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Project EU-TRACE: anticipated replacement of old distribution transformers

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Abstract

Meeting the EU's ambitious energy savings targets under the Energy Efficiency Directive (EED) requires exploiting all viable measures, including the accelerated replacement of ageing, inefficient distribution transformers. This paper presents initial insights from the LIFE-supported EU-TRACE project, which started in September 2025 and will run until March 2028. EU-TRACE seeks to develop policy recommendations to unlock the substantial energy savings potential of replacing legacy transformers with Ecodesign-compliant units.

Modern, Ecodesign compliant distribution transformers offer significantly reduced energy losses through advances in core materials, winding design, and cooling systems. Despite the clear benefit, current EU regulatory frameworks do not explicitly incentivise early replacement. For DSO-owned transformers, revenue-cap mechanisms may discourage capital expenditure where efficiency benefits are not adequately reflected in remuneration. For transformers owned by electricity end-users, split incentives and limited awareness – among other barriers – hinder a swift uptake of Ecodesign compliant units. Closing this gap requires targeted regulatory adjustments for DSOs (supported by art. 27 of the EED), and dedicated incentive mechanisms for electricity end-users (under art. 8 of the EED). Impact estimates based on available data suggest that accelerating replacement from a 2.2% to a 3.5% annual rate could deliver additional electricity savings of 2.1 TWh per year over a 20-year horizon.

The EU-TRACE project will address the challenges through the following actions:

- **Gather data on EU transformer fleets** and model different policy scenarios and their outcomes in terms of energy savings and emissions abatement.
- **Promote knowledge exchange** across distribution system operators, regulatory authorities, electricity end-users and energy agencies.
- **Propose appropriate policies** aimed at accelerating the uptake of energy efficient transformers and assisting Member States in achieving their energy saving targets.
- **Analyse the impact** of replacement policies **on the EU circular economy goals**.
- **Analyse the impact** of replacement policies **on the transformer market**, involving the entire value chain (raw material providers, OEMs, end-users)

Introduction

The Energy Efficiency Directive (EED) mandates that EU Member States achieve an average annual energy savings rate of 1.49% between 2024 and 2030 — nearly double the 0.8% requirement that applied from 2021 to 2023. Meeting this significantly more ambitious target will demand that all viable energy-saving measures be thoroughly explored. One promising avenue is the accelerated replacement of ageing, inefficient distribution transformers with modern units that comply with the minimum energy performance standards (MEPS) set out in Ecodesign Regulation (EU) 2019/1783.

The 2011 Ecodesign preparatory study on power transformers [1] identified units owned by distribution system operators (DSOs) and industry as the primary sources of potential savings, at 11 TWh/year and 6 TWh/year respectively. Given transformers' long operational lifespan, it is estimated that only 25–30% of this potential been realised to date through natural fleet replacement. Assuming the full replacement of legacy fleets would otherwise take approximately 20 years — as projected in [1] — an accelerated replacement policy compressing this period to 15 years could deliver average additional electricity savings exceeding 2 TWh/year over 20 years, equivalent to 42.5 TWh on a cumulative basis.

The LIFE project EU-TRACE (European Transformers Accelerated Efficiency) seeks to develop policy frameworks that drive such an accelerated replacement. It will focus on distribution transformers, defined as units that:

- fall within the scope of Ecodesign Regulation (EU) 2019/1783;
- are three-phase units rated between 1 and 3,150 kVA;
- have a primary winding voltage U1m ≤ 36 kV and secondary U2m < 1.1 kV;
- are owned by distribution system operators (DSOs) or electricity end-users.

While EU-TRACE proposals will primarily target transformers within this scope, the policy guidelines for regulated DSO-owned units may yield positive spillover effects on higher-power, higher-voltage transformers, such as those installed in primary substations.

The EU-TRACE project runs from September 2025 to February 2028, yet its intended measures are not expected to enter into force for at least two years and are designed to influence transformer replacement practices over a 15-year horizon. This longer-term outlook makes short-term raw material supply constraints less critical to the project's objectives — though they are by no means dismissed, and are being examined in detail. On the question of material use, it is essential to adopt a system-level perspective. Electrical energy losses carry a significant embedded material cost, as they necessitate additional generation and transmission infrastructure. Accelerating the deployment of new transformers would reduce these losses, thereby flattening energy demand and relieving pressure on generation and transmission infrastructure, which would offset the additional material use of increased transformer manufacturing.

While policymakers widely recognise the potential of accelerated transformer replacement, they often struggle to implement measures that effectively unlock the projected energy savings, and lack the tools to accurately estimate that potential and monitor real-world impact. EU-TRACE will address these challenges through a coordinated action structured around the following workstreams:

- **Data collection and modelling.** EU-TRACE will gather comprehensive data on transformer fleets across both DSOs and electricity end-users. This dataset will

underpin a modelling framework used to assess the potential impact of various policy scenarios in terms of energy savings and greenhouse gas emission reductions.

- **Knowledge exchange and stakeholder engagement.** EU-TRACE will facilitate knowledge exchange among key stakeholders to ensure that policy development is informed by diverse perspectives and real-world experience. This includes actors involved in regulated assets, such as DSOs, national regulatory authorities, and CEER, as well as stakeholders linked to privately owned assets, such as electricity end-users, national energy agencies, and the European Energy Network (EnR).
- **Policy development.** Drawing on a systematic assessment of existing national policy frameworks, EU-TRACE will propose targeted policy measures designed to support EU Member States in meeting their energy-saving obligations.
- **Circular economy impact evaluation.** EU-TRACE will promote design-for-recycling principles and the use of recyclable, high-value materials in transformer manufacturing, ensuring that replacement programmes contribute to the EU's circular economy objectives.
- **Market and value chain impact assessment.** EU-TRACE will evaluate the wider impacts of replacement policies on the transformer market and the full value chain, including original equipment manufacturers (OEMs) and raw material suppliers.

EU-TRACE examines the specific challenges and opportunities in seven EU Member States, with each country's national activities lead by its respective project partner(s): Belgium (E.DSO and ICA Europe), Germany (Fraunhofer ISI and ICA Europe), Greece (CRES), Italy (ECD), Portugal (ISR-UC), Spain (Comillas University), and the Netherlands (IEECP). Broader perspectives from additional EU Member States, pan-EU policy considerations, and best practices from outside the EU will also be incorporated into the final policy recommendations.

This paper provides an overview of three interconnected themes: the regulatory landscape and its associated challenges and opportunities for accelerated transformer replacement; the additional benefits offered by innovative transformer technologies as candidates for replacing ageing units; and the modelling approach EU-TRACE will employ to quantify impacts at the level of individual companies, Member State energy-saving and carbon reduction targets, and society at large.

1. Modern Distribution Transformers

A distribution transformer is the final stage in the power supply chain, stepping down medium-voltage electricity to the low-voltage levels required by end-users such as households, commercial buildings, and small industrial consumers. Modern distribution transformers have undergone considerable technical evolution, driven by increasingly stringent Ecodesign requirements, the integration of distributed energy resources (DERs), growing system flexibility demands, and digitalisation. While the core operating principle — electromagnetic energy conversion — remains unchanged, advances have concentrated on materials, design optimisation, and seamless integration into smart grid architectures.

1.1. Loss Mitigation Strategies

Transformer losses are conventionally divided into two categories: no-load (core) losses, which occur continuously whenever the transformer is energised, and load (copper) losses, which vary with the current drawn. Modern designs target both components. The adoption of low-loss core materials substantially reduces no-load losses — a particularly significant gain given that distribution transformers remain energised throughout their entire operational life. Figure 1 illustrates the improvements achievable through the use of higher-grade magnetic core materials, such as amorphous metals or advanced grain-oriented electrical steels. Refined conductor design and optimised winding geometry, meanwhile, reduce load losses, particularly under the partial-load conditions that characterise typical real-world operation. Finally, advances in insulation and cooling systems — notably the adoption of synthetic or natural ester fluids — improve thermal performance while simultaneously addressing environmental and safety requirements.

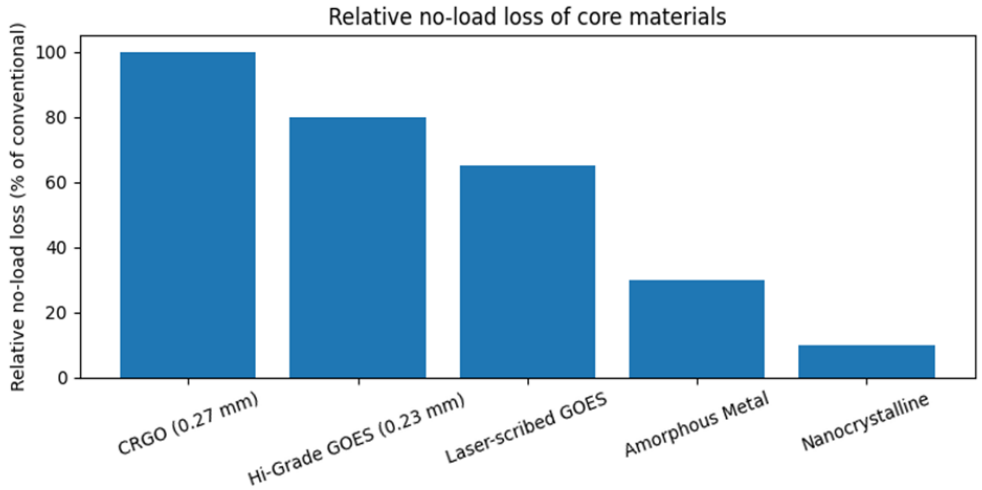


Figure 1. No-load losses in transformers with advanced transformer core materials compared to those in a unit with conventional core material.

Beyond design improvements, modern transformers are increasingly embedded within a broader digital and smart grid ecosystem. The integration of sensors, communication modules, and advanced monitoring systems enables real-time acquisition of key operational data — including temperature, load profiles, and insulation condition.

The benefits of improved energy efficiency are cumulative and long-term, and gains at unit level aggregate into system-level reductions in terms of greenhouse gas emissions and material use. Lower losses also reduce thermal stress, which can extend transformer lifetime and reduce maintenance requirements.

1.2 Digital Transformation and Smart Functionalities

A second defining dimension of modern distribution transformers is digitalisation. The energy transition is fundamentally reshaping both the demand for distribution transformers and the conditions under which they operate. The rapid proliferation of renewables, electric vehicles, heat pumps, and distributed energy resources (DERs) is driving higher electricity consumption at the distribution level and transforming load profiles — introducing greater variability, sharper peak demand, and increasingly bidirectional power flows. Addressing these shifts requires not only network reinforcements, but also the adoption of more flexible

grid operation strategies. In parallel, the broader digitalisation of electricity networks — through smart meters, advanced monitoring systems, and enhanced grid management platforms — is opening new avenues to optimise transformer utilisation.

Within this context, digitalisation is fundamentally redefining the role of distribution transformers in electricity networks, elevating them from passive voltage-conversion devices to active, intelligent grid nodes. By enabling real-time coordination across increasingly complex low- and medium-voltage networks, digitalised transformers support dynamic load management, facilitate the integration of distributed generation and energy storage, and enhance overall grid efficiency, flexibility, and resilience.

While distribution networks have historically been less monitored than transmission networks, this is starting to change. They are increasingly equipped with embedded sensors, communication interfaces, and control modules that enable continuous monitoring of key electrical variables — voltage, current, load, and power quality. These data are transmitted via standard communication protocols to supervisory control systems or cloud-based platforms, giving operators real-time visibility into grid conditions. By delivering granular, high-frequency data on load behaviour and voltage profiles, digitalised transformers support more accurate network state estimation and facilitate the identification of local congestion, phase imbalances, and voltage deviations. Furthermore, while traditional distribution systems were designed for one-way power delivery, modern networks must accommodate reverse flows from distributed generation. Smart transformers provide the monitoring and control capabilities needed to manage these flows safely and efficiently, preserving power quality and maintaining system stability. Enhanced data access could also unlock predictive maintenance capabilities, enabling operators to detect early signs of degradation — such as insulation ageing or abnormal thermal behaviour — and intervene before failures occur. The result would be fewer unplanned outages, greater reliability, and the ability to operate transformers closer to their optimal limits without compromising acceptable risk levels.

Overall, the integration of distribution transformers into IoT-enabled grid architectures can contribute directly to efficiency improvements. Real-time load and voltage management reduces technical losses and limits the need for costly network reinforcement. Improved situational awareness also enables faster and more targeted operational decisions — such as feeder reconfiguration or demand response activation — further strengthening overall system efficiency. By embedding intelligence at the distribution level, modern transformers improve network utilisation, support the coordination of DERs, and play a central role in the transition towards a more flexible and resilient electricity system.

2. Regulatory Incentives and Barriers to Transformer Replacement

Modern distribution transformers have significantly better energy performance than units pre-dating Ecodesign regulation, but regulatory incentives are key to ensure that early replacements also become economically viable. A distinction should be drawn between transformers owned by DSOs and those owned by electricity end-users:

- **DSO-owned transformers** operate within national regulatory frameworks governing investment planning and allowed financial returns. Replacement decisions are therefore shaped by the incentive structures embedded in DSO remuneration schemes.

- **End-user-owned transformers**, common among medium-voltage industrial, commercial, and tertiary sector consumers, are subject to private investment decisions. In this segment, replacement is typically driven by operational or financial considerations rather than explicit regulatory incentives.

This distinction is central to the design of policies aimed at closing the gap between replacement rates optimised for broader societal benefits and those driven solely by private returns. Achieving this would require regulatory adjustments that internalise the societal value of energy loss reductions and emissions savings into DSO remuneration frameworks, as well as targeted incentives to drive early replacement among electricity end-users. The following subsections examine how regulation across these two ownership contexts can either accelerate or hinder the uptake of higher-efficiency distribution transformers.

2.1. DSO-Owned Distribution Transformers

Electricity distribution grids are natural monopolies and are therefore subject to economic regulation. Remuneration mechanisms define how DSOs may recover their costs and earn a regulated return on their activities, with the overarching objective of providing sufficient incentives for network development and operation while keeping electricity supply affordable and reliable for end-users [2]. Modern DSO remuneration frameworks in Europe are largely based on incentive regulation and can be classified into ex-post and ex-ante approaches.

Ex-post mechanisms, commonly referred to as cost-of-service regulation, align allowed revenues with realised costs. If not carefully designed, this approach risks generating inefficiently high network charges, as it does not naturally incentivise cost efficiency. Cost-of-service regulation also tends to favour capital expenditure (CAPEX)-based solutions and the replacement of assets at the end of their regulated depreciation lifetime.

By contrast, **ex-ante schemes** set allowed revenues in advance for a multi-year regulatory period. Under these revenue-cap mechanisms, DSOs can retain efficiency gains achieved during the period, creating stronger incentives for cost efficiency. However, establishing an appropriate revenue trajectory is challenging due to the information asymmetry between regulators and DSOs. If caps are set too generously, they risk enabling excessive rent extraction; if set too restrictively, allowed revenues may prove insufficient to support adequate network development.

In practice, however, DSO remuneration mechanisms are more nuanced than a simple ex-ante or ex-post distinction. Regulatory frameworks frequently apply differentiated treatments to CAPEX and OPEX. Moreover, these schemes often incorporate supplementary design features aimed at improving operational efficiency and service quality — most commonly through incentives targeting energy loss reductions and network reliability improvements.

DSO remuneration schemes across Europe are progressively shifting towards ex-ante CAPEX remuneration. Portugal is among the jurisdictions that have already made this transition, while Italy and Spain are in the process of moving from ex-post to ex-ante recognition of CAPEX. Looking ahead, a further shift towards TOTEX-based frameworks is anticipated, incentivising DSOs to optimise total system costs and consider alternatives to conventional grid reinforcement [3], in line with Article 32 of Directive (EU) 2019/944.

Although revenue-cap remuneration schemes support greater flexibility — a core objective of EU regulation — their effects on the replacement of long-lived assets such as distribution transformers have received little attention. Revenue-cap regulation limits total allowed

revenues independently of actual costs. Under this model, DSOs can retain efficiency gains but may also face disincentives to increase capital expenditure, particularly where the efficiency benefits of early replacement — such as reduced energy losses and lower emissions from upgrading an ageing transformer to a MEPS-compliant unit — are not measured or adequately reflected in remuneration. As a result, ex-ante regulation tends to favour deferring asset replacement until the end of technical lifetime.

Despite often incorporating incentives to reduce system losses, current EU regulatory frameworks do not provide explicit incentives for early asset replacement driven by energy-efficiency considerations — particularly where existing assets remain technically compliant. This gap tends to redirect attention away from transformer loss reductions and broader system-wide benefits, such as emissions savings, towards other loss-reduction measures. Under revenue-cap schemes — or, less commonly, in jurisdictions with DSO investment ceilings such as Spain — transformer replacement must compete with other investment priorities, which can further slow down replacement rates. In addition, revenue-cap schemes may be biased towards either CAPEX or OPEX solutions – until a TOTEX framework with neutral incentives is implemented. In some cases, such as parts of Italy's distribution grid, losses cannot be calculated from direct measurements and are instead partially estimated, weakening the regulatory signal for targeted loss-reduction investment at the asset level. These regulatory barriers faced by DSOs are frequently compounded by additional obstacles, as identified by EU-TRACE in [4].

As a result, current EU regulatory frameworks risk inadvertently delaying the replacement of DSO-owned distribution transformers unless explicit incentives are introduced. This underscores the need for clearer regulatory recognition of the efficiency and environmental benefits associated with their accelerated replacement.

2.2. Electricity-End-User-Owned Distribution Transformers

Electricity end-users are typically not regulated entities. Decisions regarding the replacement of their distribution transformers are therefore governed by strategic plans and cost–benefit assessments, in which upfront capital expenditure is weighed against expected operational savings and risk reduction.

In principle, electricity end-users have a natural incentive to reduce transformer losses, since these losses translate directly into higher electricity bills. In practice, however, transformer losses are often small relative to total electricity consumption and are rarely measured explicitly. Furthermore, managing electricity infrastructure may not be a core activity for many electricity end-users, limiting their awareness of the efficiency gains achievable through Ecodesign-compliant transformers. High upfront investment costs — competing with other business priorities — can further reduce the attractiveness of early replacement. Replacement decisions are also complicated by split-incentive situations, where the entity bearing energy costs differs from the entity responsible for infrastructure investment.

Moreover, electricity end-users are not rewarded for the system-level benefits generated by improved transformer efficiency — such as reductions in CO_2 emissions or in the material requirements of power generation infrastructure. To explicitly incentivise early replacement under the EED, national energy efficiency obligation schemes could, for instance, designate the replacement of inefficient distribution transformers as a pre-accepted activity within white certificate mechanisms. This would enable end-users to monetise otherwise unrecognised system benefits through tradable energy efficiency certificates.

3. Impact Evaluation of Transformer Replacement

3.1. Energy Saving Estimates in of Ecodesign Regulation

EU Ecodesign regulation has driven the development of more energy-efficient transformers, reducing electricity losses by 17% for units sold in 2020 compared to those sold in 1990 [5]. According to the 2024 Ecodesign Impact Accounting [6], annual energy savings attributable to Ecodesign regulation for transformers are estimated at 16.2 TWh in 2025, equivalent to 3.03 Mt of CO_2eq. This estimate was derived from a characterisation of the entire EU27 transformer fleet as it stood around 2008, grouping units into broad categories — utility-owned distribution transformers, industrial transformers, and large power transformers. Energy losses were calculated by assigning average no-load and load loss values to each category and applying an assumed average load factor representative of typical loading conditions in the sector. Combined with annual operating hours, this yielded a baseline loss figure of 93.4 TWh per year for 2008. The savings estimate of 16.2 TWh per year was then derived by multiplying the number of units expected to be naturally replaced between 2014 and 2025 by the average reduction in load and no-load losses per unit, assuming a replacement rate of 2.5% per year — consistent with an assumed average technical lifetime of 40 years. On the same basis, annual energy savings are projected to reach 17 TWh by 2030.

3.2. Impact Estimates of Accelerated Replacement

Given the low natural adoption rate of Ecodesign-compliant transformers, policies designed to accelerate replacement carry substantial energy savings potential. Such policies could deliver electricity savings of up to 2.1 TWh per year over a 20-year horizon, on top of the savings already delivered by existing Ecodesign regulation.

This estimate is derived by comparing two replacement scenarios. Under the business-as-usual scenario, the current replacement rate of 2.2% per year implies full fleet replacement over approximately 20 years, with annual savings accumulating linearly from around 0.85 TWh in year one to the full 17 TWh per year by year 20. Under the accelerated scenario, the annual replacement rate is raised to 3.5% for 15 years, achieving full fleet replacement five years earlier. The annual difference in losses between the two scenarios starts at 0.28 TWh in year one, widens to a peak of 4.25 TWh per year in year 15, and then narrows as the business-as-usual scenario catches up, converging to zero by year 20. Averaging this difference across the 20-year horizon yields a mean incremental saving of 2.1 TWh per year, representing the additional energy savings attributable to accelerated replacement.

3.3. Limitations of Top-Down Models

The top-down nature of these calculations introduces several limitations. By starting from aggregate EU-wide data and applying uniform assumptions across the entire fleet, the approach fails to capture the real diversity of loss levels among installed units, which can deviate substantially from category averages depending on age, manufacturer, and operating history. Applying a single replacement rate across all Member States further obscures the considerable variation in replacement behaviour driven by differences in national regulatory frameworks, ownership structures, and economic conditions. For example, DSOs are regulated entities whose replacement decisions follow a fundamentally different logic from those of electricity end-users. The top-down approach also cannot incorporate actual load profiles — which directly determine load losses and, by extension,

the savings per replaced unit — instead relying on average loading assumptions that may not reflect real operating conditions across different network topologies and applications.

3.4. Modelling Improvements and Additional Data Requirements

Several tools exist to support transformer replacement decisions, ranging from total cost of ownership calculators designed for industry stakeholders evaluating individual replacements, to stock-level policy tools targeting policymakers — such as the UNEP U4E Energy Efficiency tool [7] and the Appliance & Equipment Climate Impact Calculator (Mepsy) [8]. However, existing tools are limited in both granularity and usability, and none currently enables policymakers to estimate the impact of early replacement programmes at EU stock level.

These limitations point to the need for a more granular, bottom-up methodology — one that starts from individual product assessments and scales up progressively to the EU level. This would involve two steps: first, a life cycle-based assessment at the level of individual transformer types; and second, a stock model that aggregates these results into policy-relevant projections.

The product-level assessment would cover the main transformer categories present on the EU market, weighted by market share, quantifying energy consumption, greenhouse gas intensity, and potentially material use across all life cycle stages. Critically, it would need to address lifetime reduction scenarios — capturing not only the operational savings from replacing an inefficient unit, but also the embodied impacts of manufacturing its replacement — thereby providing a complete picture of the net benefits of early replacement.

These results would then be integrated with actual fleet data into a stock model reflecting the real composition of the transformer fleet by type, age, and efficiency class. This structure would enable a more granular distinction between transformer types and a more accurate representation of fleet composition, supporting scenario-based projections that compare business-as-usual against accelerated replacement and producing more robust EU-level estimates of the savings potential. Developing such an integrated bottom-up stock model is a central objective of the EU-TRACE project.

Implementing this bottom-up approach would require more detailed data than is currently available at EU level, as identified in [4]. At the product level, actual measured or declared no-load and load losses for representative transformer units — alongside data on bills of materials, investment costs, and end-of-life characteristics — would be needed to underpin a meaningful life cycle assessment. At the fleet level, asset-level information on transformer age, rated power, type, efficiency class, and ownership would need to be collected from DSOs and electricity end-users, replacing the statistical estimates on which the current approach relies. Finally, actual load profiles from operational sources would be required to move beyond assumed average load factors.

4. Conclusions

This paper presents initial insights from the EU-TRACE LIFE project on accelerating the replacement of ageing, inefficient distribution transformers as a measure to help Member States meet their energy saving obligations under the EED. Modern distribution transformers deliver significantly lower losses and broader system benefits through improved core materials, design optimisation, and digitalisation — supporting efficient, flexible, and resilient grid operation. However, current regulatory frameworks do not explicitly reward the early

replacement of DSO-owned or electricity-end-user-owned distribution transformers. Moreover, existing top-down modelling approaches are insufficient to capture fleet heterogeneity, ownership structures, and real operating conditions, limiting their usefulness for policy design and monitoring.

Future work within the EU-TRACE project will address these gaps by developing accelerated replacement policies supported by improved data collection, stakeholder engagement, and a granular bottom-up stock model to quantify their impacts on energy savings, emissions, circular economy outcomes, and market effects.

The EU-TRACE project is still in its early stages. Its concluding phase will focus on assisting EU Member States in establishing policies for industrial end-users and guiding measures for distribution network operators — unlocking the identified savings potential through active collaboration with key stakeholders, including regulators, industry users, and national energy agencies, and drawing on their diverse insights and expertise to inform the project's final recommendations.

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