents a compelling alternative to enhance load-carrying capacity with less disruption and capital investment. This context sets the stage for evaluating the feasibility of strategic cable upgrades as a targeted intervention to restore design margins and ensure reliable future operation.

### 1.1 Approaching Network Maximum Capacity and Its Effects

As electrical demand steadily rises, many existing distribution networks are operating perilously close to their maximum designed capacity. This scenario, often referred to as a "strained" or "congested" network, is a critical operational challenge that transitions from a theoretical risk to a tangible set of technical and financial consequences. Operating near these limits for prolonged periods does not merely reduce performance margins; it actively degrades system integrity, leading to a cascade of negative effects.

The primary technical manifestations of this problem are:

1. Excessive Voltage Drop The voltage at the end of a distribution feeder is a function of the current flowing through the line's impedance. As load current increases toward the cable's amp city limit, the voltage drop along the conductor ( $\Delta V = IZ$ ) becomes significant. This can result in voltages at distant or heavily loaded customer points falling below statutory minimum levels (e.g., -5% or -10% of nominal). Chronic under-voltage can cause malfunction of sensitive electronic equipment, reduce the efficiency of motors, and lead to customer complaints and potential regulatory penalties for the utility.

2. Increased Technical Losses (I<sup>2</sup>R Losses) Power losses in conductors are proportional to the square of the current ( $P_{loss} = I^2R$ ). Therefore, as operational current rises toward maximum capacity, resistive losses increase exponentially. These losses represent wasted energy that must be generated and paid for, directly increasing operational expenditure (OPEX) for the utility. In a capacity-constrained network, a substantial portion of the transmitted energy is dissipated as heat in the cables and transformers rather than delivering useful work to customers.

3. Elevated Fault Risks and Reduced Reliability Operating cables and equipment near their thermal limits has several risk implications:

- Thermal Stress and Insulation Degradation continuous overheating accelerates the aging of cable insulation (e.g., promoting "water treeing" in older cables) and reduces the lifespan of transformers. This increases the probability of insulation failure, leading to short circuits.
- Protection and Security Margins the network's ability to withstand contingencies—such as the loss of another line or transformer—is severely compromised. There is little to no spare capacity to pick up additional load safely, making the system vulnerable to cascading failures following a single fault.
- Overload Protection Activation protective devices (e.g., fuses, circuit breakers) may operate more frequently to prevent equipment damage from sustained over currents, leading to more customer interruptions.

Network operating at or near its maximum capacity is not in a stable state. It is characterized by lower power quality (voltage issues), higher operational costs (technical losses), and significantly increased risk of failure and customer interruptions. This problematic triad creates a strong economic and technical imperative for intervention, making the feasibility of solutions like strategic cable upgrading not just an engineering exercise, but a critical business decision for ensuring sustainable and reliable power delivery.

### 1.2 Comparing expansion options complete reconstruction vs. partial upgrading (retrofitting).

When a distribution network approaches its capacity limits, system planners must choose between fundamentally different investment strategies. The two primary pathways are Complete Reconstruction and Partial Upgrading (Retrofitting), each with distinct implications for cost, disruption, technical outcome, and strategic flexibility.

Table 1 Complete Reconstruction vs. Partial Upgrading (Retrofitting)

Aspect	Complete Reconstruction	Partial Upgrading (Retrofitting)
Core Approach	Building a new, parallel network or entirely replacing a feeder segment with new infrastructure designed for future loads.	Strategically replacing or augmenting only the most critical, capacity-limiting components (e.g., cables, one transformer) within the existing network.
Scope & Disruption	Extensive. Requires major civil works (trenching), complete system shutdowns or complex temporary bypasses, and significant coordination with municipalities and the public. Disruption is high and widespread.	Targeted and localized. Work is confined to specific points or sections. Disruption is minimized, often allowing for phased implementation with shorter, more manageable service interruptions.

Technical Outcome	Optimal and Future-Proof. Provides a clean-slate design that can incorporate latest standards, accommodate long-term load forecasts, and integrate modern grid technologies (e.g., smart sensors) from the start.	Incremental and optimized. Alleviates the immediate bottleneck effectively. Performance is constrained by the remaining older infrastructure, offering a stepwise capacity increase rather than a full redesign.
Capital Investment (CAPEX)	Very High. Involves costs for new rights-of-way, full suite of materials (cables, joints, cabinets, transformers), and comprehensive labor.	Moderate to High, but Focused. Major cost is for new high-capacity components and their installation. Avoids the wholesale cost of entirely new trenches, poles, and secondary equipment.
Financial Logic	Long-Term Capital Deferral. Resets the asset lifecycle and may not require another major investment for decades. Justified by very high long-term growth.	Capital Deferral & OPEX Savings. Primary goal is often to defer a larger reconstruction investment for 10-15 years while also reducing ongoing losses (OPEX).
Timeframe	Long (Months to Years). Involves lengthy planning, permitting, and construction phases.	Shorter (Weeks to Months). Faster from conception to commissioning, providing a quicker response to urgent capacity constraints.
Risk Profile	High Execution Risk. Exposure to large project overruns, permitting delays, and public opposition.	Lower Execution Risk. Smaller-scale projects are easier to manage and control. The risk of not fully solving future constraints remains.
Strategic Use Case	Justified for areas with transformational load growth (e.g., new urban developments), when infrastructure is critically aged, or when a fundamental technology shift (e.g., to higher voltage) is required.	The optimal strategy for managing gradual, predictable load growth, addressing specific thermal bottlenecks, or extending the life of an otherwise sound network. It is a tactical reinforcement.

### Synthesis and Strategic Choice

The choice is not merely technical but fundamentally strategic and financial. Complete reconstruction is a long-term, high-capacity solution burdened by high upfront cost and disruption. Partial upgrading, particularly through cable replacement, is a leaner, more agile intervention that maximizes the utilization and extends the functional life of existing assets.

For most utilities facing gradual demand increases, retrofitting serves as a crucial tool for adaptive asset management. It allows for incremental investments that closely follow load growth, improving cash flow management and ensuring capital is deployed only where and when it is most effective. Therefore, a comprehensive feasibility analysis for cable upgrading must prove that this targeted approach can reliably defer a larger reconstruction investment while maintaining system reliability, thereby offering a superior net present value (NPV) over the planning horizon.

#### 1.3 Traditional cables (e.g., PVC-insulated) and their performance limitations

"Traditional cables" refer to the class of insulated power cables that have formed the backbone of distribution networks for decades, typically employing Polyvinyl Chloride (PVC) or Paper-Insulated Lead-Covered (PILC) designs for medium-voltage (e.g., 11-33 kV) applications. These cables are characterized by established, cost-effective manufacturing processes and were engineered to meet the historical load and environmental expectations of their time.

The operational constraints of these cables become critically apparent under modern, high-load conditions:

1. Limited Thermal Rating (Ampacity):
  - PVC: Maximum continuous operating temperature is typically 70°C. This low thermal threshold directly limits the current (ampacity) the cable can carry before the insulation softens or degrades.
  - PILC: While slightly more heat-tolerant, it is susceptible to drying out and insulation breakdown if overloaded. Its ampacity is ultimately constrained by the need to keep the impregnated paper insulation below its thermal limit.
2. Higher Dielectric Losses:
  - The insulation materials in traditional cables, particularly PVC, exhibit higher dielectric loss factors compared to modern alternatives. This results in greater energy dissipation as heat within the insulation itself under operating voltage, contributing to overall system losses and further constraining thermal headroom.
3. Susceptibility to Insulation Degradation Mechanisms:
  - Water Treeing (in PVC & PE), A long-term failure mechanism where micro-channels form in the insulation under the combined stress of electrical field and moisture, eventually leading to dielectric breakdown.
  - Thermal Aging continuous operation at elevated temperatures accelerates the

- embrittlement and cracking of PVC insulation.
  - Hydrolysis (in PILC): Moisture ingress can degrade the paper insulation, reducing its dielectric strength.
4. Lower Overload and Short-Circuit Withstand Capability:
- The lower thermal mass and insulation stability restrict the cable's ability to safely withstand short-duration overloads or the high thermal stresses of a short-circuit fault without sustaining damage.
5. Installation and Maintenance Drawbacks:
- PILC: Is heavy, requires careful handling to avoid sheath damage, and needs specialized jointing and termination procedures to maintain a hermetic seal.
  - PVC: Can become less flexible at low temperatures, complicating installation.

Traditional cables represent a fixed-capacity asset whose inherent thermal and material limitations create a hard ceiling on network capacity. Their maximum amp city is a primary bottleneck in aging networks. This defining constraint makes them the prime candidate for targeted upgrades, as replacing them with modern alternatives (e.g., XLPE) directly addresses the core

limitation on power flow, unlocking new capacity within the existing network footprint.

## 2. Specifications of Enhanced Cables

Enhanced cable modularity refers to the structured, scalable design of modern high-performance cables (e.g., XLPE-insulated) and their associated accessories, allowing for flexible, phased network upgrades. This approach lets utilities incrementally boost capacity and performance without requiring full-system replacement.

- Increasing Cross-Section, the relationship between cross-sectional area, resistance, and current-carrying capacity (Ampacity). Calculating the expected increase in load capacity.
- Improving Insulation Materials advantages of using XLPE insulation compared to traditional materials.
  - Higher thermal withstands (up to 90°C vs. 70°C for PVC).
  - Better resistance to moisture and treeing.
  - Suitability for higher voltages.
- Combining larger cross-section and XLPE the synergistic effect on improving transmission efficiency.

Modular Specifications:

Table 2 Modular Specifications

Component	Modular Specification	Purpose
Conductor	Scalable Cross-Sections – Standardized sizes (e.g., 150 mm <sup>2</sup> → 240 mm <sup>2</sup> → 400 mm <sup>2</sup> ) that fit existing ducts/joints.	Enables capacity upgrades without trenching new routes.
Insulation	Universal Dielectric (XLPE) – Thermally stable (90 °C), compatible with higher voltages and existing network protection.	Improves thermal rating and longevity; works with legacy protection settings.
Jacket/Sheath	Environment-Adaptive Options – Moisture, UV, chemical, or fire-resistant variants.	Allows customization for soil, aerial, or industrial environments without redesign.
Accessories	Plug-and-Play Connectors/Joints – Prefabricated, tested kits compatible with multiple cable sizes and insulations.	Reduces on-site labor, ensures reliability, and speeds up upgrades.
Monitoring	Integrated Sensor Ports – Options for DTS (Distributed Temperature Sensing) or PD (Partial Discharge) ports.	Enables real-time thermal/health monitoring without retrofitting.
Voltage Class	Voltage-Staged Design – Cables rated for 20 kV can often operate at 12 kV, allowing future voltage upgrades.	Supports network voltage uprating without re-cabling.

Benefits of Modular Design

1. Phased Investment – Upgrade only overloaded sections first, then expand.
2. Reduced Downtime – Pre-tested modular components cut installation time.
3. Future-Proofing – Compatible with smart grid sensors and higher voltages.
4. Inventory Efficiency – Fewer, standardized parts simplify logistics.

Practical Implementation

Utilities can adopt a "mix-and-match" approach:

- In high-load urban sections: XLPE + larger conductor + DTS monitoring.

- In less critical areas: Standard XLPE + existing conductor size.
- In corrosive soils: XLPE + anti-corrosive sheath.

This modularity turns cable upgrades into a flexible, cost-efficient toolkit for adaptive network reinforcement.

## 3. Feasibility Study Methodology an Integrated Analytical Model

This study employs an integrated analytical model to holistically assess cable-upgrading projects. The framework combines technical network modeling—

simulating performance to quantify gains in ampacity, loss reduction, and voltage stability—with a comprehensive financial analysis using metrics like Net Present Value (NPV) and Payback Period. By evaluating both engineering and economic outcomes within a single, systematic process, the model provides a robust decision-support tool to determine where and when targeted upgrades offer superior value compared to full network reconstruction.

- Technical Analysis:
  - Modeling the electrical network before and after the upgrade using specialized software (e.g., ETAP, CYME).
  - Evaluating performance indicators Improved voltage level, reduced electrical losses, increased loading margin.
- Economic Analysis:
  - Calculating Capital Costs: Price of new cable, excavation, laying, replacement, and outage costs.
  - Calculating Financial Benefits savings from energy loss reduction, avoidance of outage costs, deferral of major expansion investments.
  - Applying economic metrics payback Period, Net Present Value (NPV), Internal Rate of Return (IRR).

**Case Study:** Applying the Integrated Analytical Model To demonstrate the practical application of the proposed methodology, a detailed case study was conducted on an aging 11 kV underground distribution feeder in a suburban area experiencing steady annual load growth of approximately 4%. The feeder, primarily using 240 mm<sup>2</sup> PVC-insulated cables, was showing signs of stress during summer peaks, with recorded voltages at the farthest node dropping to 0.93 p.u. and loading reaching 92% of the cable's thermal rating.

The Integrated Analytical Model was applied in two phases. First, the technical module was used to model three scenarios (1) the Base Case (existing PVC cable); (2) Upgrade A (replacement with a 400 mm<sup>2</sup> XLPE cable); and (3) Upgrade B (replacement with a 240 mm<sup>2</sup> XLPE cable). The simulation quantified key outputs: Upgrade A increased ampacity by 85% and reduced technical losses by 52%, while Upgrade B provided a 28% ampacity boost and 20% loss reduction, primarily due to XLPE's higher thermal tolerance.

Second, the financial analysis module processed these technical results alongside cost data. The analysis revealed that while Upgrade A had a 40% higher initial capital cost (CAPEX), its Net Present Value (NPV) was strongly positive due to significant annual operational savings from loss reduction. Its payback period was calculated at 7 years. Upgrade B, though lower in capacity gain, offered an even faster payback of 4 years, presenting a compelling low-risk option for immediate bottleneck relief.

The case study validated the model's utility. It provided clear, quantified evidence that Upgrade A was the optimal long-term strategic investment for the studied feeder, maximizing capacity and efficiency, while Upgrade B served as a viable capital-light

alternative. This outcome underscores that the integrated model transforms upgrade planning from a subjective choice into a data-driven decision-making process, effectively balancing engineering performance with financial prudence.

#### 4. Applied Case Study Analysis of Results and Practical Challenges

Case Study Overview: Upgrading an 11 kV Residential Feeder

To ground the feasibility analysis in a practical context, this study examines Feeder 15A, an existing 11 kV underground distribution line supplying a suburban residential area. The area is experiencing annual load growth of 4.5%, driven by new housing developments and increased adoption of electric vehicle chargers. The current infrastructure consists primarily of a 240 mm<sup>2</sup>, PVC-insulated, aluminum conductor cable installed 25 years ago. Recent summer peaks have shown the feeder operating at 95% of its thermal rating, with associated voltage drops and rising fault frequency.

Three Comparative Scenarios

The analysis models and compares the following three scenarios to determine the optimal intervention:

Scenario 1: Base Case (Do Nothing). The existing network continues operation with projected load growth.

Scenario 2: Cross-Section Upgrade. The existing cable is replaced along its entire critical 3-km section with a 400 mm<sup>2</sup>, XLPE-insulated, aluminum conductor cable.

Scenario 3: Material Upgrade (Diameter Retention). The existing cable is replaced with a 240 mm<sup>2</sup>, XLPE-insulated cable (same diameter, improved insulation).

Technical Modeling Input Parameters & Assumptions

The integrated technical-economic model's reliability depends on three critical input parameters, each introducing specific considerations into the feasibility analysis.

##### 1. Load Profiles:

Projected load growth (e.g., 4.5% annually) was modeled using historical peak demand data and future adoption forecasts for EVs and heat pumps to create a 15-year load profile.

The assumption of smooth, consistent growth is a simplification. Real-world profiles with sharper peaks or seasonal variability could reduce the effective new capacity utilization, suggesting a conservative safety margin should be applied to calculated ampacity gains.

##### 2. Soil Thermal Resistivity (RHO):

A uniform soil thermal resistivity of 1.0 K·m/W (typical for damp clay) was used for underground cable ampacity calculations in the base model.

This is a significant simplification. Dry, sandy soils (RHO ~ 2.5-3.0) can reduce a cable's current-carrying capacity by up to 40%. A site-specific soil thermal survey is therefore a critical pre-requisite for final design, as inaccurate RHO values risk under-sizing cables and negating upgrade benefits.

### 3. Key Input Parameters Summary:

- Electrical base load (0.95 p.u. voltage limit), conductor resistance, XLPE/PVC thermal ratings (90°C/70°C).
- Financial cable cost per meter, excavation/installation rates, cost of losses (€/kWh), discount rate (WACC).
- Operational project lifespan (30 years), outage cost assumptions, annual maintenance savings.

The model's accuracy is directly tied to the quality of these inputs. A sensitivity analysis is recommended, particularly on load growth rate and soil RHO, to ensure the feasibility conclusion is robust across a range of realistic conditions and to identify potential project risks.

Quantitative Results: Performance and Cost Analysis  
The technical and financial outcomes of the three scenarios were simulated and calculated, yielding the following comparative results:

Table 3 Quantitative Results

Performance Metric	Scenario 1: Base Case	Scenario 2: 400 mm <sup>2</sup> XLPE	Scenario 3: 240 mm <sup>2</sup> XLPE
Max. Continuous Ampacity	340 A	630 A	435 A
Percentage Increase in Capacity	(Baseline)	+85%	+28%
Power Losses at Peak Load	48 kW	23 kW	38 kW
Percentage Reduction in Losses	(Baseline)	-52%	-21%
Voltage at Remote Node	0.92 p.u.	0.97 p.u.	0.95 p.u.
Total Project Cost (CAPEX)	€0	€285,000	€205,000
Annual OPEX Savings (from losses)	€0	€16,500	€6,700
Simple Payback Period	N/A	~9.2 Years	~15.3 Years

#### Result Interpretation:

- Scenario 2 provides the most substantial performance uplift, nearly doubling the feeder's capacity and cutting losses by more than half. Its higher cost is justified by significant operational savings, leading to a payback period within a typical asset planning horizon.
- Scenario 3 offers a more modest but cost-effective performance boost. It solves the immediate thermal overload issue and improves voltage profile with a lower initial investment, though its longer payback period is less attractive from a pure financial standpoint.

#### Analysis of Practical Challenges

Implementing either upgrade scenario presents non-technical challenges that directly impact feasibility:

1. Civil Works and Urban Disruption Excavating and reinstating roads, pavements, and gardens in a built-up residential area is the single largest logistical hurdle. It requires extensive permits, traffic management plans, and communication

with residents, often making the soft costs (planning, coordination) a significant portion of the budget.

2. Access and Phasing Complete feeder shutdown for replacement is rarely acceptable. The work must be phased using temporary bypass systems or executed during overnight/low-load windows, increasing complexity, duration, and labor costs.
3. Compatibility with Existing Assets the new cable must interface with old switchgear, joints, and terminations. This may necessitate upgrading these accessories as well, an often-overlooked cost that can emerge during execution.
4. Hidden Subsurface Conditions the feasibility study's cost estimate is based on assumed ground conditions. Encountering unknown rock, existing undocumented utilities, or contaminated soil can lead to substantial cost overruns and delays.

This applied analysis demonstrates that while technical and economic metrics strongly favor the cross-section upgrade (Scenario 2), the ultimate decision must be tempered by practical reality. The choice may come down to a trade-off: Scenario 2 offers superior long-term value if the utility can manage the higher capital outlay and greater disruption. Scenario 3 presents a lower-risk, less intrusive "quick fix" that addresses immediate reliability concerns but may require another intervention sooner. Therefore, a final recommendation must integrate the quantitative model outputs with a qualitative assessment of the utility's risk tolerance, available capital, and capacity to manage disruptive construction projects.

#### 5. Technical Modeling Approach & Methodology

This study's feasibility analysis is underpinned by a detailed technical modeling framework, designed to quantify the performance of upgrade scenarios using industry-standard principles and tools.

##### Software & Simulation Environment

Network modeling and analysis were performed using CYME Power Engineering Software (version 8.2), an industry-accepted platform for distribution system analysis. The software's Cable Ampacity and Load Flow modules were utilized to simulate steady-state conditions, calculate losses, and assess voltage profiles under various loading scenarios.

##### Fundamental Equations & Analytical Models

##### 1. Conductor Ampacity Calculation:

The continuous current-carrying capacity ( $I$ ) was calculated using the Neher-McGrath method (IEEE Std 835-1994 basis), which solves the steady-state heat balance equation:

$$I = \sqrt{\frac{\Delta\theta - W_d[0.5T_1 + n(T_2 + T_3 + T_4)]}{R_{ac}[T_1 + n(1 + \lambda_1)T_2 + n(1 + \lambda_1 + \lambda_2)(T_3 + T_4)']}}$$

"Equation 1"

Where:

$\Delta\theta$  = conductor-to-ambient temperature rise ( $^{\circ}\text{C}$ )

$W_d$  = dielectric loss per unit length

$T_1, T_2, T_3, T_4$  = thermal resistances of insulation, bedding, serving, and soil

$R_{ac}$  = alternating current resistance of conductor at operating temperature

$\lambda_1, \lambda_2$  = ratio of sheath and armor losses to conductor losses

$n$  = number of conductors in cable

## 2. Power Loss Estimation:

Total technical losses ( $P_{loss}$ ) were calculated as the sum of conductor and dielectric losses:

$$P_{loss} = 3 \times I^2 \times R_{ac} \times L + W_d \times L$$

"Equation 2"

Where  $L$  is the cable length.  $R_{ac}$  incorporates temperature correction based on simulated load current.

## 3. Voltage Drop Calculation:

Voltage drop along the feeder was determined using the simplified phasor equation for distribution lines:

$$\Delta V \approx I(R \cos \phi + X \sin \phi)$$

"Equation 3"

Where  $X$  is the conductor reactance and  $\cos \phi$  is the load power factor.

Critical Input Data & Assumptions for Case Study Simulations

### A. Network & Cable Data (Feeder 15A):

System Voltage: 11 kV (line-to-line), 60 Hz

Feeder Length: 3.0 km critical section modeled

Existing Cable: 240 mm<sup>2</sup>, aluminum conductor, PVC insulation, installed in duct bank

Upgrade Cables:

Option A: 400 mm<sup>2</sup>, aluminum, XLPE insulation

Option B: 240 mm<sup>2</sup>, aluminum, XLPE insulation

Conductor Properties: Resistivity = 0.028  $\mu\Omega \cdot \text{m}$ , temperature coefficient = 0.00403/ $^{\circ}\text{C}$

Insulation Properties:

PVC: Maximum operating temperature = 70 $^{\circ}\text{C}$ , thermal resistivity = 5.0 K $\cdot\text{m}/\text{W}$

XLPE: Maximum operating temperature = 90 $^{\circ}\text{C}$ , thermal resistivity = 3.5 K $\cdot\text{m}/\text{W}$

### B. Environmental & Installation Assumptions:

Soil Thermal Resistivity (RHO): 1.0 K $\cdot\text{m}/\text{W}$  (typical moist clay)

Ambient Ground Temperature: 20 $^{\circ}\text{C}$  constant

Installation Depth: 0.8 meters

Cable Arrangement: Triplex configuration in flat formation, 7.5 cm spacing

Load Power Factor: 0.95 lagging (constant)

### C. Load Profile & Operational Assumptions:

Base Loading: 310 A (92% of existing cable rating)

Load Growth Rate: 4.5% annually (compounded)

Simulation Period: 15-year planning horizon

Peak Load Duration: 4 hours daily at maximum rating

Diversity Factor: 0.85 applied to connected load

## D. Modeling Assumptions:

1. Steady-State Analysis, Transient and short-circuit thermal effects were excluded from capacity calculations
2. Uniform Soil Conditions, Soil thermal resistivity assumed constant along cable route
3. Balanced Three-Phase System, No unbalance or harmonics considered
4. Constant Material Properties, No aging effects on cable resistance or insulation during study period
5. Protection Coordination, Existing protection settings assumed adequate for upgraded cables after recalibration

Validation Approach, Model results were benchmarked against manufacturer's published ampacity tables (Nexans, Prysmian) and validated using simplified manual calculations per IEEE Std 399-1997. Voltage drop calculations were verified against actual SCADA measurements from the feeder during peak conditions (within 2.5% accuracy).

This rigorous technical foundation ensures that performance projections for the upgrade scenarios are physically accurate and conservative, providing reliable inputs for the subsequent economic analysis.

## 6. Practical Challenges in Distribution Cable Upgrading Projects

1. Logistical and Civil Works Complexities the most immediate challenge is the physical execution of the upgrade in operational environments. This involves: Urban Disruption extensive trenching and excavation in built-up areas disrupts traffic, business operations, and public access, requiring complex traffic management and community coordination.

Subsurface Uncertainty, Unknown ground conditions, conflicting underground utilities (gas, water, telecom), and archaeological findings can cause significant delays and cost overruns.

Access Limitations working in congested urban corridors, narrow streets, or environmentally protected areas restricts equipment movement and installation methods.

2. Technical and Integration Challenges Live Work Constraints Most distribution networks cannot tolerate extended outages. Implementing upgrades while maintaining supply requires:

Complex switching and temporary bypass arrangements, Night/weekend work with premium labor rates

Increased safety risks for field crews.

Asset Compatibility new cables must interface with existing:

Switchgear and termination points designed for older cable types, Protection systems calibrated for different cable characteristics, Jointing technologies that may be obsolete.

System Re-commissioning after installation, the upgraded section requires:

Complete testing (Hi-Pot, partial discharge, timing tests), Protection coordination studies and relay recalibration, Phasing verification and load balancing adjustments.

### 3. Financial and Regulatory Hurdles

Budget Uncertainty, Initial cost estimates often exclude:

Unforeseen ground conditions requiring specialized excavation, Compensation claims from affected businesses/residents, Archaeological or environmental mitigation costs.

Regulatory Approval Delays, Projects require multiple permits from:

Municipal authorities for road openings, Environmental agencies for protected areas, Heritage bodies for historic. Districts.

Stakeholder Management, Managing expectations of: Residents and businesses affected by disruptions, Local government officials, Regulatory bodies monitoring outage statistics.

### 4. Operational and Planning Constraints

Limited Construction Windows: Seasonal restrictions (winter freeze, rainy seasons) and peak demand periods reduce available working time.

Resource Availability, Shortages of:

Specialized jointers and cable technicians, Specific cable types or accessories, Suitable trenching equipment for constrained spaces.

Information Gaps, Incomplete or inaccurate:

Historical cable records and as-built drawings, Soil condition data, Load growth projections for accurate sizing.

### 5. Risk Management Challenges

Project Sequencing, Coordinating upgrades with: Other utility projects in the same corridor, Municipal infrastructure projects, Planned customer connections.

Quality Control, Ensuring consistent:

Installation quality across multiple work crews, Jointing and termination integrity, Testing and commissioning standards.

Contingency Planning, Preparing for:

Unexpected cable damage during installation, Weather-related delays, Equipment failure during critical phases  
Mitigation Strategies for Successful Implementation

- Advanced Planning comprehensive desktop studies using GIS and ground-penetrating radar
- Phased Implementation breaking projects into manageable sections with clear milestones
- Stakeholder Engagement early and continuous communication with affected parties
- Contingency Budgeting including 15-25% contingency for unforeseen challenges

Partnering Approach Collaborating with experienced contractors and municipal authorities

These practical challenges often determine project success more than technical specifications. A realistic feasibility study must account for these non-technical factors, as they frequently dictate the difference between a smoothly executed upgrade and a financially troubled project with community backlash.

### 6- Model Limitations & Future Grid Considerations

The analysis provides a robust static evaluation, yet modern grid evolution introduces additional complexities that future refinements must address.

1. High Renewable Penetration  
Treats load as a unidirectional net draw from the substation.

High penetration of distributed solar PV can reverse power flows, causing midday voltage rise at the same nodes that experience evening voltage drop. This bidirectional stress alters the fundamental upgrade rationale, potentially shifting the priority from pure ampacity increase to voltage regulation capability and dynamic thermal management.

### 2. Dynamic Loading & Real-Time Ratings

Uses static, seasonal peak ampacity ratings for cables. Modern Dynamic Cable Rating (DCR) systems use real-time data (ambient temperature, soil moisture) to unlock 10-30% extra transient capacity. An upgrade's business case strengthens if paired with DCR, as the new cable's higher base rating provides a larger dynamic buffer for integrating intermittent renewables and managing peak loads.

### 3. Utility Economic Planning Frameworks

Applies standard Net Present Value (NPV) and Regulatory Asset Life costing. Many utilities now employ Advanced Distribution Planning (ADP) frameworks that evaluate non-wires alternatives (e.g., demand response, storage). A complete business case must position the cable upgrade within this portfolio, comparing its Capital Efficiency (€/kVA) and Reliability Contribution against distributed solutions to justify its traditional "wires-based" approach in a modern context.

## Conclusion:

This comprehensive analysis demonstrates that targeted cable upgrading represents a technically sound, economically viable, and strategically pragmatic solution for enhancing the capacity of existing distribution networks. Confronted with the dual pressures of escalating electricity demand and the imperative to integrate renewable energy sources, utilities must move beyond traditional "build-new" paradigms toward more adaptive asset management strategies.

The study confirms that replacing traditional PVC-insulated cables with modern alternatives—particularly those with increased cross-sections and advanced XLPE insulation—yields substantial benefits. The integrated analytical model, validated through a practical case study of an 11 kV feeder, quantifies these advantages: capacity increases of 28-85%, loss reductions of 21-52%, and improved voltage profiles, all while deferring significantly more expensive complete reconstruction projects. Financially, these upgrades prove justifiable, with payback periods typically ranging from 7-15 years, driven largely by operational savings and avoided outage costs.

However, feasibility extends beyond favorable spreadsheet calculations. The practical challenges—from urban disruption and subsurface uncertainties to regulatory hurdles and stakeholder management—are substantial and often determine real-world success. These projects demand meticulous planning, robust

contingency measures, and a commitment to community engagement to mitigate implementation risks.

Strategic Recommendations:

1. Adopt a Phased, Modular Approach, implement upgrades incrementally based on criticality, using standardized components to maximize flexibility and minimize disruption.
2. Integrate Technical and Economic Analysis, Employ the presented integrated model as a standard decision-support tool to balance engineering performance with financial prudence.
3. Prioritize Proactive Planning, begin feasibility studies well before capacity limits are reached, allowing for optimal timing and budgeting.
4. Develop Comprehensive Implementation Frameworks, Address practical challenges through detailed risk assessments, stakeholder engagement plans, and adaptive project management.

Ultimately, cable upgrading is not merely a stopgap measure but a strategic component of sustainable grid modernization. By selectively enhancing the circulatory system of the distribution network, utilities can achieve significant capacity gains, improve reliability, and defer major capital expenditures—all within the existing network footprint. As load growth continues and grid resilience becomes increasingly critical, this targeted approach offers a responsible pathway to meeting future energy needs while maximizing the value of existing infrastructure investments.

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