INTERNATIONAL COMMUNITY ON ELECTRICITY DISTRIBUTION

Working Group Report

Underground And Overhead Line Life Cycle

WG 2021-3

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WORKING GROUP

Final Report

Underground And Overhead Line Life Cycle

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List of Acronyms

CapEx	Capital Expenditure
CBM	Condition-Based Maintenance.
CoF	Consequence of Failure
DSO	Distribution System Operator
ENS	Energy Not Supplied
OpEx	Operational Expenditure
PoD	Point of Delivery
PoF	Probability of Failure
SAIDI	System Average Interruption Duration Index
SAMP	Strategic Asset Management Plan
TotEx	Total Expenditure
WG	Work Group

1. Introduction

1.1. Background of the Working Group

The electrical network includes overhead and underground assets. Each is exposed to different impacts at all stages of their life cycles. Aesthetics, safety, cost, resiliency, and reliability are different for each grid topology and will influence an asset's life-cycle risk management.

One of the most important roles of the DSO is to manage the assets assuring that the network is safe, resilient, and provides the expected level of reliable service. To do so effectively and efficiently, DSO needs access to detailed asset condition data, each asset's importance to network resilience, how the assets interact with each other, and to have advanced tools to identify optimal life cycle management (costs, performance, risks), to optimise CapEx and OpEx budgets.

CIRED created Work Group WG 2021-3, to assess best practices associated with asset management of overhead lines and underground cables. The WG comprises representatives of DSO, manufacturers and service providers covering a wide and diverse geographic area.

The scope covered by this report is:

- to describe best practices and methodologies of underground and overhead lines maintenance, which involve technical end of life decisions to reduce economical risk, and to improve performance along the asset's life cycle;
- to benchmark underground and overhead networks life-cycle asset risk management among DSO;
- to identify best tools and best practices for:
  - Optimal life cycle management (costs, performance, risks),
  - Data analytics and asset performance assessment, including remaining operational life evaluation,
  - Optimal Capex and OpEx allocation, based on risk, through ranking and prioritization processes,
  - Optimal maintenance policy decision-making,
  - Asset risk-based condition assessment (health, criticality, and risks),
  - Optimal asset replacement decision-making;
- to describe existing models about asset condition, probability of failure and expected remaining useful life.

1.2. Structure of the Final Report

The final report of the Working group consists of the following chapters:

i) Chapter 2 presents best practices and methodologies of underground and overhead network maintenance and replacement. Provides an overview of methods supporting the definition of asset management policies aimed at balancing CapEx with TotEx, short-term with long-term and risk with expenditure.

ii) Chapter 3 describes tools and best practices associated with several aspects of underground and overhead asset management.

iii) Chapter 4 presents concluding remarks.

1.3. UNDERGROUND AND OVERHEAD NETWORKS ASSET MANAGEMENT BENCHMARK

This section presents a benchmark on the characteristics and asset management policies and tools across different DSOs, as described in Table 1.

Table 1 - Benchmark across different DSOs

	ENEDIS	E-REDES	Kansai T&D	Elektro Ljubljana
Scope of network operation	MV (15, 20 kV), LV	HV (60 kV), MV (6, 10, 15, 30 kV), LV, Public Lighting	MV (6.6, 22, 33 kV), LV (not including Transmission Assets)	HV (110 kV), MV (35, 20, 10 kV) LV
Surface / Pop. Density	**510 000 km2 / 62 M inhabitants / 122 Inh./km2**	**89 015 km2** / 10,3 M inhabitants / 115 Inh./km2 (urban population = 70%)	**28 713 km2** / 22 M inhabitants / 766 Inh. /km2	**6 166 km2**
PoD[3] / Network Lenght / Density	**PoD = 38.1 M / 1.391.700 km 75 PoD/km2 27.4 PoD/network km**	**PoD = 6,4 M / 232 089 km 70 PoD/km2 / 27 PoD/network km** 	PoD = 14 M / 133 308 km **500 PoD /km2 108 PoD /network km**	PoD: 353.337 17.402 km **20,3 PoD/ network km**
Network ownership	There are c.400 concessions for the network managed by Enedis. Between 2018 and 2020, 95% of them had their contract renewed for 30 years.	Two concessions: • HV and MV – one concession, granted by the State for 35 years (in 2009) LV+Public Lighting – 278 concessions (one from each municipality), granted for 20 years. 99% of those expired by 2020, and public tender will be organized. E-REDES pays 258M€/year to the grantors	Kansai Transmission and Distribution, Inc. own transmission and distribution facilities for general use in the Kansai area.	Elektro Ljubljana owns all the infrastructure with a few exceptions.

[3] Point of Delivery

	ENEDIS	E-REDES	Kansai T&D	Elektro Ljubljana
Consumption	**332 TWh (Total)** Consumption/ PoD / year: 8.6 MWh (LV: 5.8 MWh) **Peak Load: 72.5 GW**	**45.4 TWh (Total)** Consumption/ PoD / year: 7.1 MWh (LV: 3.3 MWh) **Peak Load: 8.2 GW**	**134TWh (Total)** Consumption/ PoD / year: 9.3 MWh **Peak Load: 27.4 GW**	**4 TWh** **Peak Load: 0.7 GW**
Generation	Generators: 596 000 Inst. Capacity: 36 GW **Production: 66 TWh**	Generators: 1,100 Inst. Capacity: 6 GW **Production: 11,6 TWh**	Generators: 514,000 Inst. Capacity: 6.8 GW	Generators: N/A Inst. Capacity: 409,8 MW **Production: 0,13 TWh**
Network	**MV: 658.800 km** (52% underground) **LV: 732.900 km** (48% underground)	**HV: 9.637 km** (6% underground) **MV: 74.701 km** (20% underground) **LV: 147.751 km** (23% underground)	133 309 km (10% underground)	**HV: 376 km** **MV: 5.811 km** **LV: 11.215 km**
SAIDI	**SAIDI 60 min (2022)** (Excluding exceptional events and transport grid incidents)	**SAIDI MT 71 min** (not including extraordinary events) **SAIDI BT 77 min** (not including extraordinary events)	**SAIDI 7 min** / year in 2022	135 min/user (planed and unplanned events) 72,06 min/user unplanned events 62,69 min/user planned events
Inspections	**MV**: aerial inspections every three years **LV**: ground visual inspections, predictive maintenance using smart meter IT system data	**HV and MV:** aerial inspections every three years (distances + thermography) **LV:** ground visual inspections every three years	**MV and LV: ground visual inspection every five years**.	HV and MV foot inspection every year. LV foot inspection every five years.
Sensing	Communicating Fault Indicators for MV smart meters it system used for LV.	Smart meters enable the identification of LV faults and voltage levels outside EN 50 160 recommended values.	Installation of three-phase sensors in disconnectors began in 2014. This equipment measures three-phase voltage and current, and zero-phase voltage and current. The measured data is transmitted to a server via communication lines.	Fault Indicators for MV Smart meters in LV
Regulatory / Accounting Depreciation	In France, the useful life span of distribution lines is generally considered to be about **40 years**.	**HV/MV lines & cables: 30 years** **LV lines and cables: 25 years**	In Japan, the useful life span of distribution lines is generally considered to be about **30 years**.	In Slovenija, the useful life span of distribution lines is generally considered to be about 40 years.

2. Best practices and methodologies of underground and overhead network maintenance and replacement

This chapter provides an overview from several WG contributors regarding methodologies for defining asset management policies, OpEx and CapEx (modernization) strategies, that balance costs (TotEx), risk and performance for the life cycle.

2.1. E-REDES methodology for underground and overhead assets management

E-REDES is the Portuguese DSO operating in Continental Portugal, managing the HV (mostly 60 kV), MV (mostly 10 kV, 15 kV and 30 kV) and LV networks.

Main asset categories and quantities of assets operated by E-REDES can be resumed in Table 2.

Table 2 – Main Assets Categories operated by E-REDES

Asset		Unit	Quantity (2022)
Primary Substations			**435**
HV & MV networks		**km**	**84,329**
Overhead		**km**	**68,641**
	HV (60/132 kV)	km	9,072
	MV (6/10/15/30 kV)	km	59,569
Underground		**km**	**15,688**
	HV (60 kV)	km	565
	MV (6/10/15/30 kV)	km	15,132
Secondary Substation			**70,588**
LV networks		**km**	**147,751**
Overhead		km	113,266
Underground		km	34,485

E-REDES has processes and procedures associated with each life-cycle phase of the network assets, as shown in

.

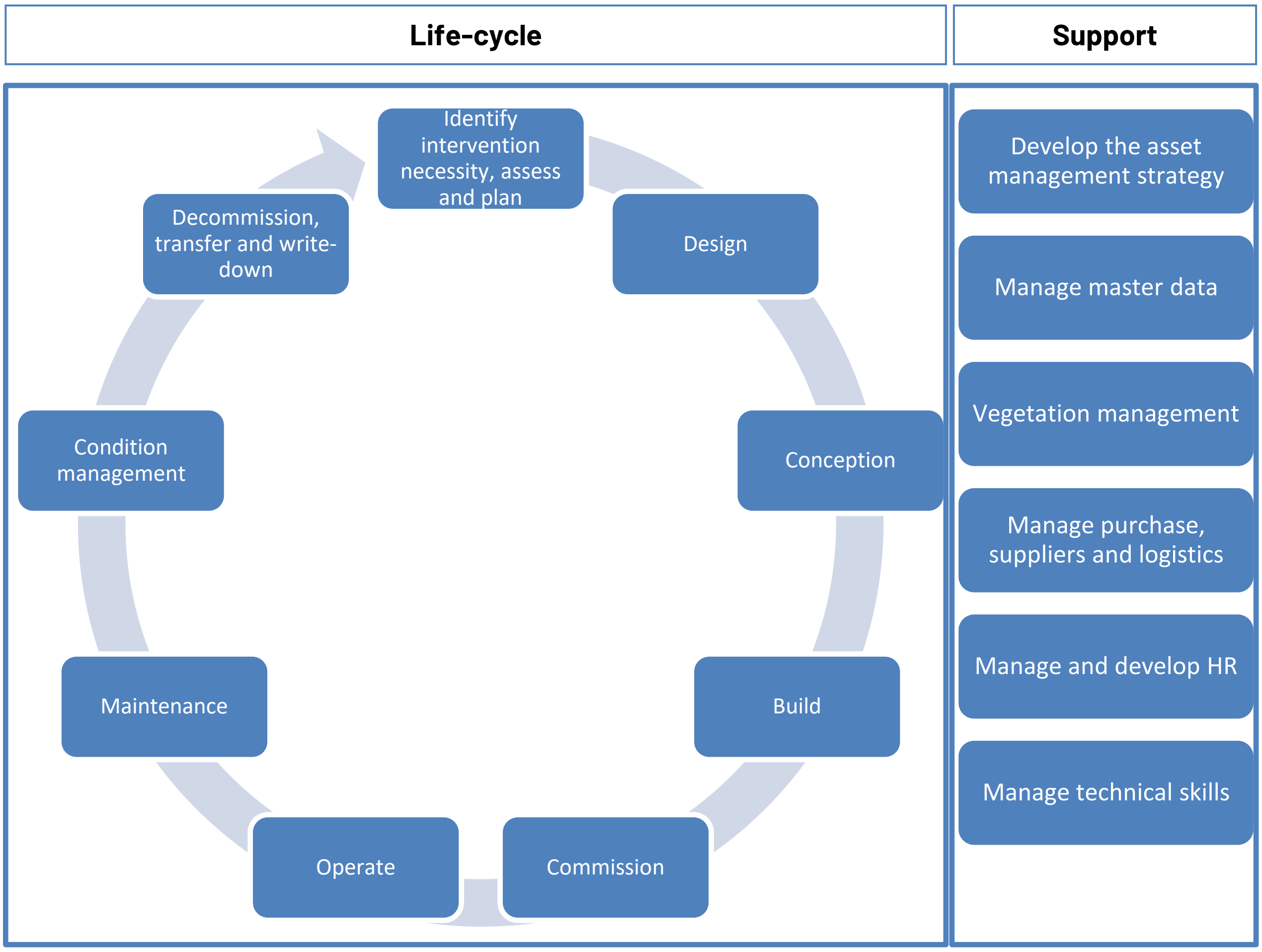

Figure 1 - Asset Life-cycle phases

Therefore, the life cycle involves defining an asset management strategy, which includes the long-term investment requirements associated with asset modernization and the maintenance policy for these assets.

E-REDES must deliver, every five years, a 5-year plan (Investment and Development Plan of the Electrical Distribution Network, PDIRD-E) to the Regulator and to the Energy Directorate[4], to be commented on by both entities and approved by the Portuguese Government. This plan is updated every other year (even years) during its execution.

Supporting the PDIRD-E, E-REDES produces an assessment of the modernization investment requirements on main asset categories, including underground and overhead network assets, with a 10-year time horizon.

This strategy benefits from ever increasing models assessing the condition and probability of failure (PoF) of individual assets and assessing the risk of failure of individual and complex assets.

E-REDES is developing models that enable the company to have an even better long-term assessment of investment requirements, while observing the CNAIM (Common Network Asset

[4] A governmental institution.

Indices Methodology) developed in Great Britain, as published by the British National Regulatory Agency, ofgem [1].

E-REDES also defines maintenance policies for its main asset categories, including overhead line assets[5]. This maintenance policy is reviewed internally every three years.

Given an existing asset management strategy, which includes both the investment and maintenance strategy, E-REDES proceeds to identify the individual interventions for its assets.

2.1.1. Risk-Assessment in Distribution Grids: Simulation Software for Supporting Asset Management

E-REDES presented its risk assessment methodology and software for risk evaluation in the CIRED Shanghai Workshop [2], also developing it in [3].

E-REDES' network analysis software is DPlan, developed by AmberTREE. E-REDES adopted a risk assessment methodology based on CNAIM's guidelines and, together with AmberTREE, promoted the development of a network analysis software to estimate the failure risk of HV and MV assets – which includes overhead lines and underground cables on those voltage levels.

The developed methodology provides an assessment of asset health and criticality, thus enabling the estimation of the failure risk. The software allows either the adoption of individual PoF values for the individual assets, or the use of reference values for that PoF.[6]

The PoF and Consequence of Failure (CoF) are related to different modes of failure of individual assets, which can be classified as:

- Catastrophic – a sudden and total failure from which recovery of the asset (or subcomponent) is not feasible;
- Degraded – a significant failure associated with advanced degradation;
- Incipient – a minor failure associated with early-stage degradation.

The methodology assesses the failure risk for four risk dimensions:

- Safety,
- Environment,
- Network Performance,
- Financial.

The methodology allows monetizing the failure impact for each one of those dimensions. It is also supported by a Risk Matrix, aimed to classify the risk level (extremely high, very high, high, intermedium or reduced), thus providing both a quantitative and qualitative risk assessment.

The total risk is the sum of the PoF multiplied by the CoF (in euros) for each component. The results of a quantitative and a qualitative risk assessment are based on the risk matrix. It is important to highlight that the monetisation of the Safety and Environmental CoF depends on

[5] But not underground cables, since they do not have an associated systematic maintenance program.

[6] If there is no data for a given asset, an assumption concerning the PoF can be made, based on reference values previously uploaded to the software library.

the company's risk aversion. The model allows the parameterization of aggravating and mitigation factors to increase or decrease the resulting CoF depending on asset characteristics and other contextual data.

Since all risk assessments are monetised, E-REDES can compare and decide which risks are unacceptable – and therefore must be mitigated regardless of cost – and which risks are acceptable or tolerable. These risks might be managed and controlled, and the decision to mitigate them is based on the ALARP (as low as reasonably practicable) principle, i.e., these risks should be mitigated if the associated cost is compensated by the risk exposure as calculated by the methodology. Furthermore, this risk quantification and the quantification of the interventions that can be executed to mitigate it will allow E-REDES to prioritise interventions.

The assessment of Safety implies estimating the cost incurred by the society when workers or the general public are exposed to a hazard associated with an asset failure. It includes an assessment of the probability of the failure causing an incapacity or fatality. It considers the location of the asset and the exposure of workers or the public to the hazard. Figure 2 illustrates the soil occupancy categories considered to calculate the safety risk.

Figure 2 - Location zones considered in Safety risk assessment

Environment risk assessment is performed for three different hazards associated with different assets and failure modes: oil spill, associated with the hazard associated with oil existing in transformers or switchgears, and which consider a location factor – namely if the asset has an oil containment reservoir or if it is in the vicinity of river basins which might exacerbate the risk; SF6, associated with the hazard of SF6, associated with the catastrophic release of the existing SF6 in busbars or switchgears, and which is measured as an equivalent of CO2 release; fire hazard, associated with a contact of assets with vegetation that might start a forest fire.

The Network Performance risk is associated with customer service interruptions resulting from asset failures. It is expressed through an expected Energy Not Supplied (ENS) measured in kWh, converted in Euros (the value implicit in regulatory incentives/penalties and which is used by E-REDES in economical evaluations is 4,5 €/kWh). The impact regarding ENS is associated with network topology, i.e., the existence or not of N-1 reserve and eventual reconfiguration and repair times.

The Financial risk is the expected direct cost of repairing or replacing damaged assets, allowing them to return to their pre-fault condition. It includes an access factor, which might result in a higher intervention cost.

AmberTREE implemented the risk assessment methodology through a new module in DPlan, the decision-making support software used by E-Redes.

This new module takes advantage of the GIS interfaces and simulation capabilities in DPlan. It combines them with new information about asset characteristics or other contextual data such as those contained in vector maps obtained from multiple sources. To perform the risk assessment as described in the previous section, DPlan inputs:

- Asset Probability of Failure: The PoF for each asset results from an analysis performed by E-Redes in other projects.
- Risk Parameters: These parameters allow the user to calibrate de simulation and assign different reference values and weights to certain asset characteristics or map classifications.
- Asset characteristics: Additional element-specific data such as construction details and extra equipment catalogue attributes.
- Maps: A large group of maps in shapefile format is read and utilised to classify various aspects of the assets in the network. This functionality was created to easily add different maps to analyse new risks and topics as they emerge.

Cartographic information is paramount to identify Safety and Environmental risks, both associated with the context of the location of the assets. Figure 3 illustrates three vector maps analysed during the risk analysis module (rivers, agricultural areas, and soil usage).

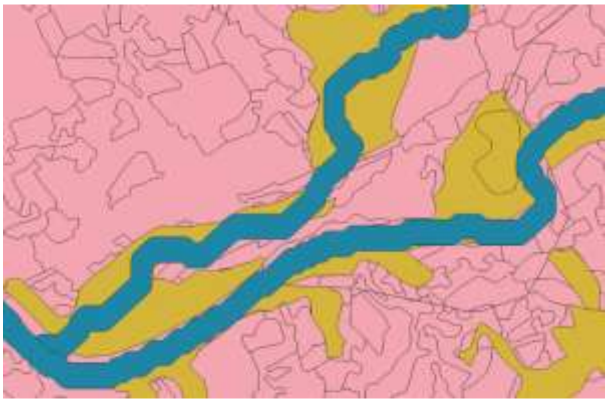

Figure 3 – Three of the maps used in risk analysis (rivers in blue, agricultural areas in yellow and overall soil usage in pink), shown using Qgis open-source software

To perform the risk assessment for each asset in the network, DPlan combines multiple inputs and layers of geographical data with the network model, the asset characteristics and the power-flow and reliability analysis capabilities. Each asset's four risk dimensions are evaluated differently according to the asset characteristics and contextual data. While dimensions such as Network Performance rely more on simulating power flows and reliability analysis (considering the failure mode probabilities of each asset, available reconfiguration possibilities and the time required to enable them), other risk dimensions rely more on contextual data such as overhead line proximity to populated areas or vegetation, proximity to water lines, buildings, etc.

To obtain a qualitative evaluation of the overall risk in each asset, the PoF and CoF are combined through a risk matrix as illustrated in Figure 4. The diagonals highlighted with arrows have the same colour and represent isorisk classifications.

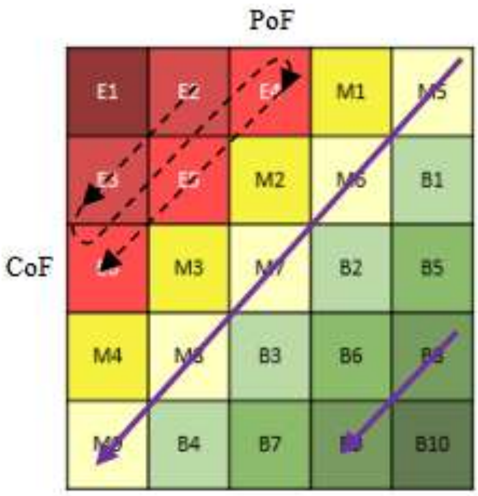

Figure 4 - Risk matrix combining the PoF (5 levels) and CoF (5 levels) resulting in 25 risk classifications. Arrows highlight the Isorisk curves.

The risk assessment results of the combination of the risk on the four dimensions previously mentioned (Safety, Environment, Network Performance and Financial), in accordance with the CNAIM Methodology [1]. That assessment is both quantitative – as mentioned, the risks on all the four dimensions are monetized and added, thus yielding a value for the Total Risk in EUR. This risk allows the asset manager to compare the cost of the interventions that are expected to mitigate that risk with the total value of the risk, providing an important tool to support decision-making.

Furthermore, risks are also evaluated qualitatively on a risk matrix. Risk matrixes allow for a simple visualization of the risks (impact and probability) and are useful elements to communicate the risks associated within the organization. Furthermore, risk matrixes allow to assess risks that are unacceptable by the organization – those risks need to be mitigated, even if the mitigation initiatives have a cost that it is higher than the benefits estimated using the quantitative methodology. The risk matrixes, by allowing an easy risk assessment, are on themselves simplistic tools and only highlight the risk dimension with the highest contribution to the total risk of failure of an asset – ignoring all other contributions.

An application of the risk matrix resumed in Figure 4 is shown on Figure 5, as an example. Let's assume two different unrelated risks. Risk A (Blue) has a Probability of Occurrence sitting in the column PoF 3 (a reasonably unlikely failure on each year). Risk B (Purple) has a higher Probability of Occurrence, placing it on the PoF 4 column.

Risk A as an extreme consequence for the Environment, should it happen (CoF 5), a reasonably low consequence on Safety (CoF 2) and low consequences both on Network Performance and Financial, it is placed on the matrix according with the line of the highest consequence (CoF 5) and according with the expected probability of occurrence (Pof 3), therefore sitting on quadrant E3. It is classified as an extreme (unacceptable) risk; therefore, it must be mitigated.

Risk B has average consequences on Safety, Environment and Financial, and a reasonably low consequence on Network Performance. It is placed according with the highest CoF, so the line of CoF 3. It is placed on quadrant M3 given its PoF. It is therefore a risk classified as average (tolerable). It should be mitigated if the quantitative assessment of the value of risk is higher than the cost of mitigation initiatives. Otherwise, it must be monitored, guaranteeing that it does not evolve towards an unacceptable risk.

The risk definitions (unacceptable, tolerable) are related with the risk aversion of the organization, and therefore must be set by the Board of Directors, with the inputs provided by the Asset Management area.

	Consequence of Failure (€)					Yearly Probability of Failure (%)				
	Level	Safey	Environment	Network Performance	Financial	PoF 5	PoF 4	PoF 3	PoF 2	PoF 1
						100-50	50-5	5-0.5	0.5-0.05	0.05-0
Seveity Level	CoF 5					E1	E2	E3	M1	M5
	CoF 4					E3	E5	M2	M6	B1
	CoF 3					E6	M3	M7	B2	T5
	CoF 2					M4	M8	B3	T6	B8
	CoF 1					M9	B4	B8	B9	B10

Figure 5 - Risk Matrix – application example

DPlan can assess the risk of failure of the entire HV and MV network, as shown in Figure 6, providing output reports assessing that risk.[7]

[7] DPlan provides two reports in excel format, one with the parameters associated with the risk analysis, and another with the auxiliar parameters that define the risk calculated for each individual asset.

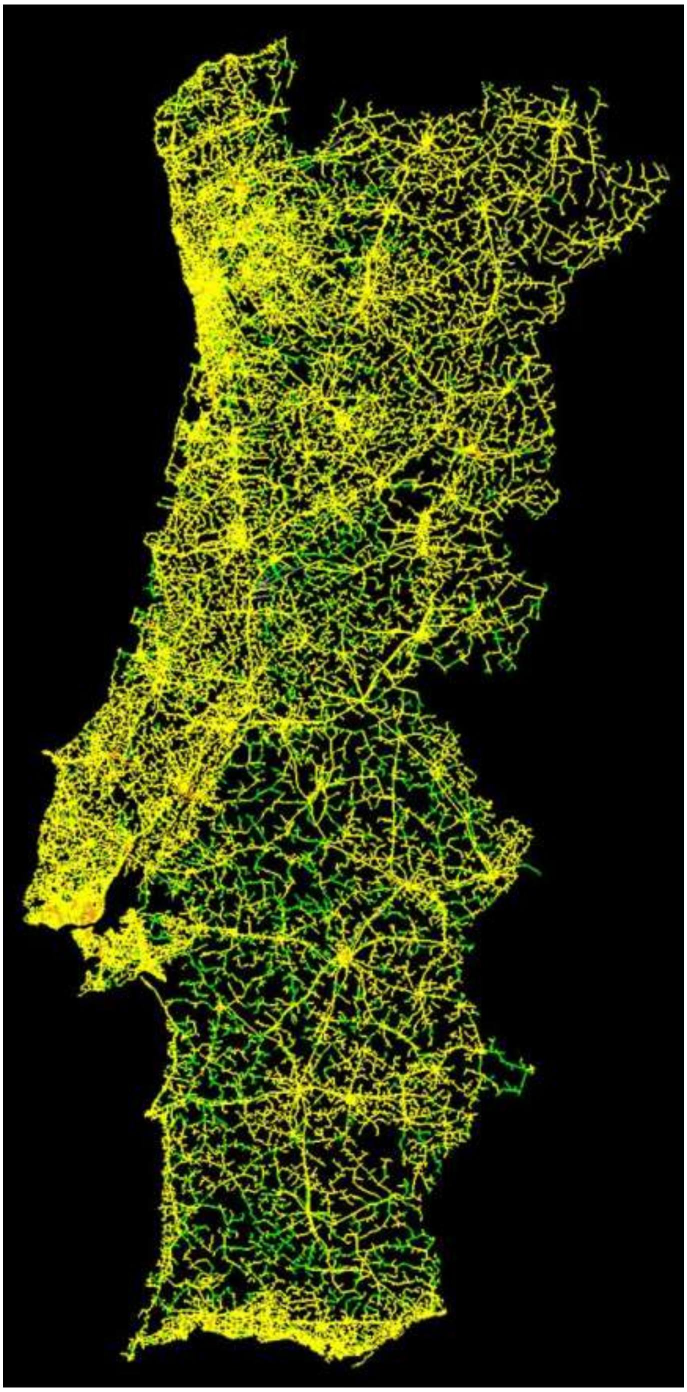

Figure 6 - E-REDES' MV network presented in DPlan

Two examples of risk analysis for a subset of the network can be illustrated, as shown in Figure 7, for an urban and a rural MV network. It presents a network with the maximum risk filter selected, highlighting each branch and site in the network with the colour corresponding to the highest risk classification in the risk matrix for each asset.

Figure 7 - Urban (left) and rural (right) MV networks, showing only HV/MV substations to improve readability

The software enables to quantify individual asset risks, as well as assessing the overall risk of network assets and the risk per asset category, and for each risk dimension.

Therefore, it enables us to visualize the total risk in euros for each asset category and to insert them within a risk matrix, as shown in Figure 8, with an example for overhead and underground line segments, HV and MV.

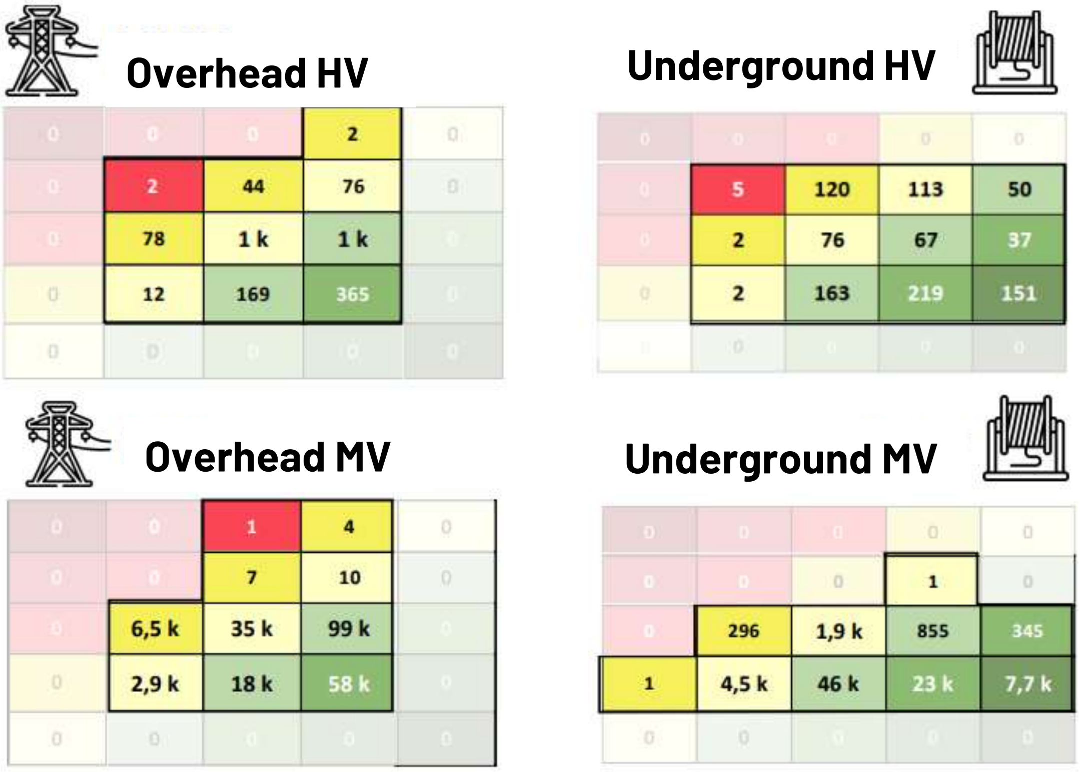

Figure 8 - Positioning of HV and MV overhead lines and underground cables in E-REDES' risk matrix (example)

For an urban network, the safety vector tends to be the dominant risk vector for overhead lines. Figure 9 shows the Safety CoF filter on the left and the Safety Risk filter on the right. The CoF filter shows two HV overhead lines in orange, several overhead HV lines in yellow and many MV underground cables in light grey are illustrated in the Risk filter with the black background. The

HV lines in orange in the CoF filter are only coloured in light yellow in the Risk filter. This can be explained because even though they have high consequences in case of failure, their PoF is low, mitigating the overall risk in this vector. Furthermore, explaining why these two HV lines have high CoF is important. The aggravating factors calculated by combining the contextual information with the asset characteristics for these two lines are the following:

- Proximity (< 25m) to more than 100 customers.
- Over high-speed roads. Figure 10 (left) zooms in on the overhead line crossing a highway.
- Passing over or near "Recreational Areas" such as parks, gardens, etc. Figure 10 (right) shows the overhead line passing near an amateur sports field.

The light grey MV cables have a different colour in the filter because they are underground and thus considered to have minimal safety risk in case of failure.

Figure 9 - Safety CoF filter layered over google maps (left) and Safety Risk filter over black background for better visibility (right)

Figure 10 - Overhead HV line with high CoF passing over highway (left) and near a sports field (right)

Figure 11 shows the impacts of the environment vector on the CoF and Risk of the assets. As can be seen in the figure, most assets are in dark or light green and light grey.

Again, the light grey represents the underground MV cables with no oil and minimal risk in case of failure. The light and dark green HV lines represent the CoF and Risk for the environment in case of failure, which are very low in an urban setting.

Figure 11 - Environment CoF filter (left) and Environment Risk filter (right). Both filters are predominantly green for overhead lines due to the urban nature of the network analysed

The network performance vector relies on the load data (which in this example was from the 18th of May 2022 at 18:00), the power-flow simulation and the reliability analysis performed by DPlan.

Figure 12 presents the results of the risk filter for the network performance vector. The results show three different colours of risk, light green, light yellow and yellow, from lowest to highest risk, respectively. The only asset in yellow is the left transformer in the HV substation. This can be explained because the left transformer has significantly higher power flowing through it than the right transformer and has higher repair times than the left HV circuit breaker.

The HV circuit breaker on the left and the transformer on the right are coloured in light yellow. Despite having different power flowing through them and different repair times, these two assets have similar values of ENS.

Figure 12 - Network performance risk filter in the network (left) and zooming in on the HV substation (right)

Figure 13 shows the Financial CoF for the assets in this example. The circuit breakers in the substation are coloured dark green (the lowest CoF colour), and the overhead HV lines and underground MV cables are coloured light green. This vector's highest financial consequences and risk are the HV/MV transformers in the substation, as they are the most expensive and hard-to-replace assets.

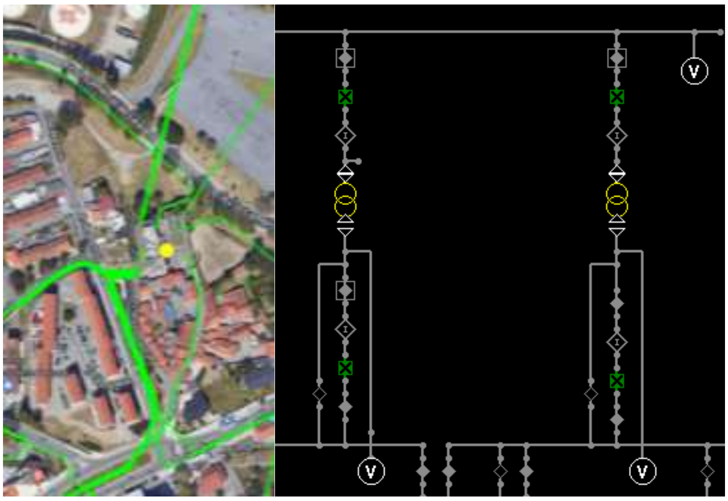

Figure 13 - Financial CoF filter in the network (left) and zooming in on the HV substation (right)

2.1.2. Modernization investment and maintenance strategies

80% of E-REDES' total HV+MV line length is established as overhead lines, which pose challenges regarding vegetation management. In Portugal, Decree-Law 124/2006, which establishes the actions preventing forest fire hazards, defines the concept of corridors for solid fuel management associated with infrastructures established in forest areas.

Each municipality is to establish its plan to prevent forest fires, which should define the regions requiring for solid fuel management. As for distribution networks, the operator of overhead lines within the areas defined in those plans should establish corridors with a width of 7 meters for each side of the outermost conductors. These corridors must be re-established every three years.

Therefore, E-REDES must establish both the normal line protection corridor and, where defined by the municipalities, fuel management corridors within forest areas.[8]

E-REDES defines the maintenance policies through maintenance manuals, which are regularly reviewed. These manuals define the Preventive Maintenance operations on assets – automatically associated with each asset in the SAP system, generating the appropriate intervention orders as scheduled.

Overhead HV and MV lines might be inspected by aerial platforms (helicopter or drone) or through visual inspections performed from the ground, which would also include measuring the resistance of the earth connection of pylons equipped with manoeuvre equipment (sectionalizers, reclosers or lightning arresters). Ground inspections are classified as condition-based maintenance, while aerial inspections are classified as preventive maintenance operations.

[8] Accounting criteria allow to consider protection corridor maintenance as OpEx, while fuel management corridors instalment and renew is CapEx.

Aerial inspections must be conducted every three years for all overhead HV and MV line segments. Therefore, based on the data presented in Table 1, E-REDES performs aerial flights on about 27,000 km of overhead lines per year[9].

Furthermore, inspections of HV and MV overhead lines by ground crews might be executed, with the technicians having two documents where data must be registered – one associated with overhead lines, the other associated with earthing systems resistance measurements.

As for LV and the Public Lighting network, a visual and thermal inspection is performed every three years, assessing the condition of the several components associated with overhead assets. The anomalies recorded are classified into three categories, determining the deadlines for their resolution (condition-based maintenance, CBM).

For HV and MV underground cables, the only preventive maintenance tasks are visual inspections of cable terminals in the installations to which they are connected (primary or secondary substations or switching stations).

E-REDES defines CBM programs, including actions to be scheduled for the next year (y+1) or two years henceforth (y+2), which are included in the maintenance budget for non-urgent interventions.

Corrective maintenance interventions might be executed to repair a faulted component.

Supporting the PDIRD-E, whose latest document was completed in October 2024, describing the investments to be made on HV and MV networks during the 2026-2030 period, and which is to be reviewed every other year, E-REDES prepares a document analysing the asset modernization investment requirements for a 10-year horizon (associated with that PDIRD-E, the assessment will be made for the 2026-3035 period).

ISO 55001 defines an asset management system on which E-REDES has been certified since 2022 [4]. The standard describes the SAMP or Strategic Asset Management Plan. E-REDES' SAMP defines the strategic objectives for asset management and evaluates the risk of not fulfilling those objectives.

2.1.3. Underground and Overhead Networks Life-Cycle Asset Risk Management in E-REDES

Section 2.1 described E-REDES' methodology for underground and overhead asset management, with section 2.1.1 describing how to estimate asset failure risk and section 2.1.2 modernization and maintenance strategies.

The evaluation of the life-cycle risk of failure implies an assessment of the ownership costs during the life-cycle of these assets and their probability of failure during their life-cycle.

Even if CNAIM [1] provides insights into the evolution of the probability of failure during the life-cycle of network assets, it is not easy to refine those models for linear assets due to their complexity and multiple asset characteristics and ages associated with each feeder or segment.

[9] Based on 2022's plan. Total value may vary per year, according with planning circumstances and tests concerning the use of alternative flight solutions to perform the prescribed tasks.

E-REDES has developed a model assessing the condition of HV overhead line segments condition (health index) and probability of failure [5], according to the CNAIM methodology [1], allowing to project the expected evolution of the condition and probability of failure.

It is presented in Figure 14 (top) the aggregate results for the line segments in exploration, bottom-left the detail for a particular segment (example) and bottom-right the projected evolution of the health index of the several segments until 2033.

Figure 14 - Aggregate values of health index for the HV overhead segments (top), detailed analysis for an HV overhead line segment (bottom, left) and forecasted evolution of health index for overhead line segments for a 10-year horizon

E-REDES is planning to expand the presented model towards MV overhead lines. It is also developing a project with an external consultant – OrxaGrid – to establish a condition and probability of failure model for 10 kV underground cables through the combination of the several data layers that describe the context, characteristics, and operational history of these assets (GIS, SAP, SCADA, landbase data).

2.2. ENEDIS UNDERGROUND AND OVERHEAD LINES ASSET LIFE MANAGEMENT: KEY ELEMENT

Enedis is the main French Distribution System Operator. Its network covers 95% of continental France and connects 37 million customers. It is the biggest power distribution network in Europe. Table 3 gives key figures about the network components.

Table 3 – Enedis operated assets key figures

Asset	Unit	Quantity (end of 2021)
Primary Substations	#	**2,300**
MV networks (mostly 20 kV)	**km**	**658,800**
Overhead	km	317,500
Underground	km	341,300
Secondary Substation	#	801,400
LV networks	**km**	**732,900**
Overhead	km	381,000
Underground	km	351,900

Classically, the simplified life cycle management of underground cables and overhead lines at Enedis can be broken down into several key stages: investment, operation, maintenance, and end-of-life disposal.

2.2.1. INVESTMENT

Article 32 of European Directive 2019/944 on the internal market for electricity, part of the "Clean Energy Package", was transposed into French law by order of March 3rd, 2021, creating a new article L322-11 to the Code Energy. This article declines the new obligation to DSOs serving more than 100,000 customers to publish a development plan network at least every two years, agreed with the parties' stakeholders, indicating the planned investments for the next 5 to 10 years. Enedis recently published a preliminary document fulfilling the obligation [5]. This document describes the different levels of consultation between all stakeholders of the French electric system to organise investments on the networks, at the country level and at a local level.

The economics of Enedis as a DSO responds to a logic of mass investments: Enedis makes hundreds of thousands of unit investments annually, which are, taken one by one, for the most part, inexpensive and relatively quick to implement once the locations are known. Therefore, the number of new connections to the grid is the main exogenous parameter in Enedis' investments. In addition to this logic of responding to user demand for connections, there is also the logic of good management over time of the industrial tool at the French level, the public distribution network.

The main principles that apply to Enedis' investments are:

- **Controlling the unit connection**: choosing the right technical solution (voltage level, type of cable, route, etc.), limiting the environmental impact, industrial management of the costs and deadlines of the construction process.
- **Controlling mass effects**:
    - Standardisation of processes;
    - Forecasting of skills and materials according to the demand for connections which is or will be arriving;
    - Detection of new trends, and exchange with the transport network in the event of a need to reinforce the upstream network.
- **Controlling the technical-economic analysis** for reinforcement, renewal, and modernisation decisions, independent of new connection and which are taken at the optimum of multiple parameters:

- Current and local assessment of different potential future scenarios, especially regarding load;
- Measured and predictable incidentology according to climatic hazards or specific risks;
- Optimisation of the implementation schedule, costs and environmental impact, concerning the benefits on quality of service and resilience, by considering different solutions, namely: traditional investments, innovative equipment, and calls for flexibility;
- Possibility of addressing several network issues simultaneously;
- Long-term operability of the network;
- Technical framework with its complexity: voltage plan, protection plan, etc.

2.2.2. Operation and predictive maintenance

Investments are made considering day-to-day operation and management. The design rulebook is defined to ensure that the network is always operated following safety and regulatory requirements. It ensures this in two ways:

- Most of the time, by ensuring that the design of the structures allows for this;
- The rest of the time, by giving the dispatch team sufficient leverage to ensure this (e.g. for maintenance task work or fault management)

In 2021, Enedis dedicated more than 320 million euros to preventive maintenance measures. Historically, vegetation management has been mostly limited to pruning trees around overhead lines. Nowadays, with smart technologies, which make it easier to collect data on network state, both on MV and LV networks, some predictive maintenance tools are emerging.

Predictive maintenance on overhead MV lines: Enedis is developing a system based on early signals analysis, more specifically on the localization on the network of the source of multiple shot reclosing. Faulty equipment or insufficient tree pruning usually triggers these transient faults. The problematic network part is localized by crossing signals from different fault indicators on the feeder. These fault indicators communicate with the centralised system through the smart meter IT infrastructure or the IOT object Enedis' platform. Thanks to massive data processing crossing the transient faults history with network characteristics and environment data, the suspect network parts are identified and notified to field operators, which can quickly go on site, check on the source of the transient faults (branches, faulty equipment, ...) and plan a maintenance work before a permanent fault happens. The system is described in the paper [6], and an example is provided in Figure 15.

Figure 15 - LEFT: in red, the network section is likely to contain an anomaly. RIGHT: branch on the line found by field operator (©Enedis)

<u>Predictive maintenance on overhead LV networks:</u>

Enedis developed a tool called CartoLine, using the mass of data relating to the voltages observed by Linky smart meters (illustrated in Figure 16). It makes a decisive contribution to the management of predictive maintenance of the low-voltage network. For experts, it offers a Dataviz interface that facilitates data analysis. But above all, an artificial intelligence system uses these analyses in "supervised learning" to be able to carry them out autonomously. These analyses aim at discriminating situations that indicate a voltage anomaly or even a future incident leading to an electrical cut on the LV network. The problems detected are for example often at the customer connection. The question CartoLine answers can be summarised as follows: do the observed voltage data lead to the programming of a technician's intervention in the field to avoid an outage?

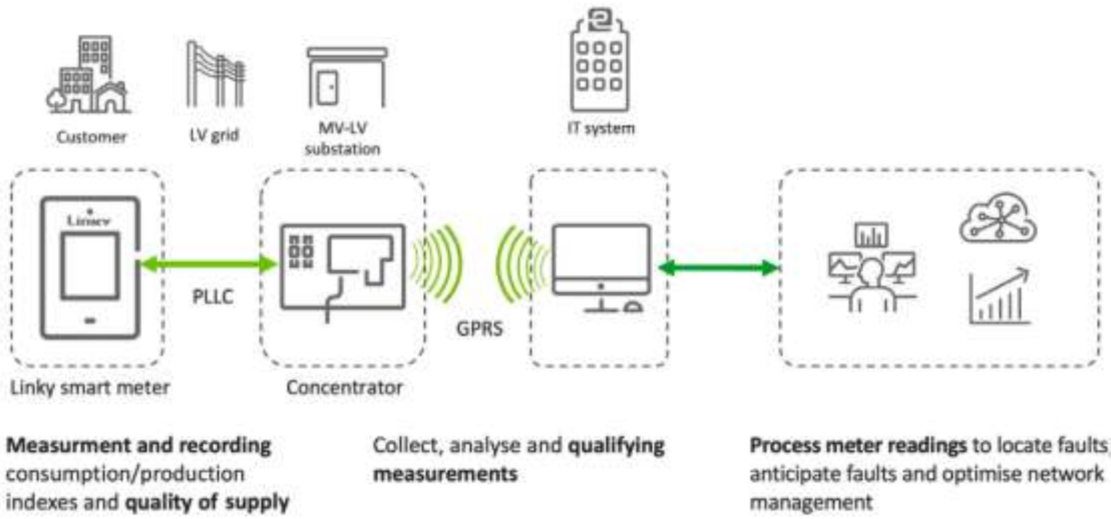

Figure 16 - Overview of the Linky system (©Enedis)

2.2.3. NETWORK RESILIENCE AGAINST WEATHER HAZARDS

An important aspect of power distribution network life is the climatic risks they are facing. After the two big storms of December 1999, EDF[10] committed to re-energising 90% of the customers

[10] Enedis became in the mid 2000's an independant subsidiary

within less than five days in case of such an event. A climate hazards resilience plan was developed to achieve this objective. Its main components are:

- Identify and map potential risks on the probability of occurrence of various meteorological hazards;
- Diagnose the status of all network components concerning these risks;
- Build targeted action plans specifying the safety objectives, the actions to be taken and the criteria for prioritising the actions.

Since then, Enedis reinforced the initial plan by integrating heat waves and floods. For this purpose, new machine learning and big data technologies helped building tool to better anticipate and prepare itself against these risks. In the paper [7] a method to forecast outages on the MV underground network during heatwave is described and in the paper [8] we describe how big data technology allows the development of a flood impact visualization tool to improve its resilience to floods, with results illustrated in Figure 17 and Figure 18.

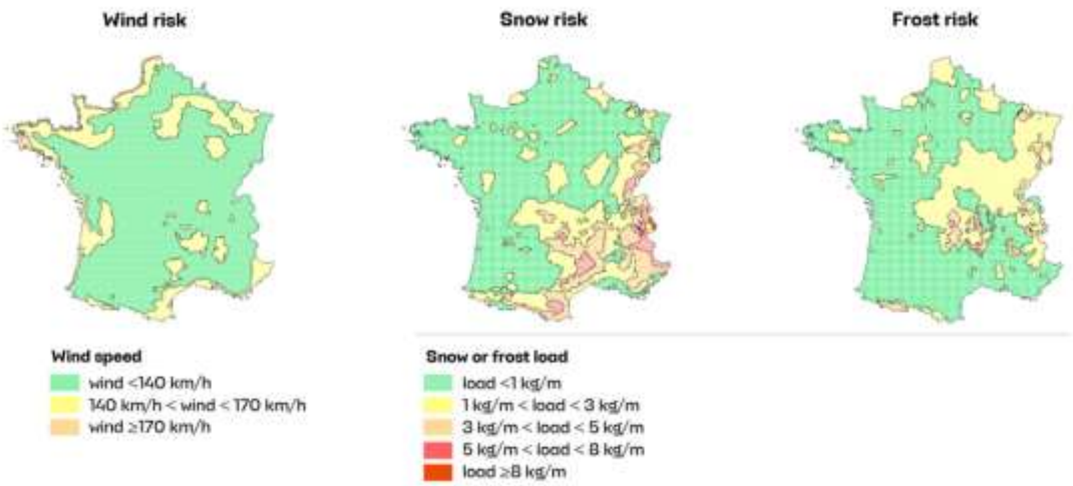

Figure 17 - Examples of climate hazard maps for the vicennial (20-year) risk of wind, snow, and frost [5] (©Enedis)

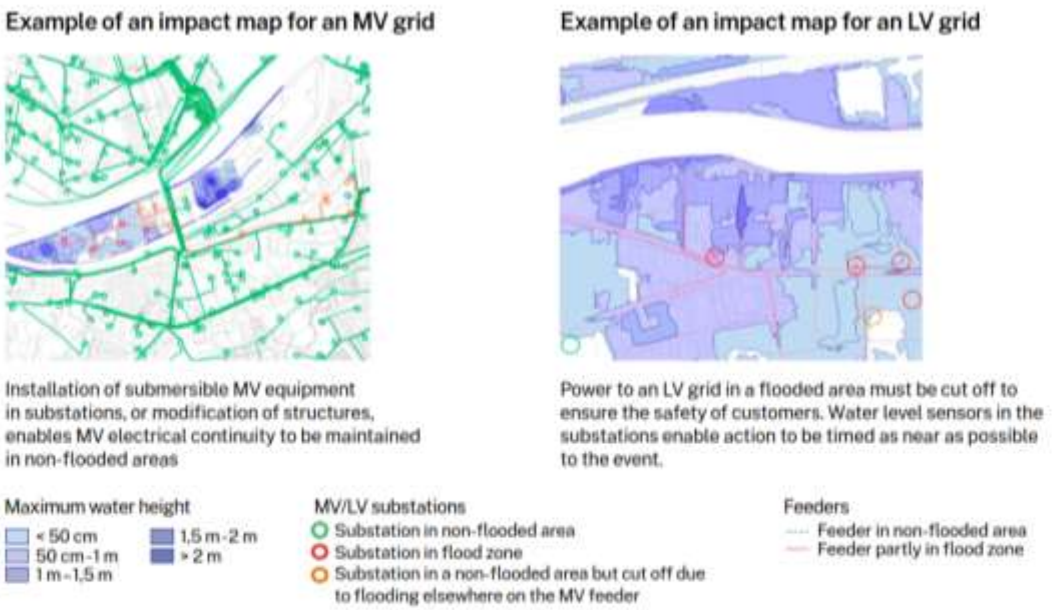

Figure 18 - Examples of the use of 3D flood mapping to improve network resilience [5] (©Enedis)

2.2.4. END-OF-LIFE MANAGEMENT: RENEWAL OF RISKY NETWORKS

Enedis deploys targeted renewal policies to make networks more reliable. To reduce the number of failures that could affect the continuity of supply, network components with abnormally high failure rates, and only these, are replaced by ones with better performance. In 2021, Enedis invested more than €1 billion in upgrading the networks, i.e., improving resilience and ensuring that the continuity of power supply is maintained daily. These investments are set to increase over the next few years. The modernisation and renewal programmes provide specific responses to the need to increase resilience or day-to-day reliability depending on the network components involved and the resources available to carry out the corresponding work.

These different policies are described hereafter:

- **Planned refurbishment on overhead MV network:** This policy regards overhead lines not taken care of by the weather hazard resilience plan described before. This programme aims to bring and maintain the reliability of the overhead MV network to a level close to that of a new overhead network. It consists of a targeted replacement of equipment that does not comply with the technical standard, with a view to investment efficiency, control of the ecological impact and reducing the carbon footprint. The programmed renovation programme allows for upgrading all HV overhead lines in 25-year cycles. Lines that have been diagnosed in year N, whether replaced, are considered reliable for the next 25 years and will, therefore, be diagnosed again around year N+25. After a ramp-up period, this will make it possible to make approximately 9,000 km of overhead HV network reliable per year. The networks eligible for programmed renovation are prioritised using mass data processing [ref paper Madrid storm]. Solutions for industrialising scheduled renovation are being implemented, for example, using an artificial intelligence (AI) module to facilitate diagnosis by drones or on foot.
- **Replacement of open wire LV networks:** The ambition is to eliminate almost all LV open (bare) wire overhead lines by 2035, as these structures have an incident rate five to six times higher than insulated overhead lines or underground cables. This should avoid around 15,000 incidents per year, improve the supply quality on low-voltage networks and be more resilient to climatic contingencies.

- **Replacement of faulty underground network from older technology eras**: paper insulated cables, as well as the first generation of synthetic insulated cables, are generally less reliable than current synthetic cables: they account for an average of 9 annual incidents per 100 km, compared to 1 annual incident per 100 km for synthetic cables in urban areas. However, this average value masks a great disparity in the behaviour of this inventory's various segments. It is therefore necessary to maximise the efficiency of the investments by prioritising the cables with higher risks of failures, weighted by the impact on the customer. In the papers [9] and [10] we describe how artificial intelligence allows choosing network portions with higher risks of failure. This method is used for LV and MV networks.

2.3. State Grid Shanghai Application of Thermal Life Analysis in Cable Binding

State Grid Corporation of China is responsible for the asset management of power equipment within its operational scope. The asset management system of State Grid covers equipment procurement, operation, maintenance, and retirement, and improves management efficiency through information technology to achieve refined asset management. In the bidding and procurement of power equipment, the evaluation criteria mainly include technical score, commercial score, and price score, and suppliers are regularly evaluated to ensure the safe operation of the power grid. The following is a new method we attempted in cable procurement.

To improve the decision-making level of equipment procurement, we have carried out the life analysis of 110 kV power cables and studied Life Cycle Cost (LCC). A cable heat transfer model was established and based on the temperature rise sampling test of cables from various manufacturers, a thermal life assessment was carried out at the procurement stage, an LCC model was established based on the thermal life assessment, and the results of the research have been successfully applied in an actual bidding and evaluation work.

2.3.1. LCC Principle

Life cycle cost management is a management methodology to minimize the whole life cycle cost by comprehensively considering the whole process of planning, designing, manufacturing, acquiring, installing, operating, maintaining, retrofitting, renewing, and up to the end of life of the equipment. The applied LCC modelling framework is:

$$LCC = C_I + C_O + C_M + C_F + C_D \tag{1-1}$$

Where *LCC* is the total cost of the cable over the whole life cycle;
C_I is the initial input cost;
C_O is the operating cost;
C_M is the service and maintenance cost;
C_F is the failure cost;
C_D is the cost of equipment decommissioning and disposal.

The focus is on analysing the differences in the thermal life of cables from different manufacturers, which affects the operating costs C_O.

2.3.2. THERMAL LIFE ANALYSIS OF CABLES

2.3.2.1. THE IDEA OF THERMAL LIFE ANALYSIS

Even if it meets the relevant technical standards, there are still some differences in the parameters of cables from different manufacturers. Differences in resistance values will lead to differences in operating losses, leading to differences in cable temperature rise. The difference in the thermal resistance coefficient of the main insulation and outer sheath material will lead to differences in the operation of the cable heat transfer performance, which in turn leads to differences in the temperature rise of the cable. Differences in temperature rise in operation can lead to differences in the thermal life of XLPE, the main insulation of the cable, as shown in Figure 19.

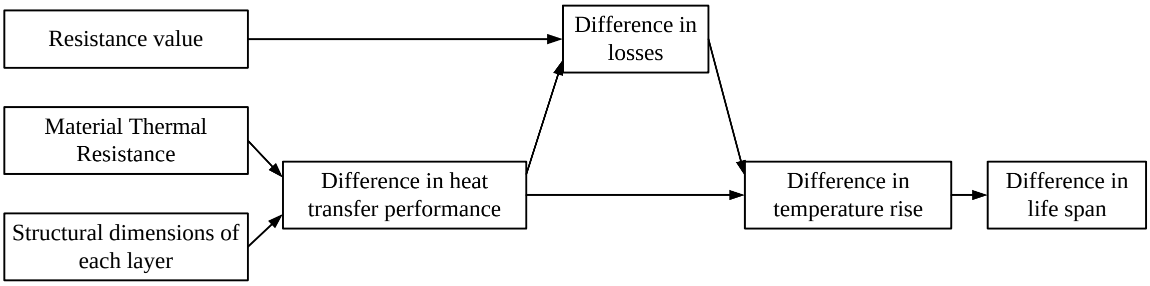

Figure 19 - Difference between cable parameters and life span

2.3.2.2. RELATIONSHIP BETWEEN TEMPERATURE AND LIFE

A close relationship exists between the life span of XLPE insulating materials and the long-term operating temperature.

In chemical reaction kinetics, from the reaction rate equation and Arrhenius equation, the heat ageing equation of polymer materials can be known as:

$$\lg \tau = a + \frac{b}{T} \tag{2-1}$$

Where: τ and T denote the life span (in h) and ageing temperature (absolute temperature in K) of the material, respectively; a is a constant related to the specified failure properties; and b is a constant related to the activation energy.

$$b == 0.401 \times E/R \tag{2-2}$$

Where: R is the gas constant (8.314 J·mol^{-1}·K^{-1}) and E is the activation energy of the material.

According to the relevant research results, the following thermal ageing equation is used to calculate the thermal life of cable insulation materials:

$$\tau = 10^{-10.673+5346/T} \tag{2-3}$$

2.3.2.3. HEAT TRANSFER MODELLING OF CABLES

The cable structure we are studying, from the inside to the outside, is in this order: conductor, conductor shield, XLPE insulation, insulation shield, buffer layer, crumpled aluminium sheath, and outer sheath. The corresponding heat transfer equation is:

$$I^2[RT_1 + R(1+\lambda_1)(T_3+T_4)] + 0.5W_dT_1 = \theta_1 - \theta_C \tag{2-4}$$

Where:

I: Current rating (A)
θ_C: Ambient temperature (℃)
θ_1: Cable conductor temperature (℃)
R: Conductor AC resistance (Ω/m)
W_d: Dielectric loss of insulation
λ_1: Sheath and shield loss factor
T_1: Thermal resistance of insulation between conductor and metal sheath (k·m/W)
T_3: Thermal resistance of the cable sheath (k·m/W)
T_4: Thermal resistance between cable surface and ambient air (k·m/W)

The basic process of cable thermal analysis is divided into three steps: (1) loss calculation; (2) calculation of thermal resistance; and (3) calculation of temperature and current rating. Based on the results of the first two steps, the parameter values can be substituted into the equation to calculate the maximum current at a given conductor temperature or the conductor temperature at a given continuous current.

2.3.2.4. ESTABLISHMENT OF THERMAL MODELLING BASED ON SAMPLING DATA

State Grid Shanghai Electric Power Company has carried out third-party sampling inspections of electric equipment and obtained much testing data on cable products. According to the recent sampling inspection of 800 mm^2 110 kV XLPE cables, DC resistance, average thickness of the main insulation, conductor temperature rise, and sheath temperature rise are obtained, as shown in Table 4; the thermal model is established based on these data, and the thermal resistance coefficients of the main insulation of the cable are calculated (also listed in Table 4). There is a certain difference in the performance of materials from different manufacturers, and the thermal resistance coefficient of the insulation of manufacturer B is significantly higher than that of other manufacturers.

Table 4 – Cable sampling and calculation results

manufacturer	20°C DC resistance (Ω/m)	average thickness of main insulation (mm)	conductor temperature rise (K)	sheath temperature rise (K)	main insulation thermal resistance coefficients
A	0.0211e-03	16.3	79.6	20.9	3.537
B	0.0204e-03	16.0	81.7	21.3	3.919
C	0.0210e-03	16.2	78.5	20.7	3.481
D	0.0210e-03	16.1	77.6	19.5	3.407
E	0.0210e-03	16.0	78.1	20.1	3.454

2.3.2.5. LIFE CALCULATION

The running current of the cable is difficult to determine. XLPE cable design life is generally 30 years. To analyse the influence of the cable thermal characteristics on the life, here we calculate the reverse cable current according to the life, after trial calculation, assuming the long-term running current of the cable is 896 A. In this case, the cable life is about 30 years.

The cable life of each manufacturer under 896A current is calculated, as shown Table 5. The calculation found that the difference between conductor resistance value and structure size is very small, and the influence on loss and life is also very small. In contrast, the thermal resistance coefficient of insulation material greatly influences life.

Table 5 – Calculation results of life and loss

manufacturer	loss(W/m)	conductor temperature (°C)	life span (year)
A	27.3789	33.8902	31.06
B	27.2883	35.2200	26.78
C	27.3063	33.9571	30.83
D	27.4494	33.8926	31.05
E	27.3287	34.1514	30.17

2.3.3. LCC-BASED CABLE BID EVALUATION

In this LCC bid evaluation, the cable design life of 30 years is taken as the calculation benchmark, and through the life cycle analysis of the cable body, all the costs incurred during the life cycle of the cable are discounted to the benchmark year (zero years) for the present value calculation, and the present value is adjusted according to the life span of each manufacturer. The specific adjustment method is as follows: for every increase of 1 year in the life span calculation value compared with the benchmark of 30 years, the corresponding LCC present value is reduced by 1% based on the previous calculation, and for every decrease of 1 year, the LCC present value is increased by 1% based on the previous calculation of the manufacturer's offer.

Table 6 shows the present value of the LCC for the five manufacturers, which will affect the award outcome.

Table 6 – Cable LCC calculation results

manufacturer	life span	LCC value of cable
A	31	0.116
B	26	0.130
C	30	0.112
D	31	0.119
E	30	0.112

3. Describe the best tools and practices used in underground and overhead network asset management

In this Section, best practices and tools associated with several aspects associated with underground and overhead asset management are described.

3.1. Optimal life-cycle management

This section provides an overview of best practices and experiences regarding life-cycle management.

3.1.1. E-REDES is developing condition assessment models fostering optimal life-cycle management

Life-cycle management must consider the trade-offs defined through the ISO 55000 standard series – short-term/long-term, Maintenance/Replacement and Risks/Costs.

E-REDES fostered its analysis capabilities by developing analytical models of asset remaining useful life (RUL) and probability of failure (PoF), internally and with academic partners.

The first such model to be developed is dedicated to power transformers (PT) and was developed with INESC TEC under the PATH (Predicting Transformer Health) [11]. The outcome of that project allows for evaluating the condition, RUL and PoF of PT, hence providing an input to failure risk analysis at the individual transformer level and allowing to appraise the expected number of transformer faults for any given year, a concern in the presence of ageing assets. A great proportion of PT used by E-REDES were built during the 1st half of the '80s and, therefore, have around 40 years, thus approaching the end of their useful lifespan.

The methodology benefits from the visual inspection of PT, DGA, and the RUL. It is based on the past and expected evolution of DP[6], as an indicator of the degradation of the paper.

In the RUL model, the team used estimators of the model parameters obtained by the least squares method to determine the coefficients associated with each factor considered.

For the analysis of the paper condition, it was considered an annual time metric, the list of significant factors and their relative importance for the model using the Mean Standard Error Percentage (%MSE). The higher the %MSE, the greater the factor weight in the model. The model was generated using 1737 samples covering 230 PT. Table 7 shows the selected factors, the %MSE value and the respective impact on the response variable $\Delta d(t)$.

Table 7 – Critical Factors of the RUL model and its impact

Factor	%MSE	Impact
Density	18%	Negative
PC1[9] (oil quality)	27%	Negative
PC2[10] (oil humidity)	15%	Negative
Total Load	8%	Positive
Delta tangent	11%	Positive
Connection group	44%	Positive/Negative
Manufacture year	66%	Negative

With the obtained results it is possible to conclude that a set of PT must be replaced in a time horizon of 5 to 10 years since they are expected to reach their considered end of life.

Figure 20 shows the probability of the paper reaching the end of life for a given number of PTs by 2020, as initially assessed by the model in 2019 (grey curve), or by 2023 (red curve) if we consider the most conservative scenario made by the RUL model (with a 95% confidence interval).

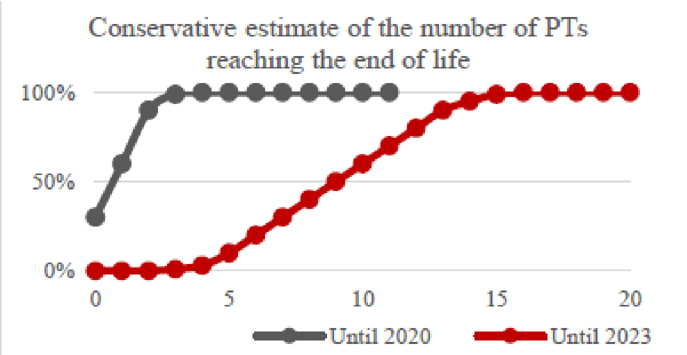

Figure 20 – Conservative estimate of the number of PTs reaching the end of life

E-REDES also developed other assessment condition models for different asset categories, including HV lines and cables, DC systems for UPS associated with primary substations and HV switching stations.

A highlight can be provided to switchgears, benefiting both from a short-term model developed through a machine learning methodology and used to assess the probability of a switchgear failing to operate properly to a command given by its protections, developed within the EDP Group [12], and another model for the assessment of the RUL, developed with INESC TEC, under similar methodological procedures as PATH.

As for the machine learning project mentioned, developed on a SAS platform, it allows data from the SAP system (which registers asset interventions). Furthermore, SAP contains the technical data associated with the switchgears in service (approx. 8,000).

The methodological approach that was followed can be divided into four main phases, each having a different SAS tool functioning as a technological support, preceded by an initial phase of data extraction from the Source System: (1) Data extraction from source systems; (2) Data treatment and Feature engineering - SAS Enterprise Guide[11]; (3) Data modelling - SAS Enterprise Miner; (4) Data visualization - SAS Visual Analytics, as illustrated in Figure 21.

[11] It deserves to be noted that often a great proportion of the time and effort allocated to large data projects is the verification and eventual correction the date imported from exiting databases.

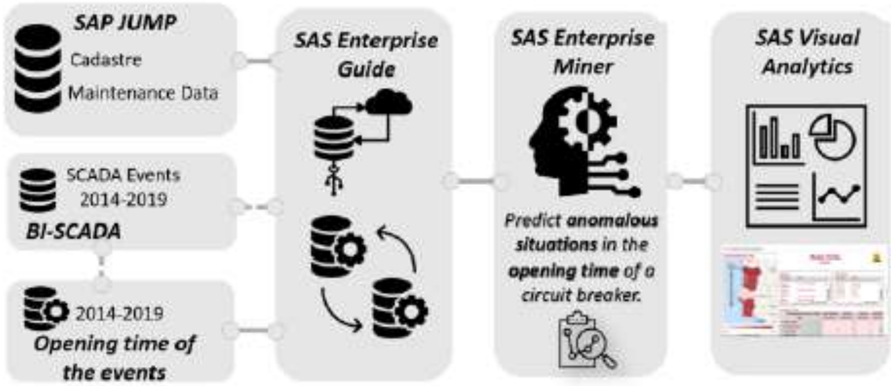

Figure 21 – Methodological approach to build the model

The data was divided into Training Data, Validation Data and Test Data. Training data allows to train of the forecasting algorithm. Based on this data, the model will look for patterns and/or identify correlations between the input and target variables.

Validation data avoids over-learning the predictive model to the training set. Without this set, in a limited situation, the model could only predict failure when the patterns found in the actual data followed exactly the patterns in the training data. To avoid over fitting, the model developed based on the training set is applied to the validation data and truncated in the iteration that minimizes the error in the validation set (or in the iteration from which the error in the validation set stabilizes). Thus, on the one hand, it avoids overfitting the model to the training data; on the other hand, we avoid unnecessary complexity.

The test data serves, as the name implies, to test data provided by the model since they are the data that best simulate actual data.

On SAS Miner, several predictive models were tested, belonging to the following three families: (1) Neural networks; (2) Decision trees; and (3) Logistic regressions. Ensembles were also considered, i.e., models that combine several predictive models (possibly from different families).

Two predictive models were created: (1) a 15-day model for planning predictive maintenance actions; (2) a 180-day model for planning predictive maintenance. In both models, the output is the probability, in the range of 0 to 1, that the Breaker will not open in the correct opening time when given the next protection command for the next 15 days or after 180 days. The discretization of this probability in a failure/non-failure (binary) prediction is made according to the following criterion: if the probability is less than 0.5, the model classifies it as 0, otherwise it classifies it as 1.

The selection criterion for the winning predictive algorithm was the Misclassification Rate, to minimize the error associated with the poor classification of the target variable. In both models, the winning predictive model was a decision tree.

A dashboard for the forecasting models was built in SAS Visual Analytics, presenting the model's results visually and appealingly and assisting the maintenance teams in planning their actions. Each model has a summary and detailed information, according to the user's preference. This platform is shown in Figure 22.

Figure 22 – Visualization platform obtained using SAS Visual Analytics

The variables selected in the model generated in the report in SAS Miner are shown in Figure 23. It is possible to conclude that there are three major groups. The "last opening times" are the most influential variables, proving the operational sensitivity. There is a second group with the "year of manufacture" and "entry into operation", "the type of control", "the means of interruption", and "the location of the circuit breaker". One last group is irrelevant (as shown in Figure 23 – comprising all the variables that didn't get any data).

It can be concluded from Figure 23 that the variables selected by the model for the failure forecast are Opening times history, Command Type, Year of Entry into Operation, Year of manufacture and Location (ARC).

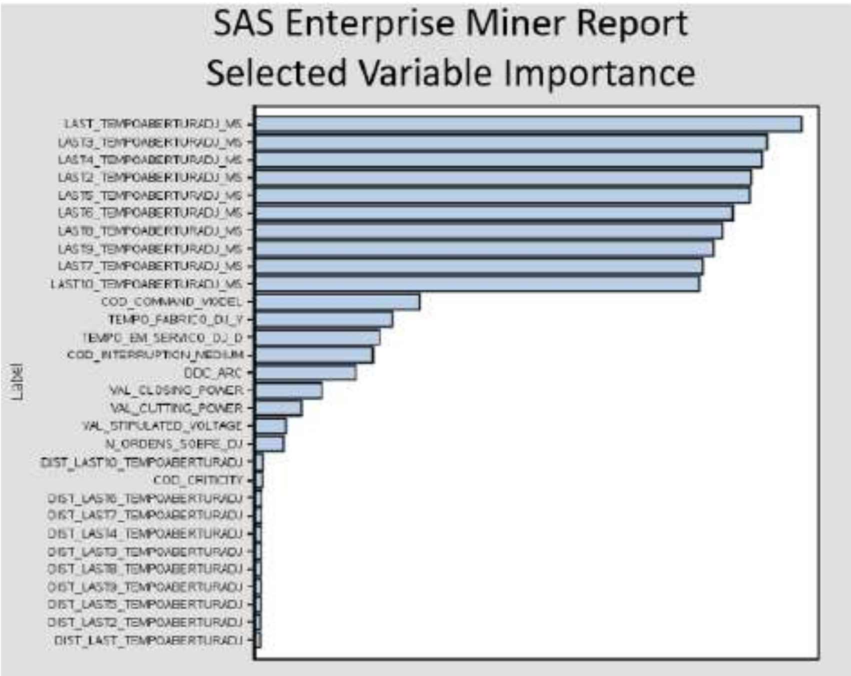

Figure 23 – Influential Variable of the model

The confusion matrix obtained confronting the predictions offered by the model with the observed reality is shown in Table 8. It shows when the model predicted a failure (Predictive Model value 1) and whether that failure happened (Real Event 1) or not (Real Event 0). It also shows when the model did not predict a failure (Predictive Model 0) and whether a failure occurred (Real Event 1) or not (Real Event 0). A good model will have a high proportion of True Negative events (the model did not foresee a failure and there was no failure), and True Positives (the model predicted a failure and it happened).

Table 8 – Confusion Matrix[12]

		Real Events	
		0	1
Predictive	0	**90% TN**	10 % FN
Model	1	18 % FP	**82 % TP**

Overall, it is a valid conclusion that, with the source systems used (SAP, BI-SCADA), and even with the well-known difficulties related to data quality, it is possible to build capable predictive models and to do it essentially using internal knowledge about techniques and advanced analytics tools. This project thus opens an optimistic perspective on the future of predictive maintenance of HV and MV circuit breakers and it demonstrates that it is possible to derive value from the existing asset data.

The model was further field-tested within a region of E-REDES, assessing the performance regarding the capacity to improve the performance of switchgear, reducing the number of failures through preventive maintenance operations as determined by the model, and on the number of maintenance operations executed, when compared with the traditional, TBM strategy. Results showed that it was possible to decrease the number of failures without increasing the number of maintenance operations. Therefore, the preventive maintenance operations prescribed by the model were included in the Maintenance Manual as a tool that complements and substitutes other maintenance strategies. It does not fully substitute other maintenance interventions due to the difficulty of covering all failure modes (for instance, associated with corrosion evolution) through this model.

3.1.2. HIGHVOLT

HIGHVOLT, in cooperation with the university of Dresden, is developing new methods to monitor underground cables. The main part of the development is a new PD method using the transfer function of the cable (determined at regular intervals) to localize and determine each pulse of partial discharges (TruePD method). Results are spatially resolved PD views, risk analyses and recommendations of actions. The heart of the system is a transient recorder with implemented AI algorithms.

3.1.3. NEXANS SUPPORT FOR STRATEGIC ASSET MANAGEMENT FOR LINEAR ASSETS

When building a 5-to-10-year plan, anticipating the volume of assets to be replaced is a priority.

Online monitoring may not be sufficient to achieve such task. Indeed, it may not be economically viable to deploy monitoring at scale. In addition, today's solution may not predict on a 5-year time horizon probability of failure based on monitoring data only.

Combining different approaches from off-line and on-line monitoring and available data sources is essential to improve planning practices progressively. In addition, because of uncertainties, best practices in asset management recommend adopting a whole life cycle approach to

[12] TN – True Negative. FN – False Negative. FP – False Positive. TP – False Positive.

decision-making when it comes to replacement or major renewal decisions. The whole lifecycle approach requires consideration of both failure probability and consequences.

The CNAIM methodology is a good illustration of such an approach. The CNAIM framework provides the initial benefit of the calibrated probability of failure in the UK distribution networks failure event which can work as an initial proxy for other countries. The CNAIM methodology provides rules to establish evolving probability of failure law and current health scoring based on fixed influencing factors. Integrating those data in a software allows us to build a model in the future of the health index of the different assets that can be complemented by the consequence index capturing & monetizing risk of failure.

As an illustration of the Asset Electrical solution, shown in Figure 24, combines asset register and CNAIM framework to automatically provide risk metrics and health score distribution for different years in the planning horizon.

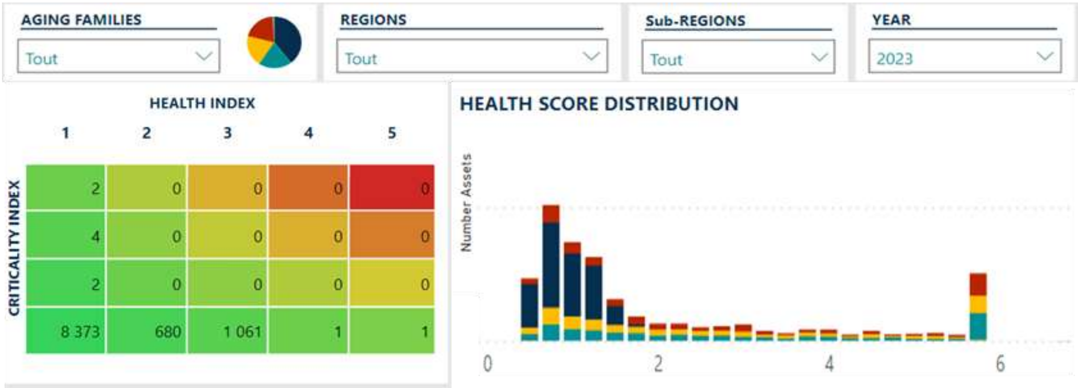

Figure 24 – Illustration of risk matrix & health score analysis

This information also allows us to run some simulations to validate the effect of different maintenance and renewal strategies on the KPI of interest, as shown in Figure 25.

Figure 25 – Illustration of typical simulation results, including operations planned based on defined strategies, resulting evolution of the health index, SAIDI or network financial value (non-exhaustive illustration of results)

Due to growing uncertainty, digital twin simulation provides the capability to run sensitivities analysis to assess potential risk and opportunities better. Most importantly, as the power grid evolves with new operational conditions due to the changing power mix and climate conditions, it becomes essential to rely on past event learnings and future event simulations to capture risks and conditions and design relevant long-term plans. This unlocks the potential to analyse the effect of climate change on network conditions and evaluate different technology change options, such as network burying options.

Digital twin simulation supports DSO by providing a comprehensive view of such uncertainty from a technical standpoint and an economic and environmental standpoint. Cables and lines represent a large financial value for a DSO; it is, therefore, essential to consider the financial impact of renewal strategy by modelling the evolution of the financial value of the assets together with the failure's consequences representing different types of risk (financial, environmental, safety, network performance). Finally, the availability of skills is also the centre of the strategy. Considering the need to renew the ageing grid, a large expansion plan could lead to a human resource shortage; hence strategic plan should consider resource constraints to deploy the most suitable strategy to be able to deliver the strategy.

Groupe E case study, Digital Twin Simulation Application in Switzerland

Groupe E, a DSO in Switzerland, has been deploying simulation digital twins since 2019 to support its strategic asset management activities. Embedding the CNAIM [1] methodology the solution deployed in Switzerland provides a long-term view on all relevant KPI. Several simulations have been developed, analysing more than one hundred thousand cable sections within the digital twin to verify the possibility of extending the lifetime of the assets considering both network performance, financial performance and impact on the end-user tariffs. Groupe E unlocked significant savings.

3.2. DATA ANALYTICS AND ASSET PERFORMANCE ASSESSMENT

This section provides examples of data analytics and asset performance tools developed by some DSOs.

3.2.1. ELEKTRO LJUBLJANA: IDENTIFIED FACTORS CORRELATING WITH DEFECTS BASED ON OPERATING EXPERIENCE

Replacing cables based only on their age turns out to be irrational. On the other hand, using modern data-driven approaches can be challenging, since some parts of the cable infrastructure can be a couple of decades old, many historical data might be lost or never collected at all. Elektro Ljubljana identified seven factors correlated to defects based on operating experience and available historical records to identify the most critical cable segments with available data. The approach is meant to prioritize cable replacement based on risk assessment; therefore, not only the health of the cable but also the consequences of failure are incorporated into the assessment. The methodology described in this section was also published in [13].

1. **Cable type:** Based on operating experience, as shown in Table 9, some cable types proved to have different weaknesses, making them vulnerable to failure.

Table 9 – Cable operating experience

Cable type	Operating experience
XHP	This category of cables was produced in the 1980s. The production technology was not fully developed, leading to air bubbles and water trees forming in the insulation, which in turn caused cable defects. Due to these unfavourable characteristics, the expected lifespan of these cables was shortened from 40 years to 33 years.
IPO 04	These are oil cables that were manufactured in the early 1980s. They lack mechanical insulation, making them prone to mechanical damage. This disadvantage is particularly noticeable when the cables are installed in cable sewers, especially at the junctions from pipes to cable pits. This disadvantage is not as prominent when these cables are buried in the ground.
IPO 13	These cables were produced from the pre-war era until 1980. The outer insulation is jute and bitumen, which deteriorates under external conditions. As a result, the mechanical insulation and lead sheath are exposed to the environment and degrade.
IPO 14	These types of cables feature an external insulation composed of PVC, which is robust and long-lasting. They were incorporated into the energy system post-1980.
IPZO	These are uncommon oil cables, each containing a single wire within their lead sheath. Their drawbacks include incompatibility with other cable types and the lack of cable joints.
IPHO	These oil cables are operationally reliable.
XHE	Reliable, newer, technologically advanced cables.

2. **Cable condition assessment:** Experts can assess the cable's condition by visually inspecting it. When the opportunity for visual inspection arises (during maintenance, inspection, intervention, etc.), the cable is graded based on the state of its mechanical protection.

3. **Defects or Number of Cable Joints per km:** The frequency of past defects strongly correlates with cable condition and serves as a predictor of future issues. However, historical defect records are often incomplete or missing entirely. In such cases, the number of cable joints can serve as an alternative indicator, as defects typically result in the installation of joints unless the entire cable is replaced. To ensure accuracy, joints should be counted separately for each cable section to avoid misattributing connections between different segments, which could lead to overestimation and misinterpretation of defect distribution.
4. **Cable age:** A strong correlation exists between cable age and reliability. According to our records, cables older than 35 have significantly more defects than cables under 35.
5. **Cable laying method:** Cable lying in a cable tunnel is easier to replace than cables laying directly in the ground. Therefore, we can accept a higher risk of defect. On the other hand, defects on cables set in a common infrastructure tunnel can cause damage to other infrastructure. Additional attention must be paid to cables running under buildings as they are impossible to approach and fix in case of a defect.
6. **Underground water:** Underground water can leak into the cable structure causing damage and defects. Based on operating experience, this is causing problems mostly on oil cables.
7. **Grid topology:** The time needed to restore electricity supply after defect depends on whether the cable is designed in open loop or radial line.

3.2.2. E-REDES Analytics Tools

Condition assessment projects are supported by an Analytics for Assets concept, allowing for the collection and usage of data from multiple sources (GIS, SAP, operational data associated with SCADA system and fault register, and external data that can provide context, such as topographical data and weather data). The models built allow for a better forecast of asset performance from the short-term to the long-term, as illustrated in Figure 26.

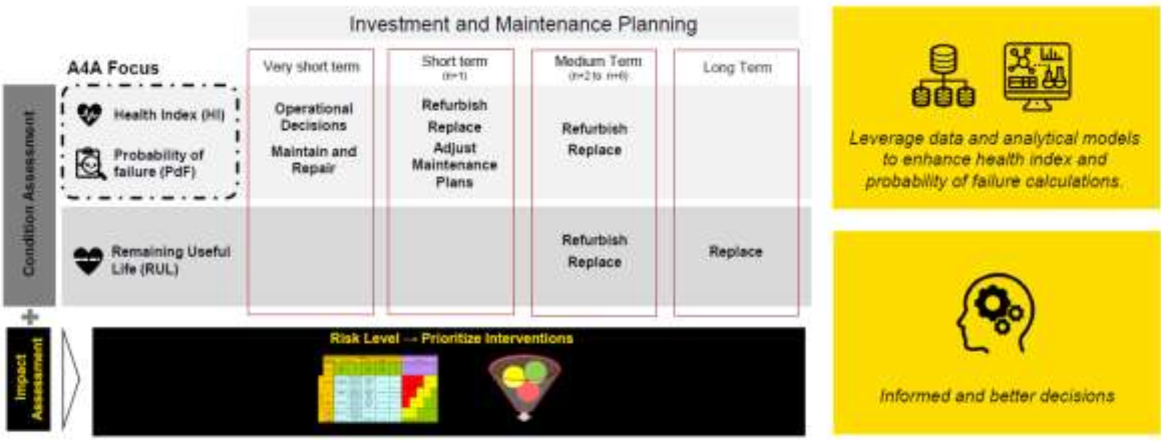

Figure 26 – Analytics for Assets concept

The asset data infrastructure of E-REDES is based on SAP, combining technical and financial data (gross value, depreciation, net value) of all assets. SAP is also the registry of all asset interventions (maintenance or investment), allowing E-REDES to assess the life-cycle performance and cost of the assets. It is complemented by a GIS system based in GE Smallworld, which contains the geographical location of network assets and a trove of context geographical information (including but not limited to boundaries of urban areas, water bodies, forest areas and dominant vegetation species, archaeological or protected sites, agricultural areas, protected areas), all in vectorial format. It also includes the geographic information (coordinates) of all end-user points of connection.

Furthermore, operational systems such as RedeAtiva allow the registry of fault events based on SCADA data, allowing to relate faults with the location and category of failed assets, as well as failure mode and context (weather conditions at the time), including the information whether the fault was originated by an asset failure or due to external factors (vehicle collision with an asset or a tree falling on an asset, for instance).

Asset management aims to relate these data points to build a comprehensive overview of the condition, probability of failure and useful life of the assets, as well as the costs for the entire lifecycle, thus supporting asset management decisions. Furthermore, context information and load diagrams allow simulations that, combined with the probability of failure, indicate the failure risk (probability and consequence) associated with the several failure modes of each asset.

3.2.3. ENEDIS USE OF "BIG DATA" FOR ASSET RENEWAL PRIORITISATION

The effectiveness of renewal (or planned refurbishment) programs for overhead medium-voltage (MV) networks depends on accurately diagnosing assets with the highest probability of failure. To improve this diagnosis, Enedis uses large-scale data processing (known as "big data") and statistical learning ("machine learning") techniques to establish short-term failure prediction laws applied to appropriate portions of assets (low-voltage feeders or MV pockets between two switching devices).

The purpose of "machine learning" is to determine the best correlation law between large amounts of data (network description, incident history and location, environmental data, etc.) and known output data (incidents that occurred in the learning years that the model is trying to reproduce).

These processing operations rely on significant computing power. The law thus defined is then applied to the most recent network image to estimate the risk of failure for the considered asset portion for the coming year. This is, therefore, a predictive approach.

Depending on the number of customers or the power delivered by the asset, this prioritisation is revised by assessing the failure's impact. They are thus classified according to a risk impact criterion. This mathematical model is part of an ongoing improvement process: it is enriched yearly with new data. It incorporates the results of its processing from the previous year: which feeders had an incident and what factors may have influenced the occurrence or non-occurrence of an incident.

3.2.4. State Grid Shanghai Evaluation of Cable Remaining Life

3.2.4.1. Sample collection and testing

Two hundred thirteen samples of XLPE cables with different ageing degrees over the past 30 years were collected, with voltage levels of 10 kV and 35 kV. We tested key parameters such as activation energy, onset of decomposition temperature, tensile strength, and carbonyl index of the insulation of these 213 cables. We obtained the characteristic parameters to characterize and evaluate the state of their cable insulation.

According to the different manufacturer, service life, current load and laying conditions, 6 typical cable samples were taken and their insulation materials were tested by AC breakdown voltage test, dielectric spectrum analysis, water tree observation, tensile test, FTIR spectrum, thermogravimetric analysis (TG), differential scanning calorimetry (DSC), thermal aging test, etc.

Furthermore, according to the test data of cable samples with different ageing degrees, each micro characteristic quantity's sensitivity and accuracy in characterising the insulation's ageing are compared and analyzed. Finally, five main microcharacteristic quantities reflecting the changes in the macroscopic performance of the cables are derived: activation energy of thermal cracking, onset of decomposition temperature, elongation at break, service time, and carbonyl index. The ageing model is established to evaluate the ageing state of cable insulation.

3.2.4.2. Influence of operating conditions on ageing

(1) The influence of operation time on the ageing of cable

With a 5-year interval, all cable samples are divided into four groups according to the operation time, as shown in Figure 27. It can be seen that with the increase in operation time, the number of severe and moderate ageing of cables increases correspondingly. The number of mild ageing decreases, indicating that the ageing state of cables becomes more and more serious with the increase of operation years.

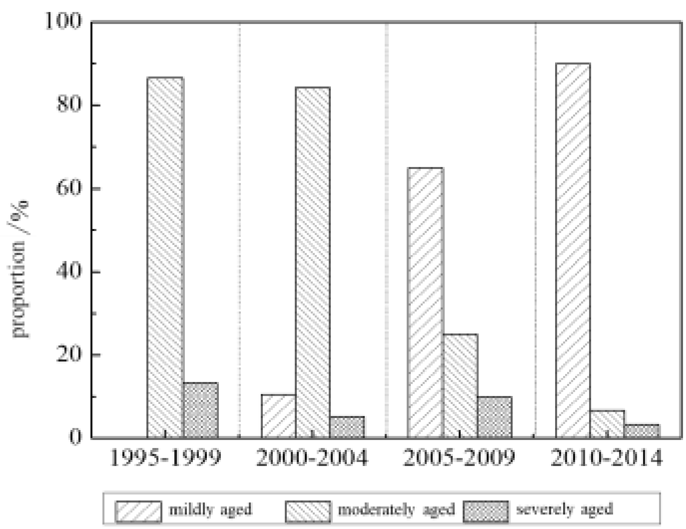

Figure 27 – Distribution of cable ageing degree at different operation times

(2) The influence of the laying method on the ageing of the cable

Statistics on the impact of the two laying methods of duct banks and direct buried on the ageing state of the cable, the statistics are shown in Figure 28. It can be seen that the ageing degree of the duct banks method is lower than the direct buried method, but the difference is not very large.

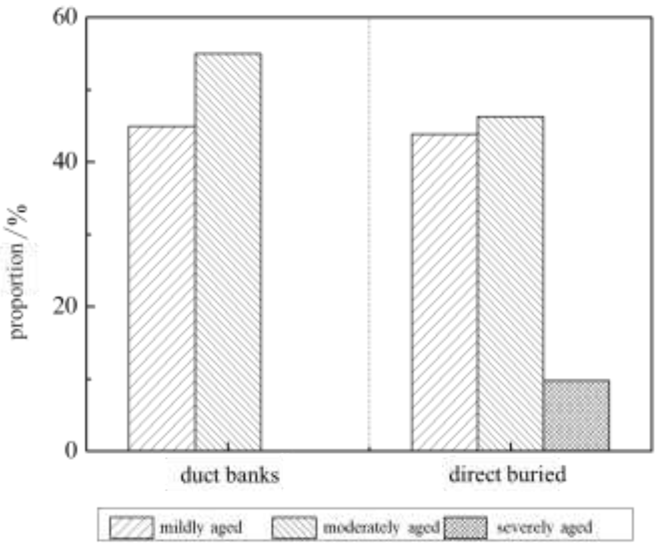

Figure 28 – Cable ageing distribution in different laying modes

(3) Effect of cable current on cable ageing

We collected the maximum cable current in a year to study the effect of operation current on cable ageing. It is shown in Figure 29 below. It can be seen that the higher the cable's current during operation, the shorter the remaining life of the cable.

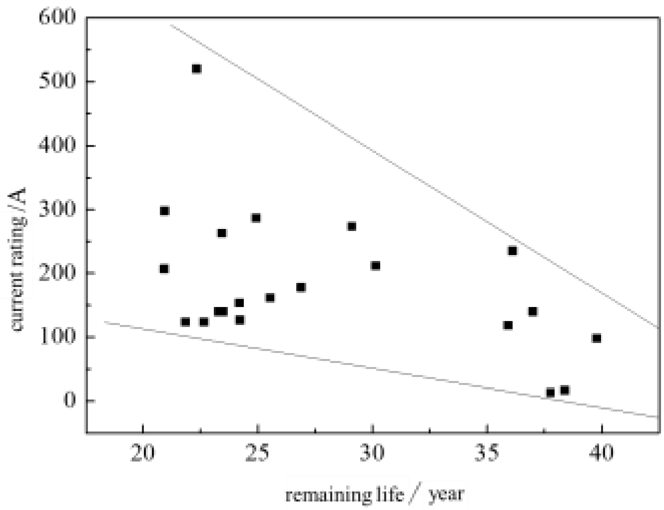

Figure 29 – Relationship between cable current and remaining life

3.2.4.3. AGEING ASSESSMENT SYSTEM

Based on the above work, the cable condition assessment and ageing trend management system's design and development have been completed, and the ageing assessment database of the cables in operation has been established. The cables with more serious insulation ageing can be replaced in advance to avoid unnecessary losses.

3.2.5. PG&E FUNDAMENTALS OF DATA ANALYSIS IN ASSET MANAGEMENT

Data analysis and all its methodologies, which range from data visualization techniques to regression and Monte Carlo, and training methods such as Machine Learning, are as good as the data gathered itself. As power grid was slowly growing in late 1890's, there was not much to gather about the very limited assets we had. Gradually in 1910's to 1930's, as the network expanded, the data management systems gained importance. Data management has different steps: creation, storage, usage, and archiving or destruction. Early ages of the power system, up until recent development of computers and their elaborate use in power systems, benefited from mere paper records kept in each district or territory of the utility serving customers. Even with neglecting the fact that data management practices may have varied between these different regions of a utility, passage of time and developments in technology have altered the data management systems, which in turn forced their noise into the data we have inherited from our preceding generations of engineers.

Utilities are now faced with data quality issues that are, as said, inherited from these gradual and temporal changes: a fuse that is installed in 1950 on a line that now shows as underground, a SCADA recloser on a small wire lateral, a steel pole that shows as having a recent wood pole treatment, or an underground manhole showing a switch that does not exist when inspected; these are all issues that happen here and there.

Another group of data quality issues are not that nostalgic, especially in the creation step of data. This may cover data creation when an asset is installed, such as not filling in the forms correctly, or even not requiring certain important data to be gathered at this stage. It also includes data gathered at inspection of each asset, most importantly on the second category as said in the previous example: did we just check "asset is operational", or did we know how detailed of information we may need years in the future when we are performing a root cause analysis of a recent failure.

While very important to fix historical issues due to storage and archiving, and critical to rethink the data creation methodologies, the mitigations are not abundant, as the organic growth of the grid has so evolved into networks of trunks, laterals, and secondaries that require enormous manhours to inspect and gather new "correct" data on every asset. Hence, recent attention has been on defining techniques that can improve data management systems, fed by data gathered at inspection by the field personnel. The most important layer of this effort is creating smart methods to fill in the "null"s and fixing the anomalies of the data we have inherited now.

3.2.5.1. ASSET DATA IMPROVEMENTS IN PG&E

PG&E is an example of an old inherited grid [14], with both the challenges with the data itself, and the severity of impacts a potential data issue can have. Recently, a dedicated team has initiated targeted steps to systematic data quality improvements in both asset data registry, focused on asset data such as installation year, type, use, etc., as well as improvements in other data sources related to assets such as inspection archives, replacement records, etc. [15]. For this purpose:

- All data attributes related to an asset registry, regardless of the source or the archival record, are deeply investigated to see their impact on regulatory needs, each line of business, and risk prioritization.
- These attributes were then trimmed to the critical data elements (CDEs) that impact any of the said dimensions.
- Data Quality Rules were then defined and are continuously improved to improve data quality that directly improves performance.

3.2.5.2. DATA CREATION IMPROVEMENT

An important step in data management is creation of the data, as mentioned earlier. Looking at the archival data of inspections and maintenance, there comes times that the engineering team denotes "if more data were available" scenarios. This has initiated improvements in how the data is captured when an asset is being inspected, or a troubleman is at the scene responding to a failure or an outage. These improvements not only cover how the data is entered to the system, but also cover what data is entered, at which dimension, and in which database.

A simple example is creation of a field that the troubleman can select as the "largest contributor to the failure" as seen at the very scene of the failure of an asset seen through the eyes of the troubleman, as an example of what data is entered. Dimension can also see improvement to include the best potential contributors that are offered to the troubleman to select as a dropdown, instead of a free-text option. The database that stores this data can also be improved to have its own data quality rules and standards for optimized tracking of the causes as an archival dataset that can derive preventive maintenance vision.

3.3. CAPEX AND OPEX BUDGET

Description of CapEx and OpEx medium and long-term budget elaboration, based on TotEx and risk optimization and describing prioritization criteria for asset interventions.

3.3.1. E-REDES INVESTMENT AND MAINTENANCE PLANS

In preparation for the ISO 55 001 certification, E-REDES developed its Strategic Asset Management Plan, with a 10-year horizon. The SAMP explicitly mentions the objectives of the asset management system, a description of the asset portfolio (including critical assets, where HV overhead lines and underground cables are included) and the strategic goals for asset management. These strategic goals include (among several others):

- Overall system performance objectives;
- The expansion of the underground HV and MV network (therefore reducing the proportion of overhead lines in E-REDES' network total length);
- Increase of remote control capabilities associated with the MV network;
- Evolution of the average age of several asset categories, including HV network assets, which are allowed to increase their average age, given that they have a good overall condition, allowing to prioritize the modernization of other asset categories;
- Increase the system hosting capacity for RES;

- The development of advanced modelling algorithms, assessing the condition of critical assets.

All goals have quantifiable KPIs associated with, and an assessment of the risk of not being achieved within the intended time frame of the SAMP, and on the 5-year horizon of the PDIRD-E.

Furthermore, E-REDES also prepares detailed investment information for Y+1, to be delivered to the Regulator (in June of the year Y).

Also, E-REDES must submit detailed information to the Regulator, allowing it to identify costs, revenues, assets and liabilities, investments and equity associated with the operation as a regulated entity. This information is ex-post and ex-ante (forecast for Y+1).

This information required by the Government and Regulator frame part of the budget preparation process, which also involves the shareholder. It results in preparing business plans describing CapEx and OpEx associated with all network assets and IT systems (and non-network assets).

Preparing the budget involves assessing the objectives stated in the SAMP (long term) and the PDIRD-E (short to medium term), allowing E-REDES to assess the required resources for those objectives. That information is also useful for other stakeholders (including the Regulator), who know the relation between available resources and expected goals (including system performance, i.e., expected SAIDI).

3.3.2. ENEDIS' NATIONAL INVESTMENT TRAJECTORY BY 2032

Enedis has published in [5] an investment trajectory for the next ten years. This is based on several assumptions that can be summarized as follows:

- Stability in consumer connections;
- Significant development of Electric Vehicle Charging Infrastructure;
- Strong development of renewable energy facilities.

Figure 30 synthesizes these assumptions.

Figure 30 – Key figures from Enedis' baseline investment scenario [5](©Enedis)

Investments generate benefits beyond their primary triggering cause, including contributing to the network's renewal and preparing for future connections. While it is possible to categorise them based on their main triggering cause, it is more complex to break them down according to their effects. An investment often brings, beyond its primary purpose, various benefits to the network.

For example, the climate hazards plan, which aims to bury overhead MV networks exposed to climate risks, may lead to restructuring the network. It contributes not only to the network's resilience to climate risk but also to the overall improvement in the quality of supply for customers in the area.

Investments made in the network also benefit future customers. Investments in network renewal, reliability, or resilience can generate greater capacity due to equipment ranges, optimal cable choices, and consideration of future load evolutions.

The network created for connecting new consumer customers, or adapting to the increased needs of existing customers, can also later serve to accommodate producer customers, and vice versa.

Finally, whenever investments addressing a specific challenge led to the substitution of new facilities for existing ones, they contribute to the overall renewal of the network.

Figure 31 lists historical and projected expenses based on the main objective of investment decisions.

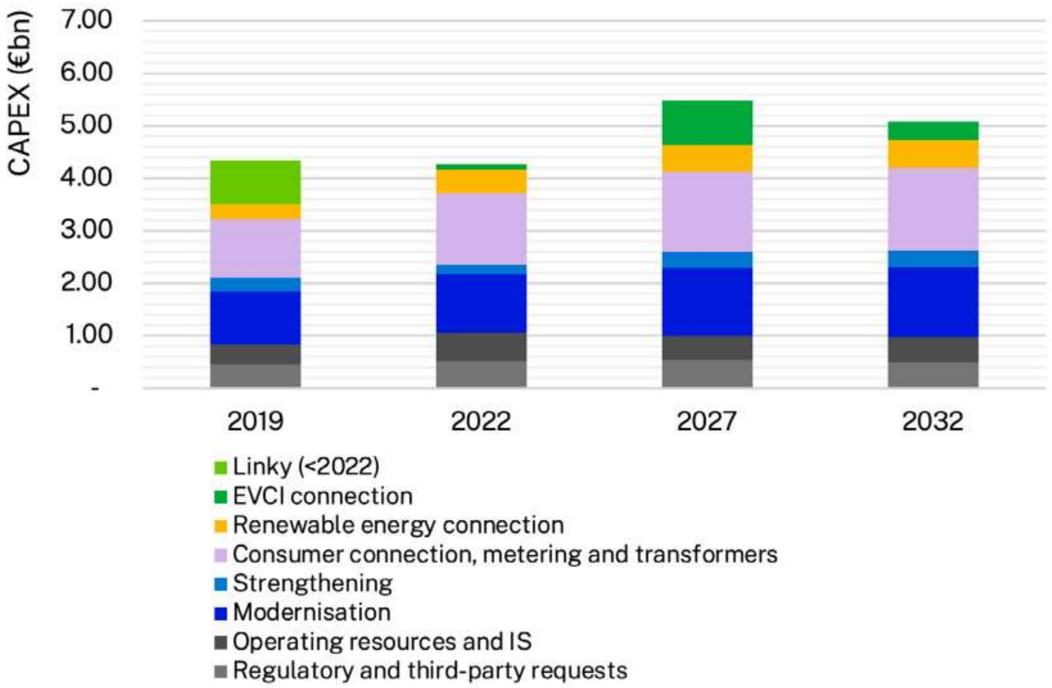

Figure 31 – Annual investment amounts within Enedis' remit by 2032, broken down by main investment purposes [5](©Enedis)

3.4. MAINTENANCE POLICY DECISION MAKING

Describe methodology and criteria to define maintenance policy for underground and overhead network assets, including legal/regulatory requirements.

3.4.1. E-REDES Maintenance Policy decision making

As a part of the policy decision process, E-REDES prepared maintenance manuals for all the assets with associated preventive maintenance interventions. These manuals are regularly revised and updated.

Maintenance manuals are a tool for the Asset Management team to define the best maintenance strategy that balances cost with performance and the extension of the asset lifetime with modernization investments.

Overhead line maintenance represents a great share of overall maintenance operations performed by E-REDES. Also, one should mention that interventions might be related to overhead line assets per se, and vegetation management associated with line corridors.

Maintenance Manuals define Time-Based Maintenance (TBM) interventions associated with overhead lines, including the supporting documentation to be prepared by the technicians executing those interventions.

Maintenance Manuals undergo a three-year revision cycle [13]. They are prepared under the coordination of the Asset Management team, involving the asset services teams, legal department and IT (list non-exhaustive), intending to produce a maintenance strategy adapted to the existing legal framework, asset condition and operation capabilities to execute the interventions, as well as guaranteeing that prescribed strategies are developed considering their cost and benefits (thus considering the trade-offs between Cost and Risk and between CapEx and OpEx).

The current manual prescribes TBM interventions every three years for HV and MV overhead lines, which are far more frequent than the Portuguese legal framework, thus accounting for a risk aversion towards vegetation growth in line corridors that might create vegetation contact hazards. The TBM interventions include both inspections through flights (mostly helicopter, with the technological evaluation allowing for a gradual transition towards drone flights). These allow both to assess the distance between lines and obstacles (including vegetation) and to detect hot spots associated with accessories in overhead towers (insulators), using infra-red cameras. Furthermore, ground inspections are to be made, aimed at measuring at performing visual inspections and measuring earth resistance where the pylons are connected to the earth.

Anomalies must be described with pre-determined criteria that allow to consider the priority that must be given to solve those anomalies (according to risk criteria).

Underground cables only have TMB associated with visual inspections of their terminations (dry cables) and visual inspections and oil pressure assessment in oil-insulated cables. These inspections are performed at the installations where the cables have visible terminations (primary and secondary substations and switching installations), therefore being a part of the TBM interventions associated with those installations.

Vegetation management is an area where E-REDES is always striving to improve, also developing new technologies to foster vegetation management associated with LV overhead lines. [16]

[13] Nonetheless, the organization might procedure to an extraordinary revision during the period if reglementary, legal or technological evolutions justify so.

3.4.2. Elektro-Ljubljana Maintenance Policy decision making

As detailed in [17], the maintenance approach in Slovenia is standardized across all five distributions and outlined in a Maintenance Manual for the distribution electric power network. Within the Slovenian electric power industry, the concept of reliability-centred maintenance (RCM) is generally adopted.

The manual delineates the maintenance method, types of maintenance work, specific maintenance tasks, and associated deadlines for underground and overhead lines, irrespective of device or building ownership. It also sets forth deadlines for conducting inspections.

Inspection involves assessing device conditions through observation, measurements, or testing of device characteristics. Typically, inspections cause minimal disruption and are carried out during normal operation of the element, plant, or system. The manual specifies the intervals and tasks for maintaining underground and overhead lines, among other assets.

The methodology described in this section is detailed in [17].

Annual ground inspections of MV (medium voltage) overhead lines are mandated, covering the following aspects:

- Corridors;
- Conductors and protective ropes;
- Suspensions;
- Insulators and surge arresters;
- Pylons;
- Pole-mounted circuit breakers;
- Mounted disconnect switches;
- Pole-mounted isolators;
- Remote control and automation equipment.

Vegetation management is prescribed when needed and depends on the results of ground inspection.

Ground inspections of MV underground cable lines and cable ducts are required every five years, covering the following aspects:

- Condition of cable terminations and cable connections;
- Condition of the cable route (settling, cable pits, changes in nearby infrastructure, overgrowth along the route);
- Condition of mechanical protection;
- Condition of cable parts above ground (entries in buildings);
- Condition of metallic parts and structures;
- Condition of grounding devices;

- Condition of cable markings;
- Condition of cable joints (accessible);
- Condition of locks on cable pits.

Distribution companies or network owners create maintenance plans in accordance with manual instructions and internal regulations.

Faults and deficiencies within the network are identified through preventive inspections, involving observation, measurements, and diagnostics. These inspections are prompted by operational events such as outages or notifications from third parties. Upon gathering additional information, decisions regarding further maintenance or repair work on the affected devices are made based on their condition.

3.4.3. NEXANS SUPPORT FOR THE DEFINITION OF MAINTENANCE STRATEGIES

Four strategies of maintenance are deployed for linear assets depending on their characteristics, network level and criticality[14].

- Corrective maintenance (CM), to repair or replace broken items.
- Time-based maintenance (TBM), to perform preventive maintenance based on a specified predetermined schedule.
- Condition based maintenance (CBM), to perform preventive maintenance based on the present condition (based upon periodic measurements or monitoring) of the component (condition assessment).
- Reliability based maintenance, to perform maintenance based on the targeted level of service of the system.

While run-to-failure (Corrective Maintenance) is often applied as a strategy for low voltage underground network due to the low value of the assets & relatively low risk, preventive maintenance (Time, Condition, or Reliability based) is deployed more frequently for MV networks. The decision-making process for preventive maintenance can be built based on three different types of approaches:

- Inspection-driven methodology with Offline Diagnostic for Condition-Base Maintenance.
- Destructive Diagnostic supporting health assessment via decommissioned cable lab diagnostic.
- Data-driven methodology to define maintenance to be conducted based on multiple criteria (including Reliability Base Maintenance).
- Online Diagnostic with Partial Discharge monitoring technologies create an opportunity for predictive maintenance.

3.4.3.1. DIAGNOSTIC METHODOLOGIES AND PROCEDURES

1. Off-line Diagnostic

[14] Source: CIGRE TB 825.

Several diagnostic techniques are available for underground MV networks to deploy condition-based or predictive maintenance. Different non-destructive off-line monitoring solutions can be used in inspection to assess or confirm the state of health of a cable system (cables, joints and terminations):

- **Voltage test –** Voltage testing is a basic measurement involving the application of a low-frequency alternating voltage between phase and earth, generally 2xUo for existing cables and 3xUo for new cables. This test is used to check the quality of the cable if it's new, or its residual resistance to voltage stress.
- **Sheath test –** A sheath test generally supplements the voltage test to determine the condition of the cable's outer sheath and ensure that it is not punctured.
- **Measure of tangent-delta –** The tangent-delta is a measure of dielectric losses in cable insulation, enabling us to assess the overall degree of ageing. While it is not mandatory, it is also recommended to have a baseline reference measurement, which can then be used throughout the cable's service life. This will provide useful comparative information about the cable's general condition when combined with other types of measurement.
- **Acquisition and analysis of partial discharges –** Partial Discharge (PD) measurements are used for the maintenance of power cables, with a focus on identifying and localizing sources of partial discharge activity. Here are the key principles:
    - **Background**: PD measurements use a VLF (Very Low Frequency) waveform. The partial discharge activity is associated with cable segments, joints, or cable terminations.
    - **Localization**: PD measurements are employed to directly pinpoint the location of partial discharge activity within the cable system. This localization is critical for identifying potential issues.
    - **Distance Dependency**: The level of PD activity measured depends on the distance from the partial discharge source to the measurement point. This distance affects the magnitude of the PD signal.
    - **Source Location**: In XLPE cables, the partial discharge source is typically found in cable accessories like joints rather than within the cable insulation. Locating the source is crucial to prevent cable breakdown.
    - **Measurement Levels**: For on-site PD diagnostics, PD levels in the range of around 100 pC are considered relevant. Knowing the precise location of the PD source is more important than the level.
    - **IEC 60270 Standard**: Conventional PD measurements, as per IEC 60270, are usually performed at the cable end. This standard outlines techniques for measuring partial discharges in high-voltage systems.
    - **Measurement Setup**: The measurement setup typically involves a VLF generator to create a symmetrical sine-wave voltage, a high-frequency filter to remove disturbances, a coupling capacitor to detect recharging current, and a PD detector for recording and monitoring PD events.
    - **Purpose**: PD measurements help in assessing the condition of power cables, especially XLPE cables. They provide insights into the health of the cable system, detect defects, and support maintenance decisions.
    - **Calibration**: IEC 60270 mandates on-site calibration for PD measurements. This calibration ensures accurate measurement results, considering the attenuation of the PD signal along the cable.
    - **PD Inception and Extinction**: PD activity is characterized by its inception voltage (PDIV) and extinction voltage (PDEV). PDIV is the voltage level at which PD begins, while PDEV is where it stops. These values help assess the severity of PD activity.

- **Advantages of VLF PD Diagnostic**: VLF PD measurements offer advantages such as continuous monitoring, length-independent measurements, accurate localization, and detecting PD sources that may activate after a certain time.
- **Result Interpretation**: Interpretation guidelines for PD measurements depend on the cable type. For XLPE cables, acceptable PD levels differ for new and aged cables. For PILC and mixed cables, scattered PD activities are common, but specific levels indicate potential issues. For offline PD testing, both the magnitude of the PD events and the pulse shape are critical diagnostic parameters. Magnitude indicates the severity of the defect, while pulse shape provides insights into the defect type and mechanism. In online PD monitoring, additional dynamic factors become significant, such as the change in PD magnitude over time and the repeatability of PD signals. Persistent trends of increasing PD levels and consistent signal patterns are strong indicators of potential insulation degradation. Incorporating these parameters enhances defect detection accuracy and supports proactive maintenance strategies.

2. Destructive Diagnostic

While off-line monitoring forms part of the non-destructive testing available for underground assets, destructive diagnostic can contribute to enriching the information based on cable ageing. Cables are already decommissioned as part of preventive plan, for other technical constraints, such as cable rerouting, grid reinforcement, or planned groundwork opportunities. Running some lab diagnoses on those decommissioned cables can bring additional information on the state of health of the underground network, and lifetime extension possibility and adds to the data-driven approach.

Several laboratory diagnosis techniques are listed as follows:

- **Thermal analysis: maximum operating temperature –** DSC (differential scanning calorimetry) analysis is used to estimate the maximum temperature the insulation reaches during operation. It can only be carried out on synthetic insulations.
- **Finding and measuring of water tree structures in polymer insulation –** Water treeing is a defect that grows in synthetic insulation in presence of both water and electric field. The observation of water treeing requires to cut slices of material and systematically observe the insulation by optical microscopy.
- **Determining the state of recrystallization of lead and quality of paper insulation** – As lead sheaths age, they can undergo recrystallization and lose their radial tightness. This analysis consists of metallographic observation of the surface of the lead sheath lightly etched by a special chemical solution, which reveals the size of the lead "crystals". A crystal approaching 1 mm is considered the maximum tolerated limit. This measurement can also be carried out on-site. We can also analyse the condition of the cable at the end of its life if it breaks during simple folding.
- **Control of humidity content in solids and solids and liquids Karl Fischer –** The water content can be measured by directly titrating water molecules using Karl Fisher's measurement. This technique can be used on synthetic and paper insulation. The storage of material is critical for this measurement and can be a strong limitation to getting representative results.
- **Oxidative products analysis (FTIR measurement)** – Directly observing hydroxyl chemical bonds through FTIR enables identifying and quantifying oxidation products created during thermos-oxidation ageing. This technique requires to cut slices of the material.
- **Tensile measurement –** Mechanical properties of synthetic insulation represent the general condition of the polymer network. High elongation at break and tensile strength

guarantees the insulation's resistance toward mechanical stress. This test can be performed on samples extracted from each layer of the aged cables.

- **Thermo-mechanical test (Hot Set Test – HST) –** Crosslinking of insulation material is evaluated through the material's capability to keep its shape during heating under mechanical stress and to recover its initial shape once the mechanical and thermal stress is stopped. This test (hot set test) can be performed on aged material to evaluate the crosslinking performance, as ageing may damage the polymer network.
- **Oxidation Induction Time –** In synthetic insulation systems, thermal endurance performance is ensured by adding antioxidants that prevent oxidised species formation. Oxidation Induction Time can be performed by heating the polymer at a temperature of typically 150 to 200 °C and measuring the time before degradation is observed to evaluate the presence of antioxidants in the material.

Table 10 summarizes a list of test methods used to determine cables' condition status, especially in MV [18].

Table 10 – Test methods used to determine the condition status of cables

			Insulated cable																
	major component		Insulation					Screen					Sheath						
	method	failure	Water treeing	electrical breakdown	partial discharge	mechanical destruction	thermal oxidation	moisture intrusion	oxidative corrosion	grounding continuity disruption	galvanic corrosion	short circuit overshoot	mechanical integrity destruction	Thermal oxidation	Chemical aggression	Photo-oxidation	Overbending stress cracking	Water ingress	Impact
Electric test	Voltage test		X	X	X														
	sheath test									O			X	O	O	O	X		
	Tan delta		X	X			X												
	Partial discharge			O	X	O	O												
	Time Domain Refectometry			X		X				X									
	Breakdown voltage test		X	X			O	O											
	Continuity									X									
Chemical analyses	Moisture content (KFT)		X					X										X	
	Thermal testing (DSC)						X						°	X	X			O	
	Chermical composition (TGA)						O							O					
	Oxidative product analysis (FTIR)						X		O							X			
	Tensile measurements		O				X							X	X	X			
	Thermomechanical strength (HST)						X							X	X	X			
Other	Optical microscopy observation		X	X					X		X								
	Visual inspection			X		X			X		X	O	X				X	X	X
	Accelerated ageing			X			X							X		X			

3. Online Monitoring

Online monitoring can be deployed to perform real-time continuous partial discharge (PD) monitoring to improve the performance of the condition-based approach. The real-time partial discharge activity monitoring presents the benefit of following the evolution of the PD activity in magnitude and occurrence, making it more efficient to detect signs of early weakness in the cable. Installing online PD monitoring can be cost-effective, particularly for monitoring circuits where the cost of interruption is higher (high-density area, low redundancy, critical customer). Online PD monitoring devices can be installed with limited space on cable termination. The data acquisition unit sends the data to a software running analysis to interpret the PD signals, send warnings in case of unusual PD activities, and recommend interventions. The system is designed to locate the PD activities' origin and identify which part of the cable system needs replacing. Such systems present the additional benefit of providing fault location in case of a failure (for instance, due to external excavation work).

3.5. ASSET RISK-BASED ASSESSMENT

Describes methodologies to assess failure risk, including criticality and risk assessment.

3.5.1. E-REDES RISK-BASED ASSESSMENT

E-REDES risk-assessment methodology is based on CNAIM [1]. It assesses the failure risk of network assets, including but not limited to overhead lines and underground cables, across the four risk dimensions described in CNAIM:

1. Safety;
2. Environment;
3. Performance;
4. Financial.

All the risk dimensions are assessed quantitatively and qualitatively (risk matrix).

While for underground cables the biggest risks are associated with Performance and Financial, overhead lines often also present risks on Safety (particularly when associated with areas with large population densities, or on infrastructure interceptions, for instance motorway crossings), Environment (associated with fire hazard in forest areas).

One major risk managed by a DSO with 80% of its network infrastructure established in overhead lines is related to fire hazard, managed through vegetation management.

Fire risk hazard is assessed through DPlan, asset management functionality, as described in [3] and Section 0. Based on the topological description of the network, based on GIS data, and context data – cartographical, vectorial data – describing the soil occupancy, it is possible to determine where overhead lines are associated with areas with different impact levels (national park, ecological reserves, etc.), what are the dominant vegetation species (rapid growth trees such as Acacia, Pinetree, Eucalyptus, slow growth trees, fruit trees, or protected species like Cork Oak, Holm Oak, etc.). It also allows us to consider the dimension of the forest area – a large forest and forest area will provide a higher risk of fire propagation than a small or sparse forest area.

This information is used to assess the fire impact, enabling DPlan to assess the risk by estimating the probability of a failure associated with overhead line failure modes that might cause any contact between energized components and treetops. This risk is assessed both quantitatively and qualitatively. It implies setting a value, in euros, to the environmental damages, as well as on safety, network performance and financial. Figure 32 exemplifies the output results provided by the Dplan for the failure risk of a given overhead line segment.

Figure 32 – Risk Assessment Results – Quantitative and Risk Matrix for an overhead line segment

3.6. ASSET REPLACEMENT POLICY DECISION-MAKING

Describe the methodology and criteria to define modernization (replacement) policy for underground and overhead network assets.

3.6.1. E-REDES REPLACEMENT POLICY DECISION MAKING

Interventions start with investment opportunity identification. These can be based on the information given to the asset management area by operations or asset services areas (or any other area, even those that identify most situations that might lead to new investment projects).

These necessities identified within the organization are then evaluated regarding the associated failure risk. This evaluation allows to:

- Prioritise interventions.
- Compare required interventions and their risk level with the available budget (given a cost estimation associated with the solution to mitigate the identified risks).

This identification follows a cycle:

- Yearly minor interventions are to be considered in the Y+1 investment plan.
- Multi-yearly for major interventions to be considered in the 5-year investment plan (PDIRD-E, see Section 3.3.1).

Interventions are assessed by the network planning team (network studies), who, given the network's expected development, the demand and the security of supply, determine the best solution for the interventions based on a CBA[15].

Also, network planning determines investment opportunities based on several criteria, including:

- Expected short-circuit currents and the stipulated capacity of conductors to withstand that current, which might result in reinforcing lines and branches, particularly those located next to primary substations.
- Expected load and generation growth, that might require in the reinforcement of local hosting capacity (with investment scenarios evaluated through a CBA).
- Quality of supply, comparing the expected performance of individual networks with E-REDES' goals for network performance.

Furthermore, asset management evaluates asset management strategies that might result in investment programs dedicated to certain asset categories when the risk is justified. These programs might include, for example:

- Programmed replacement of overhead lines with reduced cross-section – these are overhead lines that typically were installed in the '80s or before, are completely depreciated and, even when adequate to the low load currents that they might supply, given their age and the mechanical vulnerability to weather events associated with reduced cross sections, can be considered as a target for asset modernization.
- Programmed replacement of underground, non-armoured dry cables (1st generation) – these cables were installed mostly in the eighties/early nineties and are proving themselves vulnerable to water treeing, particularly 10 kV cables used in the Lisbon region. A replacement programme of these cables might be considered, starting in the Lisbon region and then expanding to other major cities, including Porto, where the MV voltage level is 15 kV.
- Reduce overhead line risk exposure in forest areas by changing overhead lines into underground areas when the distribution network is installed in areas with a high risk of forest fires and/or exposure to extreme weather events.
- Long-term investment strategies are considered on the SAMP and the PDIRD-E elaboration as medium-term investment strategies. Both these plans must have the approval of the Board of Directors. PDIRD-E is discussed with the Regulator and must be approved by the Council of Ministers (Decree 15/2022).
- Individual projects must be evaluated on their merits, from a failure risk assessment and a CBA.

[15] Cost-Benefit Analysis. It also includes the estimation of the Net Present Value, NPV, and of the Internal Rate of Return (IRR). The investment benefits are determined quantitatively for the investment life-cycle, conservatively estimated in 30 years, based on network losses reduction, ENS (Energy Not Supplied) reduction and, if applicable, energy not supplied due to technical constraints, i.e., asset overload, or with excessive voltage drops. All these dimensions have a reference value in EUR, which is compared with the expected investment and maintenance costs.

3.6.2. KANSAI T&D LONG-TERM REPLACEMENT PLAN

During the period of rapid economic growth in Japan between 1955 and 1973, Kansai Transmission and Distribution constructed a significant number of transmission and distribution facilities to accommodate the growth of electricity demand. Approximately 60 years have passed since the construction of these facilities, and the deterioration of the facilities has increased. Therefore, there is a pressing need to replace these deteriorated facilities.

Since the lack of construction capacity is a serious problem in Japan, systematic and efficient replacement is needed to replace these ageing facilities. The rough procedure for considering systematic replacement is shown below.

Step 1: Assess the deterioration by accumulating data from periodical observation (In Kansai Transmission and Distribution, all overhead facilities are visually observed every five years).

Step 2: Assess the risk of failure of each facility from the data such as age, kind of facility, and environment.

Step 3: Consider the long-term replacement plan. In this plan, the replacement volume is levelled for each year.

The examples of the long-term replacement plan considered are shown hereafter.

3.6.2.1. OVERHEAD DISTRIBUTION LINE

The left figure of Figure 33 shows the volume of distribution lines by age. In this figure, the orange bar shows the volume of the old type of conductor, and the green bar shows the volume of the new type of conductor.

The year in which conductors should be replaced was calculated as shown in the bar graph of the right figure. In this calculation, 240,000 km of distribution lines should be replaced as of 2023. However, it was impossible to replace them because the volume was too large.

Therefore, it was planned to replace 12,631 km per year to have a levelled yearly replacement volume. In addition, stringers have been attached to the old type overhead conductors to ensure public safety.

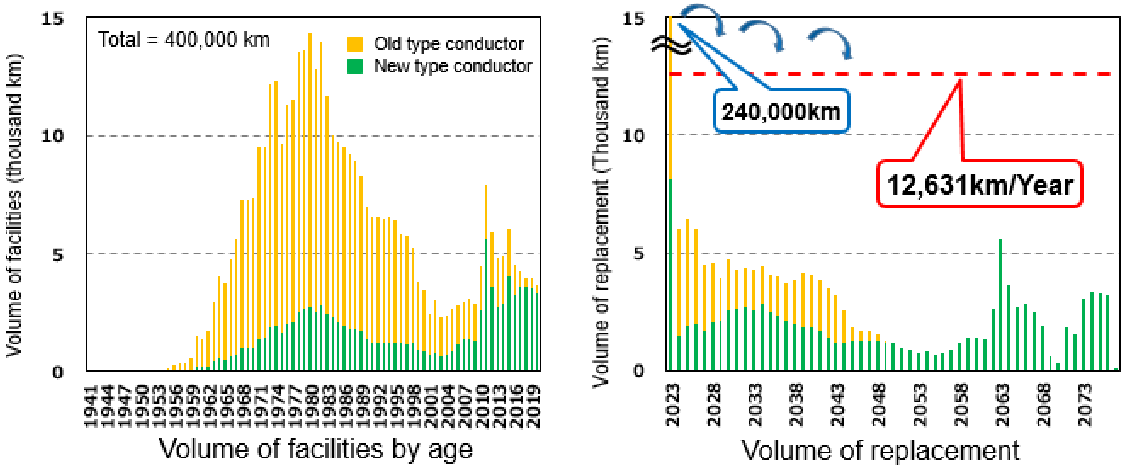

Figure 33 – Calculation of the long-term replacement volume of distribution lines

3.6.2.2. DISTRIBUTION CABLE

The left figure of Figure 34 shows the volume of distribution cables by age. In this figure, the orange bar shows the volume of the old type of cable, and the green bar shows the volume of the new type of cable.

The year in which cables should be replaced was calculated as shown in the bar graph of the right figure. This graph shows a gap period from 2023 to 2050, and the peak is 600 km in 2056.

It was planned to replace 101 km per year to have a yearly levelled replacement volume.

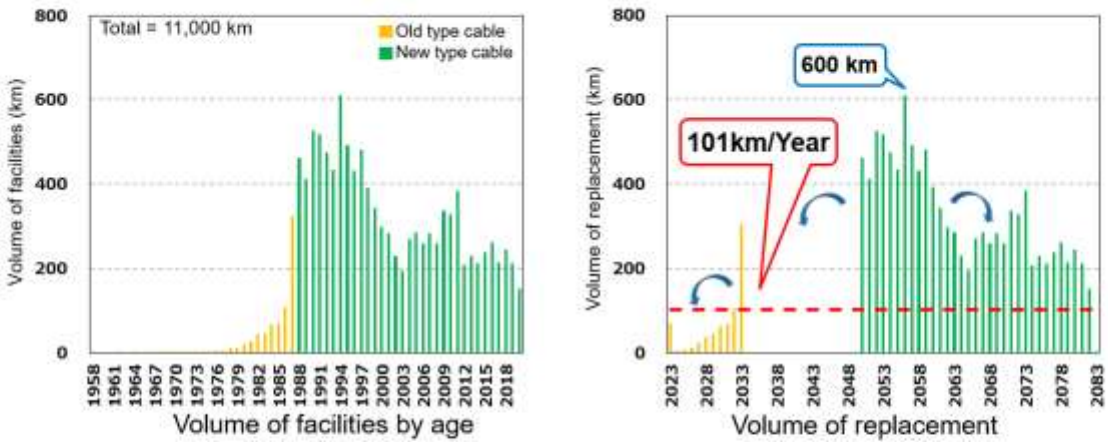

Figure 34 – Calculation of the long-term replacement volume of distribution cables

3.6.3. PG&E NOVEL CONSIDERATIONS FOR RISK PRIORITIZATION IN ASSET LIFE CYCLE MANAGEMENT

As mentioned earlier, utilities generally consider risk as the main criteria for prioritization of their fleet of assets when it comes to budget allocation, time criticality in their planning horizon, and responses to regulatory board requirements. Traditionally risk has been considered as some combination of probability of an "event" happening either caused directly by the asset or by external factors that eventually lead to asset causing an issue, and the consequences of the event happened.

3.6.3.1. THE EVENT

To elaborate "the event", consider the issue being a pole falling to the ground. Now this issue may be caused by the rotten core of the pole, as an example of the pole directly causing the issue, or the pole coming down because of a tree falling on the pole. Now, the root cause of the event directs utilities in their proactive mitigation strategies. For a pole rot, improved inspections both in time (more frequent) and better techniques (both in technology used and methods to perform the inspection) may prevent further similar events in the future. For a tree fell, more vegetation management, hardening, or under-grounding can help.

3.6.3.2. THE CONSEQUENCES

Consequences of an event are also different. If a pole comes down near a school, public safety is endangered. If the pole comes down with live wires in a High Fire Tread District, there will be risk of wildfire. Reliability is also a traditional consequence considered in planning and risk mitigation of electrical assets. Consequences are more discussed in the next section; this section denotes the importance of comprehensive risk management in utility planning that encompasses most of the probabilities and consequences.

3.6.3.3. THE MITIGATIONS

Knowing the event and the consequence, mitigations can best planned. Mitigations cover actions that can be taken to avoid the event in the future for good, reduce the probability of it happening, or to reduce its impact.

This last part is usually less focused: it is important to note that mitigations also cover the consequence aspect of the risk, meaning, this step considers that the event has surely happened and then focuses on reducing the dimension of the impact. A simplified example is the case of the rotten pole: either replace the pole to avoid the event (reactively), or to use pole stubbing upon the inspection (proactively) so the event probability is limited. These are the two first parts of the mitigations as explained above.

Now while replacing the pole may ensure the reduction of risk by a lower probability of the event, there may still be a chance that the new pole gets broken by internal rot after a while. Most significant to recall here is that the new pole may break due to a fallen tree, which was not the event we mitigated in this example (we mitigated a broken pole due to internal rot). Hence, reduction of consequence does not discriminate between the root cause of the final result, i.e., what happened that the pole fell down; rather, it focuses on what happens when the pole fails. Therefore, the mitigation thought-process will hesitate here and go back to evaluate the two selected approaches to eliminate or reduce the probability of the pole falling down, especially if the pole is in front of a shopping mall or a school (public safety consequence), or in an area with elevated risk of wildfires.

3.6.3.4. NOVEL APPROACHES TO IMPROVE ASSET MANAGEMENT

As the dimensions of the asset management universe expand (event, multi-dimensional consequence, many possible mitigations, etc.), decision making becomes harder, especially considering that the patient -distribution grid- is alive and dynamic, faced by even more threatening external factors as the electrification grows and the impacts of climate change become more prominent.

- **Asset-Threat-Control** – It is important to know the distribution system element by element, whether parts of the electrical flow such as conductors and transformers, or the parts who indirectly help this flow, such as poles, insulators, etc. As such, a detailed team of engineers with expertise ranging from electrical to chemical engineering is needed to assess what may happen to each asset and define controls that may detect and mitigate such threat factors.
- **Integrated Grid Planning** – Among the different mitigations that may be selected for an event, considerations such as cost and burden, effectiveness of the mitigation, probability of the event happening, and most importantly, the consequence of the event reduced by each mitigation should be massaged together to create one single attribute that can be tracked by utility leadership as key performance indicators. This is what a framework such as integrated grid planning pursues.
  For instance, consider options that a utility has for mitigating the impacts of a potential wiredown on a long, old, small wire span: replacing may help reduce the reliability and safety impact, adding a recloser or sectionalizer may help with CAIDI and hence improve

reliability, and going underground can help with improvement in reliability, reduction of public safety risk, and also of wildfire risk. Traditionally, depending on the cost and benefit study, one of these options have been selected in similar situations. Now, under integrated planning, the utility will look at the circuit, and in some cases at the total grid, all together: can putting a recloser also help with other sections, either upstream or downstream?; can undergrounding this section improve the reactive power needs of the circuit beyond the risk reductions?; can replacing with a tree wire reduce the momentary interruptions that have affected the industrial plant downstream?

- **Considering customers with Bundling the work –** Utilities have done tremendous work in the last decade improving their reliability while considering safety of the public as their priority. More is needed for improvements in the viewpoint of customers so they can both benefit from translation of the work into their daily lives and appreciating what is being done in other aspects such as safety and reliability.
  Customers may historically experience multiple planned outages: one for a pole replacement, one for a switch placement, and one for a safety maintenance of an overhead conductor. The goal of bundling is to perform all the corrective maintenance on the line segment in one isolation zone at once, so the utility can work more efficiently to help reduce the backlog of notifications, reduce the number of planned customer outages required, and improves customer satisfaction. Through bundling in isolation zones, asset maintenance teams can coordinate with other lines of business so that customers only experience one planned outage while all the work needed in that zone are done at one time.

4. Conclusion

Overhead lines and cables represent an important category of the assets managed by utilities. As linear assets, they cover the territory where DSOs operate and are vital assets to guarantee power delivery across that territory. They also represent a high percentage of the overall value of fixed assets operated by DSOs. They are the assets whose reliability usually represents a larger contribution to the overall network performance. They are also the assets more exposed to the elements, hence included among the ones more critical to address when a DSO aims at increasing its resiliency. ENEDIS is an example of significant investments in improving the resiliency of its MV network.

Asset management systems are being continuously improved, using, for example ISO 55000 standard series as a reference. This improvement aims to enhance decision-making processes and support tools, thus enabling better decisions that balance the trade-offs between short-term and long-term, modernization and maintenance (CapEx / OpEx trade-off), and risk and investment. Examples from E-REDES, Enedis, Elektro-Ljubljana and State Grid Shanghai allow us to assess the state-of-the-art underground and overhead lines asset management and how DSOs are developing better, more analytical, and quantitative risk assessment tools.

Maintenance of underground cables and overhead lines – particularly more exposed ones – is a critical topic addressed by DSOs, aimed at improving the condition and life cycle of assets and as a risk mitigation strategy. This paper also addressed that topic, presenting different maintenance strategies to present the state-of-the-art regarding maintenance policy. Examples of the development of maintenance methodologies and policies, including assessment of condition, probability of failure and risk, are provided by E-REDES, Enedis and State Grid Shanghai.

Cable manufacturers have a deep understanding of the characteristics associated with cable technologies and, therefore can support DSOs in assessing the condition – diagnostic methodologies – helping to define adequate maintenance strategies. Cable information can be collected through several different off-line diagnostic methodologies, destructive diagnostic or online monitoring. Nexans is presented in this report on how a cable manufacturer can contribute to the definition of maintenance strategies.

This report illustrates that DSOs are fast evolving their asset management capabilities associated with overhead lines and underground cables, fostered by the technological evolution of diagnostic technologies and the development of IT and data management capabilities.

DSOs also face challenges associated with the energy transition, which, due to the electrification of energy consumption, is expected to increase the electrical energy demand that must be met by electrical energy distribution infrastructure, which is also set on a backdrop common to several DSOs of modernization requirements associated with ageing infrastructure.

Hence, the continuous improvement of asset management capabilities associated with asset management, including those associated with the linear assets described in this report, is expected to be maintained during the next years and even decades.

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