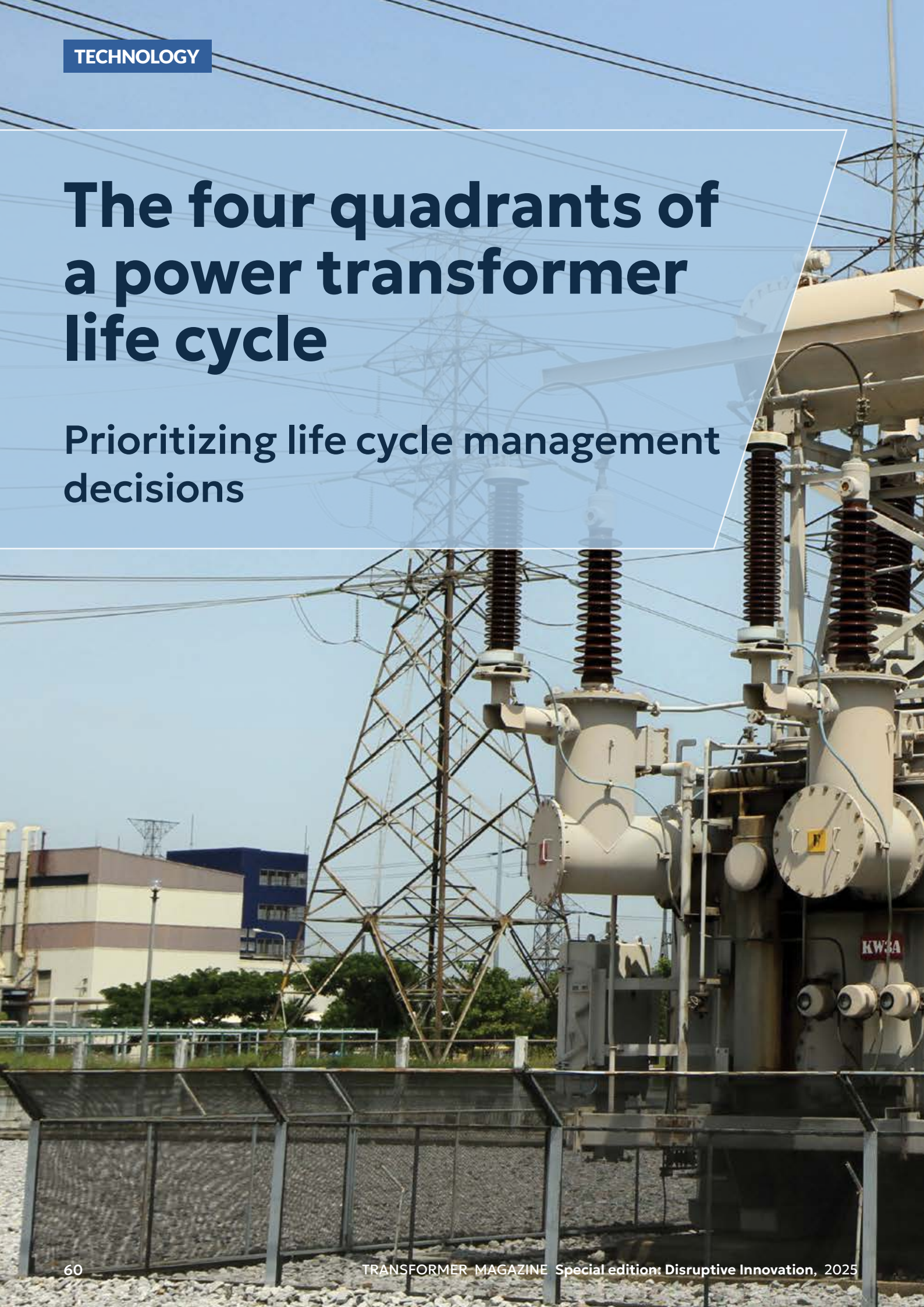


# The four quadrants of a power transformer life cycle

## Prioritizing life cycle management decisions





## ABSTRACT

As the total cost of ownership (TCO) of power transformer fleets continues to rise, electrical utilities are increasingly seeking new approaches to optimize life cycle decisions. Determining the optimal strategy for the right unit at the right time is a complex challenge. This article introduces a structured framework for transformer life cycle management (LCM), including a novel four-quadrant model to support prioritization of maintenance, refurbishment, and replacement decisions.

## KEYWORDS:

life cycle management, prioritization, targeted maintenance, refurbishment, transformer fleet

## Power transformers are the most critical, complex, and expensive substation equipment

### Introduction

Electrical utilities worldwide face a common reality, characterized by aging infrastructure and critical assets, increasing cost of ownership, extreme weather events, supply chain disruptions, and prioritization challenges. One of the biggest challenges that we all face is the life cycle management of critical substation assets. In the current context of the substation equipment market and the aging fleet profile in North

America and Europe, developing reliable prioritization tools for condition assessment, maintenance, refurbishment, and replacement must be one of our top priorities.

This article shares some insights about typical LCM strategies and discusses how we can challenge the status quo, how we can be more efficient in the interpretation of data, and the prioritization of the best possible action on substation assets, more specifically,

power transformers. Power transformers are the most critical, complex, and expensive substation equipment. Collectively, utilities are approaching or have already passed a tipping point, where the total cost of ownership trend of transformer fleets has become a significant issue.

### Challenges

The transformer sector is undergoing rapid transformation, propelled by large-scale electrification, pervasive digital integration, and the modernization of grid infrastructure. This evolution is occurring amidst significant challenges, including skilled labor shortages, supply chain volatility, and the need for synchronized capital investment strategies.

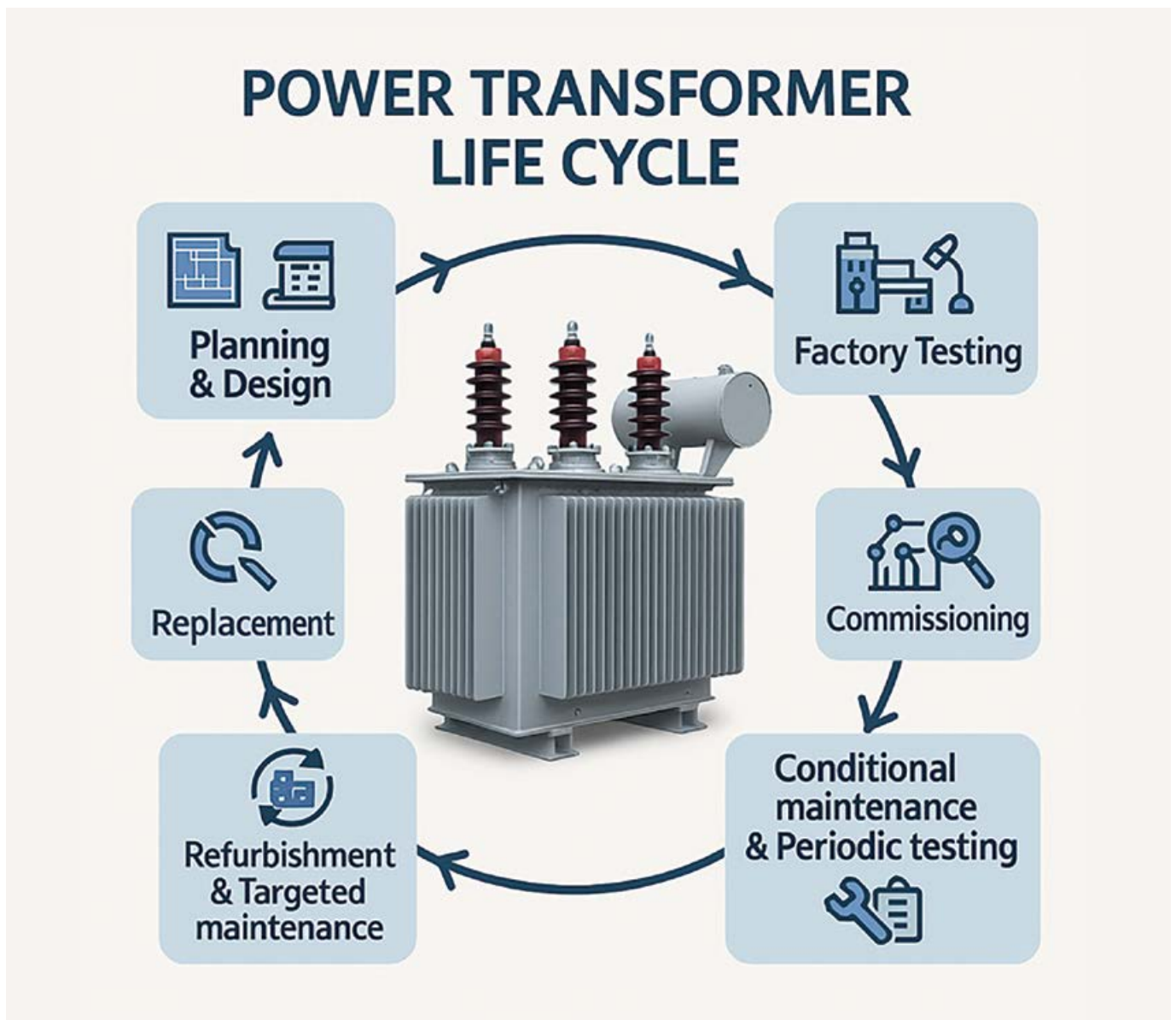


Figure 1. Typical life cycle of power transformers

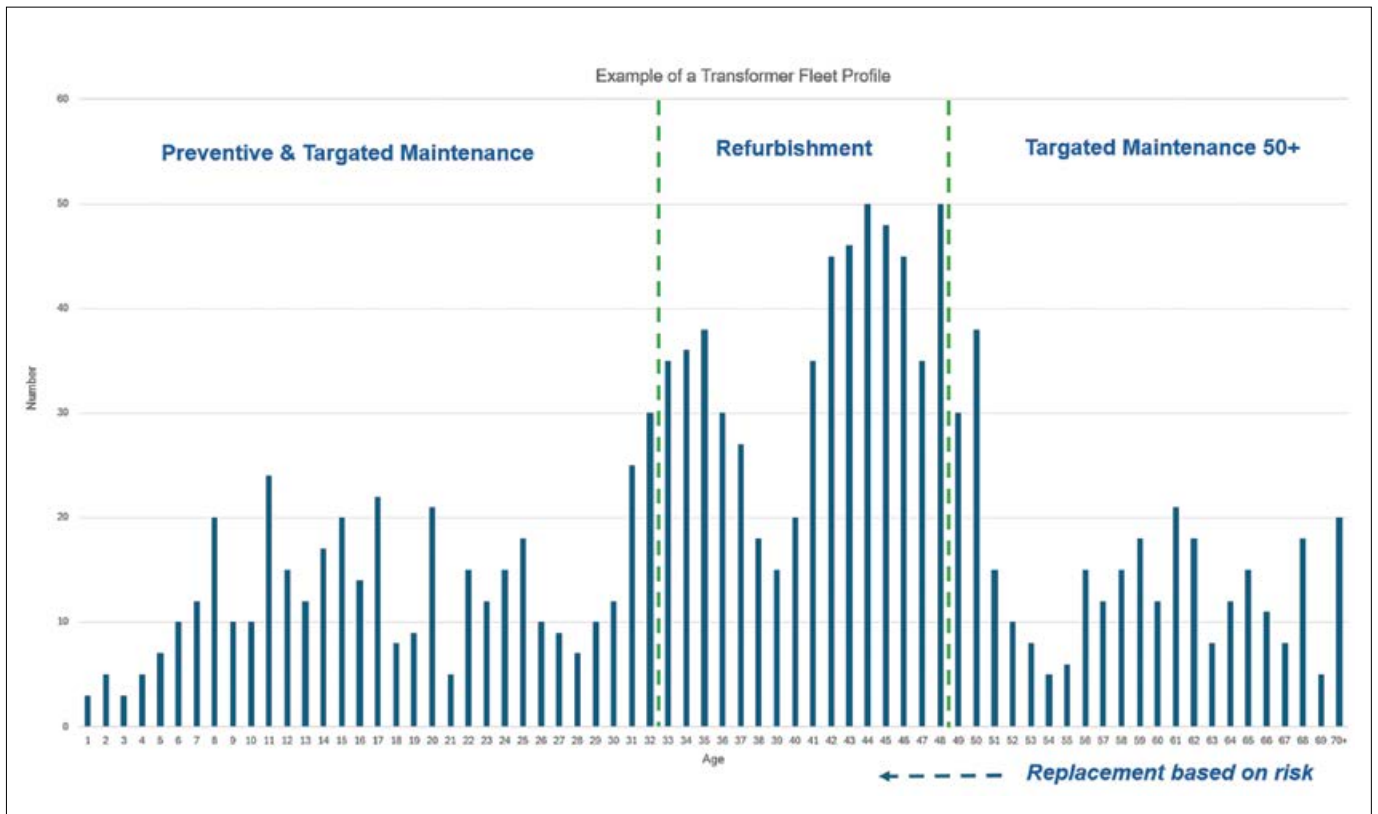


Figure 2. Typical fleet age distribution in North America

## The transformer sector is undergoing rapid transformation, propelled by large-scale electrification, pervasive digital integration, and the modernization of grid infrastructure

The world's leading transformer manufacturer has issued a critical alert regarding the sector's current capacity constraints, citing an inability to scale production in line with surging global demand for grid infrastructure. This shortfall poses a significant risk to the timely deployment of renewable energy projects reliant on grid expansion. Despite the urgency, manufacturers are pursuing capacity growth with caution, tempered by historical lessons from prior market cycles such as the 2007–2008 boom, and mindful of capital discipline and supply chain resilience.

Supply chain disruptions are, of course, not the only challenge. In many Canadian provinces, for example, electricity network rollout proceeded apace throughout the 1940s to 1980s but has slowed in recent decades. Many significant items of equipment are now operating close to, or even beyond, their expected retirement age. The average age of the critical

equipment fleets and the current slow rate of replacement mean it would take hundreds of years to renew all assets. This has significant reliability implications.

The aging rate of a transformer's insulation system is a function of its operational age and condition. Assuming all transformers are evaluated under a consistent loading profile and temperature rise, the apparent aging rate—derived from diagnostic assessments—can exceed the chronological aging rate. For instance, if the average chronological age of a large power transformer (LPT) fleet increases by 1.2–1.4 years annually, the apparent age, which reflects condition-based degradation, may increase by 1.6–1.9 years per year. This discrepancy highlights the nonlinear nature of insulation aging, particularly beyond the 40-year service mark, where aging accelerates significantly. At this stage, transformers require more frequent con-

dition-based maintenance and advanced diagnostic testing, which were previously unnecessary during earlier operational years, to ensure continued reliability and performance.

### Condition assessment is a strategic tool that ensures the reliability, safety, and longevity of critical assets by making informed decisions based on real data and trends

The condition assessment of transformer fleets is more important than ever.

## Between routine maintenance and full replacement lies a third dimension: targeted interventions such as condition-based maintenance and refurbishment.

Condition assessment is a strategic tool that ensures the reliability, safety, and longevity of critical assets by making informed decisions based on real data and trends. Transformer condition assessment is challenged by poor data quality, uncertainty in interpreting condition indicators, and the complexity of integrating multiple failure modes into a single evaluation. Limited sample sizes, diverse equipment designs, and the indirect nature of most condition metrics further complicate accurate risk modeling. Addressing these issues effectively requires close collaboration between transformer manufacturers and utilities to improve data sharing, standardize methodologies, and co-develop advanced assessment tools.

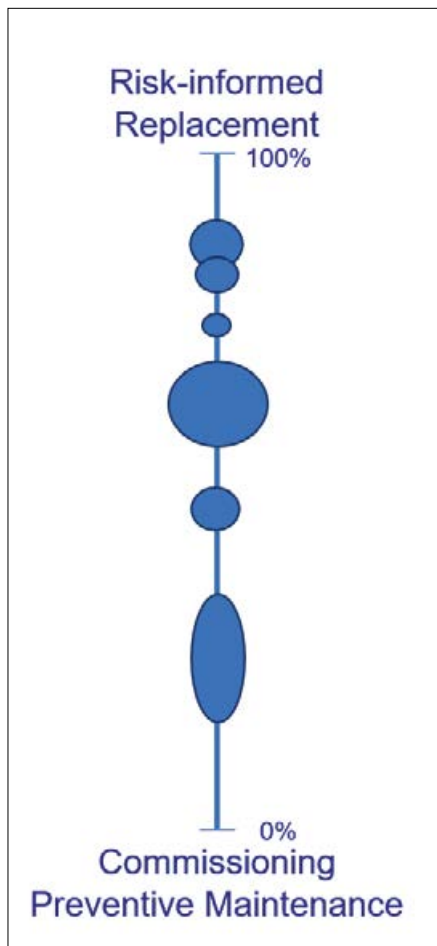


Figure 3. One-dimensional prioritization

In the next era of machine learning, AI, and reliable big data analysis, utilities must invest in finding the best methodologies for automated asset management decision recommendations based on predicted time to failure and proposed maintenance action options with estimated costs.

### Life cycle management practices

Several stakeholders are involved in different stages of the life cycle of power transformers, from planning to end-of-life decisions. For most of the utilities, life cycle management of transformer fleets is mainly driven by the application of preventive activities, which are condition assessment actions such as oil sampling, electrical testing, and replacement strategies. Most replacements are triggered by the risk-informed decision-making process. Most utilities replace approximately 1–5% of their fleets annually, with 20–30% of replacements being unplanned due to failures—a figure that may rise.

Between routine maintenance and full replacement lies a third dimension: targeted interventions such as condition-based maintenance and refurbishment.

### What is refurbishment or life extension?

Transformers are complex devices equipped with numerous accessories. The complexity of a transformer de-

pends on the specific requirements dictated by the power grid. While the fundamental design principles of transformers have remained largely unchanged since the 1950s, what has evolved are the design optimization tools. These advancements allow manufacturers to use less copper and steel while still meeting contractual performance requirements—an important factor for maintaining competitiveness in the market.

From a design perspective, a transformer can be divided into two main parts:

- The active part, which includes the core, windings around the core, solid insulation, and
- The accessories or external components, which support operation and monitoring.

All critical components (bushings, tap changers) must function properly to ensure reliable operation. A failure in any one of these components or accessories can lead to a partial or total failure of the equipment. The typical lifespan of the active part ranges from 60 to 80 years. Accessories generally have a shorter lifespan—around 30 to 35 years—which means that the end-of-life of a transformer is often dictated by the degradation of its accessories.

It is common to replace transformers that are 40–50 years old, not because the active part has failed, but because the accessories are severely degraded. We sometimes throw out the good with the bad, replacing otherwise healthy transformers due to failing accessories. Utilities are also seeing a significant increase in interventions and forced outages due to accessory failures starting around the 30–35-year mark. It's also important to note that accessories such as bushings, tap changers, cooling systems, and monitoring devices represent approximately 25–35% of the total cost of a new transformer.

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Implementing a transformer refurbishment program requires careful planning across several technical and operational dimensions. First, selecting suitable candidates is critical and should be based on a combination of condition assessment of the active part, reliability performance, cost-effectiveness, and total cost of ownership (TCO) analysis. Only units that demonstrate a clear economic and technical advantage over replacement should be considered. The refurbishment must be significantly more cost-effective than procuring new transformers, while still delivering acceptable performance and reliability. Additionally, minimizing downtime is essential. Refurbishment activities must be executed within tight operational windows defined by system operators, with contingency plans in place to ensure rapid return to service in case of unexpected issues.

A typical distribution of a transformer fleet by age in North America looks a lot like Figure 2. A significant population would be near “the sweet spot” of refurbishment, 35 years of age.

## For diverse and complex power transformer fleets, an efficient life cycle management strategy would be to segment the life cycle into three major intervention phases

For diverse and complex power transformer fleets, an efficient life cycle management strategy would be to segment the life cycle into three major intervention phases, each tailored to the technical condition and associated risk level of the equipment.

Phase 1: Full Performance (0-30 years)

During the first 30 years, transformers are generally in their full performance phase, where TCO is relatively low.

## The refurbishment must be significantly more cost-effective than procuring new transformers, while still delivering acceptable performance and reliability

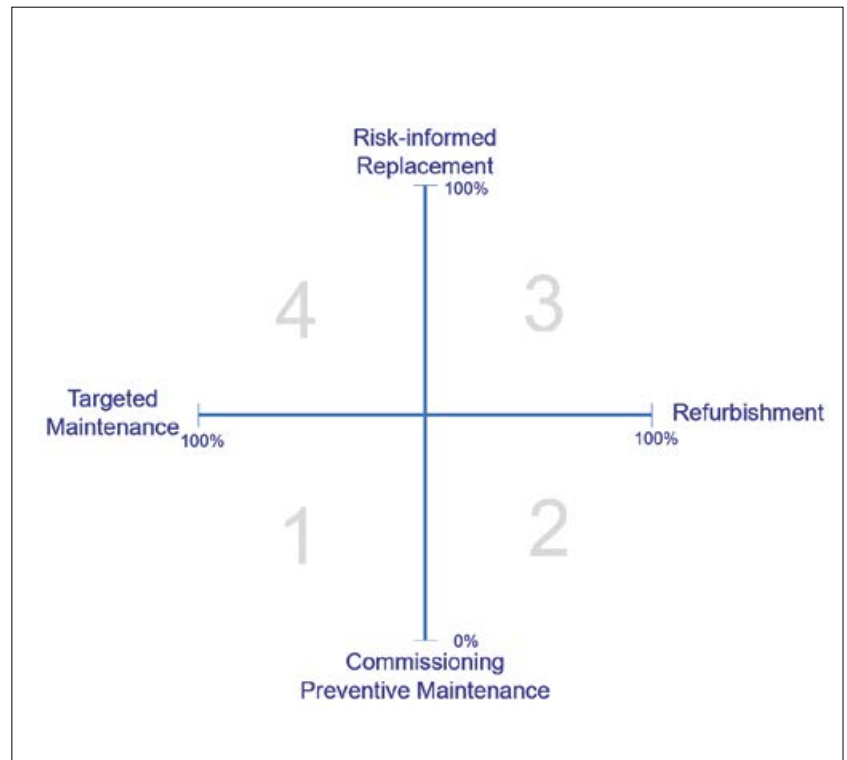


Figure 4. The four-quadrant model

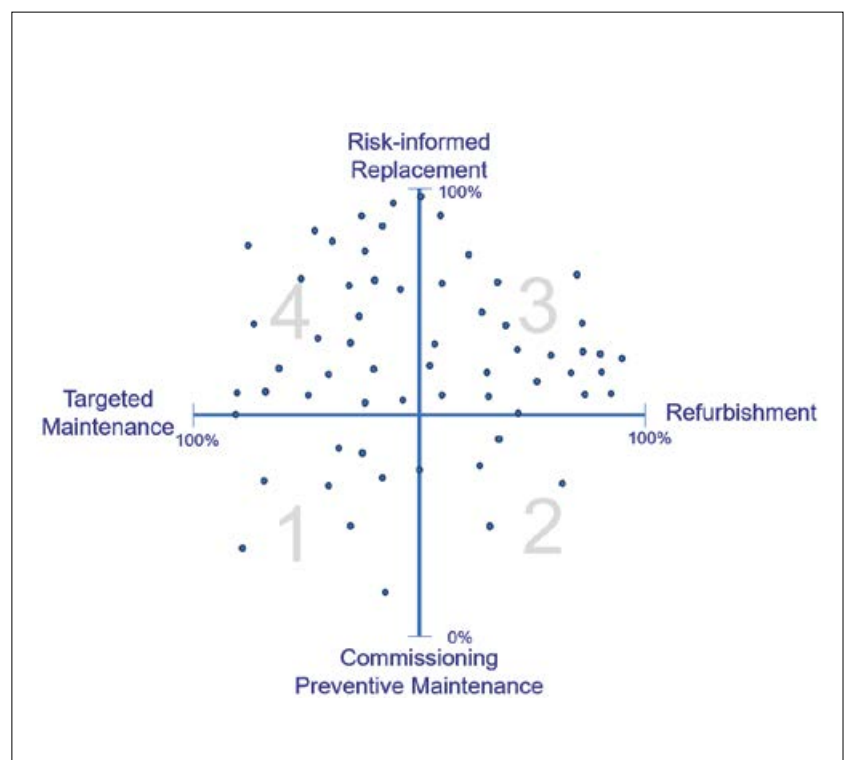
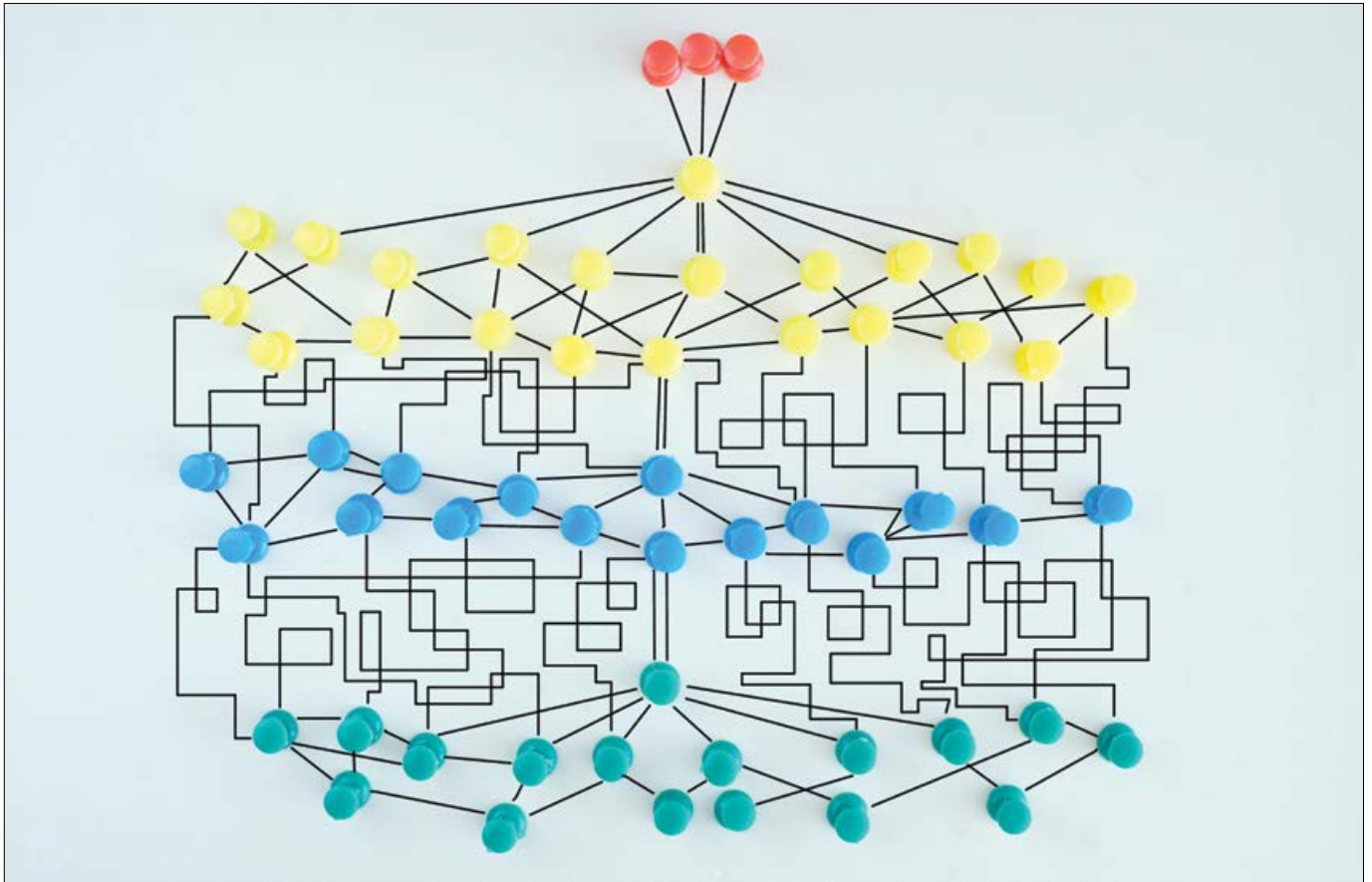


Figure 5. Fleet mapping in the model



## A transformer fleet can be mapped on a 4-quadrant of life cycle to compare intervention options according to several technical or non-technical parameters

The preferred approach is preventive or targeted maintenance, supported by regular diagnostics and monitoring tools to ensure optimal reliability, detect early signs of aging, and prevent unexpected failures.

Phase 2: Rehabilitation Potential (30-50 years)

Between 30 and 50 years, transformers undergo a thorough evaluation to determine their refurbishment potential. It is

considered only for equipment whose active part remains in good condition. Transformers with advanced degradation of their active part are directed towards replacement projects.

Phase 3: End-of-Life (50+ years)

Beyond 50 years, most transformers enter an end-of-life phase, where the probability of failure becomes significant. At this stage, maintenance on non-rehabilitated transformers could be targeted and guided by continuous assessment of their actual condition.

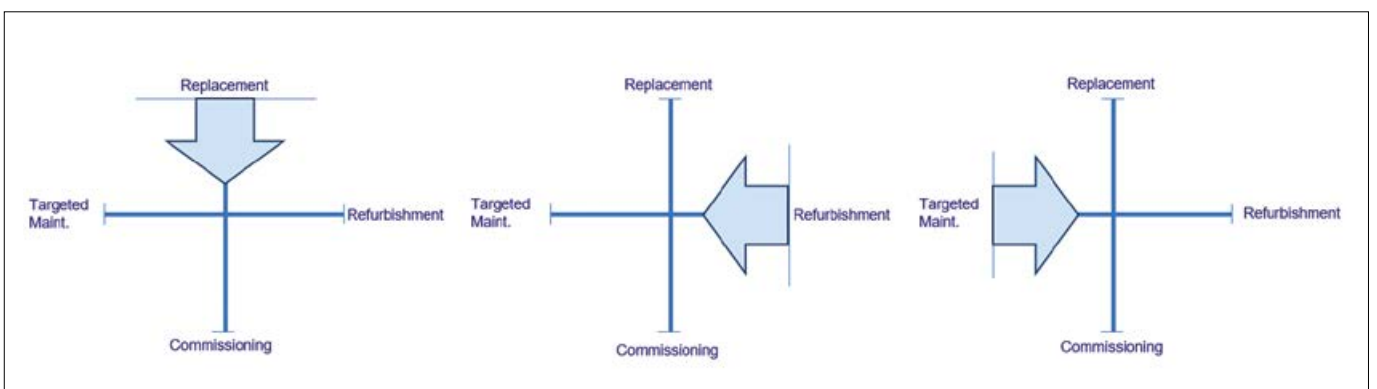


Figure 6. Prioritization by intervention type

Replacement prioritization is primarily based on two criteria: the condition of the active part and the probability of failure. This approach focuses investments on the most critical assets, ensuring continuity and operational safety of the grid from a sustainable asset management perspective.

## A new method: The four-quadrant model

The challenge in implementing this strategy will be to establish links between different interventions and prioritize them according to various criteria. For example, the transformers that will be rehabilitated must fall within a certain age range, their active parts must be in good condition, and the profitability index should be considered. Prioritizing for replacement requires risk analysis and planning studies. Different interventions, such as maintenance or replacement, must be compared on a common basis. It is necessary to find the links and correlations between all the possible life cycle management decisions.

For this challenge, a multi-dimensional prioritization method can be used to make the best possible decision on an asset. A transformer fleet can be mapped on a 4-quadrant of life cycle to compare intervention options according to several technical or non-technical parameters.

All utilities use a version of a risk-informed decision methodology to prioritize replacements. Figure 3 shows a one-dimensional form of simple prioritization based on a percentage scale where the population of the fleet is represented by the size of circular shapes.

## Each transformer begins in Quadrant 1 and progresses toward Quadrant 4, where replacement becomes necessary

## The proposed four-quadrant model offers a practical tool to align maintenance, refurbishment, and replacement strategies with asset condition and risk

Now we must incorporate two other life cycle management decisions that have important investment implications: targeted maintenance and refurbishment. These interventions add another dimension to the prioritization overview: a new axis.

As shown in Figure 4, each transformer begins in Quadrant 1 and progresses toward Quadrant 4, where replacement becomes necessary. For instance, a transformer with a healthy active part and within the investment age period would only appear in zone 3, after the investment age limit, it would then switch to zone 4. This representation allows us to better analyze and prioritize interventions based on common criteria. Total cost of ownership and specific parameters could be tailored based on utility priorities for prioritization of each type of intervention. Targeted maintenance would focus more on health indices of accessories, where the refurbishment scale would be calculated based on the ageing rate of the active part.

Based on intervention-specific parameters, a given transformer fleet can be mapped in this new model, which would help simulate budget requirements more accurately. Figure 6 shows how prioritization per type of intervention can be achieved.

As utilities face mounting pressures from aging infrastructure, rising costs, and evolving grid demands, a structured and data-driven approach to transformer LCM is essential. The proposed four-quadrant model offers a practical tool to align maintenance, refurbishment, and replacement strategies with asset condition and risk. Collaboration between OEMs and utilities, supported by standardized methodologies and advanced analytics, will be key to optimizing investment decisions and ensuring long-term grid reliability and sustainability.

## References

- [1] Electric Grid Supply Chain Review, Large Power Transformers and High Voltage Direct Current Systems, U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains"
- [2] Analysis of AC transformer reliability, CIGRÉ Technical Brochure A2.939
- [3] Large Power Transformers: new fleet management strategy, A. TIMERA, R. BLANC B. IZAC P. CLAUDE



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