

Balancing energy, material, and cost factors in distribution transformers

Assessing the impact of potential scenarios for stricter minimum efficiency performance standards

ABSTRACT

European Union (EU) regulation in the area of ecodesign is evolving to meet the requirements of the Ecodesign for Sustainable Products Regulation (ESPR), which places greater emphasis on the circular economy. This leads to the question of whether the energy performance levels of distribution transformers should be further improved. The answer must take the wider context into account, basing its calculations over the entire lifetime of the units concerned and including the impact on power generation capacity needs. After garnering fresh insights, the International Copper Association has reviewed and fine-tuned its earlier analysis published in the April 2024 edition of Transformers Magazine. The new assessment, comparing a range of scenarios and design strategies, identifies the most favourable options, offering a 5% reduction of no-load losses and a 10% reduction of load losses compared to prevailing values.

KEYWORDS:

distribution transformer; energy efficiency; EU ecodesign regulation; material efficiency; life-cycle cost



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Fine-tuned assumptions in a fresh design exercise

Energy efficiency has been high on the European Union (EU) policy-making agenda for many years, while material resource conservation has relatively recently become such a pressing issue. The rationale behind this issue is not merely environmental. It also encompasses concerns over the EU's resource sovereignty. This is reflected in recent assessments in the context of EU ecodesign regulation, which is evolving progressively towards the Ecodesign for Sustainable Products Regulation (ESPR).

Since energy-efficient devices generally use more material in their manufacture than less efficient equivalents, taking both factors into account often results in a complex balancing exercise. This also applies to distribution transformers and raises the question of whether introducing higher energy performance levels is worth the additional material use and investment cost of the transformer. The answer to this question can only be meaningful if the wider context is considered, taking the impact on power generation capacity needs into account, as well as the entire life cycle cost of the unit.

We presented the results of such a comprehensive assessment in an earlier Transformers Magazine article (Volume 11, Issue 2, 2024), comparing a range of regulatory scenarios. Calculations were based on a liquid-immersed, 3-phase, 50 Hz, 630 kVA transformer (MV Um ≤ 24 kV, LV Um ≤ 1.1 kV, short circuit impedance 4%), in two versions — one with two aluminium windings and one with two copper windings.

The bills-of-material (BOMs) were cross-checked and refined by two transformer manufacturers, and M070 grain-oriented electrical steel (GOES) was used, which is considered to be the best available technology in Europe. Material price assumptions were also derived from consultations with transformer manufacturers. A 40-year transformer lifetime, an average root mean square (RMS) load of 30%, a net present value (NPV) actualisation rate of 2%, and a constant electricity price of €0.13 per kWh were assumed for that exercise, based on data from EU ecodesign preparatory studies.

Following this initial analysis, we continued to question our assumptions. Further consultations with transformer manufacturers and steel suppliers revealed that a general market move to M070 might be challenging since this is the highest quality of GOES, for which large-scale supply could be compromised. We conducted a

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Table 1. Total energy savings per transformer for different regulatory scenarios

| Regulatory scenario | Tier 2 | Tier 3a | Tier 3b | Tier 3c |
|--------------------------------------|--------|--------------|--------------|--------------|
| No-load losses (W) | 540 | 540 (-0%) | 510 (-5%) | 480 (-10%) |
| Load losses (W) | 4,600 | 4,140 (-10%) | 4,140 (-10%) | 4,140 (-10%) |
| Root mean square load | 20% | 20% | 20% | 20% |
| Total losses (kWh/year) | 6,342 | 6,181 | 5,918 | 5,655 |
| Reduction compared to Tier 2 (kWh/y) | 0 | -161 | -424 | -687 |
| Root mean square load | 30% | 30% | 30% | 30% |
| Total losses (kWh/year) | 8,357 | 7,994 | 7,732 | 7,469 |
| Reduction compared to Tier 2 (kWh/y) | 0 | -363 | -625 | -888 |
| Root mean square load | 40% | 40% | 40% | 40% |
| Total losses (kWh/year) | 11,178 | 10,533 | 10,270 | 10,007 |
| Reduction compared to Tier 2 (kWh/y) | 0 | -645 | -908 | -1,171 |

further analysis using GOES quality M075, which would be more in line with EU supply chain possibilities.

The electricity price was adjusted to €0.16 per kWh based on the in-depth analysis in the European Green Deal impact assessment, which covered price predictions for various future scenarios. Our assumption also took into account Eurostat's electricity price figures for non-household consumers and wholesale electricity prices published by the European Network of Transmission System Operators for Electricity (ENTSO-E). We also conducted sensitivity analyses on both the electricity price and the RMS load since these values are subject to future uncertainties and can vary significantly between EU Member States.

Searching for the most favourable Tier 3 scenario

In our initial exercise, a regulatory scenario involving a 10% reduction in both load losses and no-load losses compared to Tier 2 was selected as the most fa-

With lower-quality electrical steel, reducing the no-load losses might prove more difficult, which is why we complemented Scenario Tier 3c with two additional scenarios with 0% and 5% reduction in no-load losses

vourable since it showed a significant reduction in energy losses combined with the lowest total cost of ownership (TCO) and the least material use at system level of all the scenarios. We refer to this as **Scenario Tier 3c**.

With a lower-quality electrical steel, however, reducing the no-load losses might prove more difficult. For our new exercise with M075 steel, we complemented Scenario Tier 3c with two additional scenarios, maintaining a 10% reduction in load losses but reducing the no-load losses for 0% (**Scenario Tier 3a**) or 5% (**Scenario Tier 3b**). Table 1 compares the

annual energy savings between the selected scenarios based on three different RMS load values: 20%, 30%, and 40%.

Material use and volume

A transformer design, with its associated BOM, was created for each of the selected scenarios and cross-checked with manufacturers. As discussed earlier, switching from Tier 2 to Tier 3 energy performance levels will increase the quantity of material used to manufacture the transformer itself but will also save material by reducing the power generation capacity needed upstream in the



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system. To quantify this saving, we need to know the average marginal additions to the electricity mix over the transformer's 40-year lifetime.

Figures for the period between 2025 and 2050 from the European Green Deal impact assessment reveal that onshore wind (56%), offshore wind (16%), and solar PV (28%) will be the main additions to the generation infrastructure. We assumed the electricity mix would remain stable between 2050 and 2065. We also assumed that the infrastructure lifespans would be 20 years for onshore wind and 25 years for offshore wind and solar PV. The figures for material use in the power generation units under consideration were taken from the Renewable Energy Materials Properties Database (REMPD), a consolidated, public data repository maintained by the US

Department of Energy (US DOE), listing the types and quantities of materials required per megawatt (MW) of generation capacity. The annual productivity for each of the technologies was derived from 2022 ENTSO-E figures on installed capacity and annual energy production in the EU-27.

Combining all this input, the material used for the EU marginal electricity mix was calculated to be 750 g per kWh per year for all materials combined and 150 g per kWh per year if only metals are taken into consideration. From this, the material use related to the energy losses in the transformer could be calculated. A sensitivity analysis was conducted to see the effect of different RMS loads. Adding this to the BOM of the transformer itself resulted in the total material use at the system level, shown in Table 2.

These figures reveal that the Tier 3b scenario uses the least material at the system level if all materials are taken into account. This results in a reduction of between 0% and 4% compared to Tier 2, depending on the type of winding material and the RMS load. When taking metal use only into account, all Tier 3 scenarios show a modest increase compared to Tier 2, but this increase is at its lowest for Tier 3b (a 4% to 9% increase depending on the type of winding material and the RMS load). Note that Tier 3a and Tier 3b allow for a reduction in metal use compared to Tier 2 by switching from aluminium to copper windings, which is not the case for Tier 3c. The volume of the transformer increases for each of the Tier 3 scenarios, but this increase is less marked for Tier 3a and Tier 3b, while Tier 3c sees a more substantial increase in volume. The increase in volume can also be avoided by switching from aluminium to copper as a winding material.

Note that the figures in Table 2 describe the system impact of one transformer only, with the aim to investigate the effect of an energy performance optimisation. A higher RMS load leads to more material use when considering one

Table 2. Material use at the system level and transformer volume in different regulatory scenarios

| SYSTEM MASS (transformer + generation) ALL MATERIALS | Aluminium | | | | Copper | | | |
|--|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| | Tier 2 | Tier 3a | Tier 3b | Tier 3c | Tier 2 | Tier 3a | Tier 3b | Tier 3c |
| Total mass for RMS load 40% (kg) | 10,726 | 10,564 | 10,388 | 10,430 | 10,288 | 9,973 | 9,912 | 9,992 |
| Total mass for RMS load 30% (kg) | 8,604 | 8,655 | 8,479 | 8,520 | 8,166 | 8,064 | 8,003 | 8,082 |
| Total mass for RMS load 20% (kg) | 7,089 | 7,291 | 7,115 | 7,156 | 6,651 | 6,700 | 6,639 | 6,718 |

| SYSTEM MASS (transformer + generation) METALS ONLY | Aluminium | | | | Copper | | | |
|--|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| | Tier 2 | Tier 3a | Tier 3b | Tier 3c | Tier 2 | Tier 3a | Tier 3b | Tier 3c |
| Metal mass for RMS load 40% (kg) | 3,584 | 3,772 | 3,765 | 3,937 | 3,221 | 3,297 | 3,374 | 3,605 |
| Metal mass for RMS load 30% (kg) | 3,172 | 3,401 | 3,395 | 3,567 | 2,809 | 2,926 | 3,004 | 3,235 |
| Metal mass for RMS load 20% (kg) | 2,878 | 3,137 | 3,130 | 3,302 | 2,515 | 2,662 | 2,739 | 2,970 |

| TRANSFORMER VOLUME | Aluminium | | | | Copper | | | |
|--------------------|-----------|---------|---------|---------|--------|---------|---------|---------|
| | Tier 2 | Tier 3a | Tier 3b | Tier 3c | Tier 2 | Tier 3a | Tier 3b | Tier 3c |
| Inside volume (m³) | 0.74 | 0.84 | 0.86 | 0.94 | 0.47 | 0.50 | 0.55 | 0.59 |

transformer but will reduce material use at the grid level because fewer transformers will be needed for the same power demand. A study of the parameters affecting the load factor and the influence of the load factor on the material use of the electricity system is out of the scope of this article.

Total cost of ownership

The total cost of ownership (TCO) of the transformers in the different scenarios was calculated by adding the cost of the materials used to manufacture the transformer to the cost of the energy losses over the transformer's lifetime. Table 3 shows the material price assumptions.

As can be seen in Table 4, and assuming electricity costs 0.16 euro/kWh, Tier 3 scenarios indicate a modest reduction in TCO compared to Tier 2, ranging between -0.5% and -5% depending on the regulatory scenario, the type of winding material, and the RMS load. The TCOs of Tier 3b and Tier 3c scenarios are similar. These conclusions remain largely the same when adjusting the cost of electricity to a higher (0.19 euro/kWh) or lower

value (0.13 euro/kWh). Only at the lowest electricity price (0.13 euro/kWh) and the lowest RMS load (20%) does the TCO of Tier 3 scenarios start to show a modest increase, around +1%.

Conclusions

Summarising the results, the most favourable scenario appears to be Tier 3b, with its 5% reduction in no-load losses

Assuming electricity costs 0.16 euro/kWh, Tier 3 scenarios indicate a modest reduction in TCO compared to Tier 2, ranging between -0.5% and -5% depending on the regulatory scenario, the type of winding material, and the RMS load

Table 3. Transformer material price assumptions

| Material | Cost per kg |
|--|-------------|
| Aluminium | €6.00 |
| Copper | €12.00 |
| Magnetic sheet (quality M075 = 0.75 W/kg at 1.7 T) | €3.20 |
| Oil | €2.00 |
| Tank + cover | €4.50 |

Table 4. TCO of the transformer for different regulatory scenarios at an electricity cost of 0.16 euro/kWh

| TOTAL COST OF OWNERSHIP at electricity price 0.16 €/kWh | | Aluminium | | | | Copper | | | |
|---|--------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| | | Tier 2 | Tier 3a | Tier 3b | Tier 3c | Tier 2 | Tier 3a | Tier 3b | Tier 3c |
| RMS 40% | Unit material cost | 8.169 € | 9.265 € | 9.313 € | 10.233 € | 10.434 € | 10.904 € | 12.145 € | 13.175 € |
| | NPV load losses | 28.588 € | 25.733 € | 25.733 € | 25.733 € | 28.588 € | 25.733 € | 25.733 € | 25.733 € |
| | NPV no-load losses | 20.975 € | 20.975 € | 19.814 € | 18.648 € | 20.975 € | 20.975 € | 19.814 € | 18.648 € |
| | TCO | 57.732 € | 55.973 € | 54.860 € | 54.614 € | 59.997 € | 57.612 € | 57.692 € | 57.556 € |
| RMS 30% | Unit material cost | 8.169 € | 9.265 € | 9.313 € | 10.233 € | 10.434 € | 10.904 € | 12.145 € | 13.175 € |
| | NPV load losses | 16.083 € | 14.474 € | 14.474 € | 14.474 € | 16.083 € | 14.474 € | 14.474 € | 14.474 € |
| | NPV no-load losses | 20.975 € | 20.975 € | 19.814 € | 18.648 € | 20.975 € | 20.975 € | 19.814 € | 18.648 € |
| | TCO | 45.227 € | 44.714 € | 43.601 € | 43.355 € | 47.492 € | 46.353 € | 46.433 € | 46.297 € |
| RMS 20% | Unit material cost | 8.169 € | 9.265 € | 9.313 € | 10.233 € | 10.434 € | 10.904 € | 12.145 € | 13.175 € |
| | NPV load losses | 7.149 € | 6.434 € | 6.434 € | 6.434 € | 7.149 € | 6.434 € | 6.434 € | 6.434 € |
| | NPV no-load losses | 20.975 € | 20.975 € | 19.814 € | 18.648 € | 20.975 € | 20.975 € | 19.814 € | 18.648 € |
| | TCO | 36.293 € | 36.674 € | 35.561 € | 35.315 € | 38.558 € | 38.313 € | 38.393 € | 38.257 € |

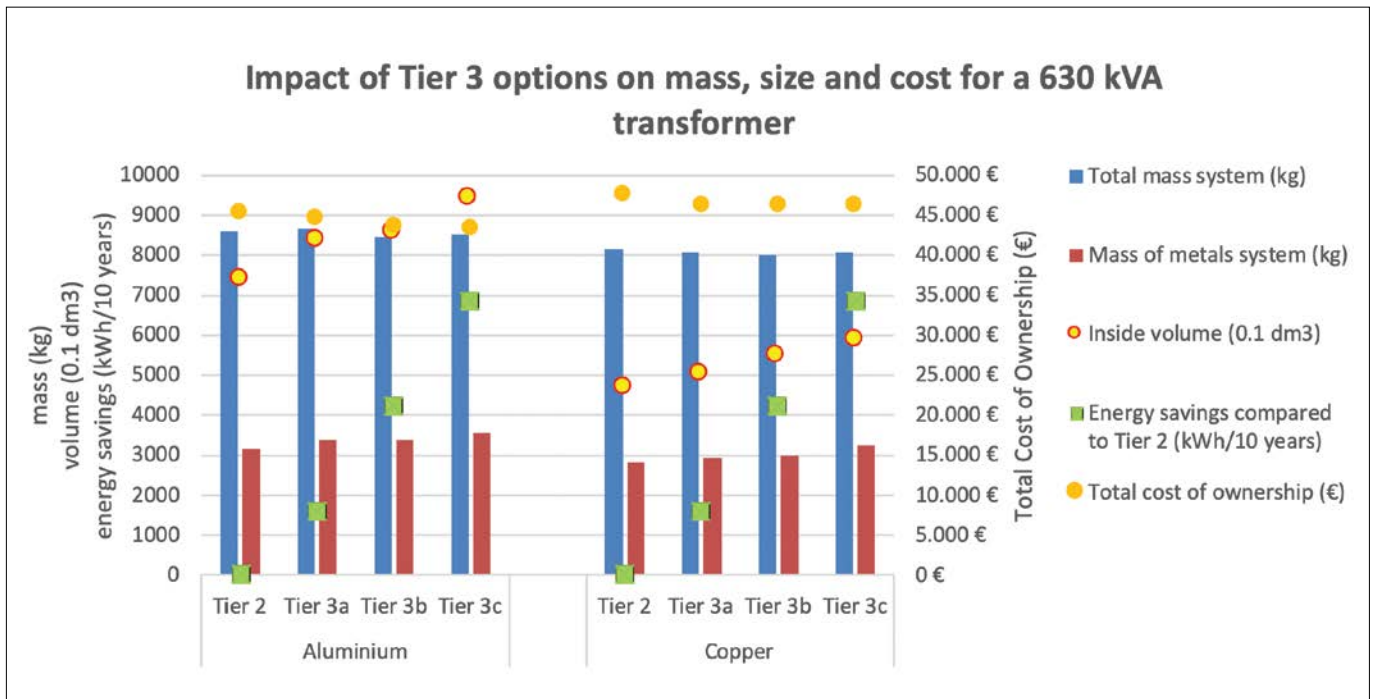


Figure 1. Overview of the impact of various potential scenarios for Tier 3 MEPS in terms of mass, size, and cost, based on an electricity cost of 0.16 euro/kWh and an RMS load of 30%

and 10% reduction in load losses compared to Tier 2. This scenario incurs a substantial reduction in annual energy use (-6% to -8%) and a slight reduction in total material use at the system level (0% to -4%). Moreover, Tier 3b has the most favourable TCO of all the options, less than the TCO of a Tier 2 transformer (-0.5% to -5%) except in the unlikely case of a very low electricity cost combined with a very low RMS load, which can result in a modest increase in TCO (around 1%). Scenario 3b incurs an increase in metal use at the system level (around +7%) and transformer volume (16% to 17%), but both effects can be avoided by switching from a unit with aluminium windings to a unit with copper windings.

The Tier 3c scenario incurs a smaller reduction in total material use at the

system level than Tier 3b, with a similar TCO. The increase in metal use is more substantial than for Tier 3b (+9% to +18%), and, in this case, the increase cannot be avoided by switching from aluminium to copper windings. Tier 3c also incurs a more substantial increase in transformer volume (+25% to +27%),

even though this can still be avoided by switching from aluminium to copper windings.

In the Tier 3a scenario, material use at the system level is less favourable, there is less gain in energy use, and the TCO is higher compared to Tier 3b.

The most favourable scenario appears to be Tier 3b, with its 5% reduction in no-load losses and 10% reduction in load losses compared to Tier 2

Authors



Bruno De Wachter has 25 years of experience as a freelance engineer-copywriter in B2B and EU advocacy communication. He combines his technical background with a passion for employing precise forms of expression and a wide-ranging knowledge of energy transition and policy-making. Since 2011, he has been an in-house consultant and copywriter for the European Copper Institute, focusing on topics related to renewable energy systems, transformers, motors, and electrical safety.



Fernando Nuño graduated as an energy engineer in Bilbao (Spain) and ENSPM School (France) in 1998. He worked in the development of combined heat and power plants at Air Liquide company, then he joined the French Energy Regulatory Commission, where he was in charge of electricity markets regulation. Later on, he worked in the automotive sector at Renault's powertrain division before joining the International Copper Association in 2007, where he was in charge of regulatory and technology aspects of copper-based technologies, notably transformers, cables and motors. He also manages promotional campaigns and leads multiple publicly funded EU Horizon projects.