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Comparative Life Cycle Assessment of a 630 kVA Liquid-Immersed Distribution Transformer

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Abstract

This paper discusses a comparative life cycle assessment (LCA) carried out on 630 kVA liquid-immersed distribution transformers with different winding conductor materials and energy performance levels. The LCA methodology for power transformers is still under development. Most LCA projects only take the manufacturing phase and its upstream value chain into account. If the transformer use phase is incorporated, assessments are conducted with the electricity mix of today, and usually only for the climate change impact category. This paper provides an LCA approach taking the manufacturing phase, use phase, and end-of-life phase into account, for several major impact categories, calculated with a projection of the electricity mix in the EU-27 over a 40-year period. Compared to existing approaches, this approach has the advantage of providing insights for determining the environmental trade-off between material use in the transformer and energy losses during transformer usage, while also taking into account the ongoing decarbonisation of the electricity supply.

Keywords: aluminium; carbon emissions; climate change; copper; distribution networks; ecodesign; environmental factors; energy efficiency; life cycle assessment; power transformers

1. Introduction

Life cycle assessment (LCA) can help to determine the net balances of environmental impacts. LCA extends the impact assessment by looking upstream in the life cycle, encompassing the production of the raw materials used to manufacture the product. Using the same logic, the environmental impact of energy losses during a product's use phase (also called "operational phase" or "in-service life") can be assessed by looking upstream at the different types of electricity generation units needed to provide this energy and their respective environmental impacts. LCA is an internationally recognised approach, standardised by ISO 14040 [1] and ISO 14044 [2]. Its application to distribution transformers, however, is recent; a common agreement is lacking on how system borders should be drawn, as well as on the characterisation and sourcing of the input data [3].

Most of the published LCAs of distribution transformers—such as [3–7]—assess the climate change impact category only. This is understandable, given the focus on greenhouse gas (GHG) emissions by EU regulators, but those studies do not provide a complete picture of the environmental impacts. Moreover, many of the existing LCAs on power transformers only include the manufacturing phase ("cradle-to-gate") and do not take the use phase into account [6–8]. While cradle-to-gate LCAs are useful for certain purposes, they are

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not helpful for considering the trade-off between using more materials in the transformer to reduce energy losses, or accepting more losses. Since the first preparatory study for EU Ecodesign Minimum Energy Performance Standards (MEPS) in 2011 [9], this trade-off has been a pressing issue—see, for example, a presentation at the CIRED International Conference in 2011 [10]. Reducing no-load and load losses of distribution transformers will reduce the environmental impacts of the electricity grid. However, most technology options to enhance the energy performance of transformers involve the use of additional materials in the manufacture of the units, and this will also entail various types of environmental impacts. For each type of environmental impact, there is an optimal energy performance level that results in a minimal net environmental impact; a "cradle-to-grave" approach is required to determine such an optimum.

Including the transformer use phase makes the LCA region-specific. Indeed, the electricity that is needed for the energy losses is produced using a mix of various types of power generation units—a mix that differs according to the country or region, and that evolves over time. The first LCAs with a cradle-to-grave approach were published in the context of the initial Ecodesign regulation for distribution transformers in 2011 and used the electricity mix of the EU-25 of that time [9,10]. More recently, similar studies have been published, calculating with the electricity mix of the EU-27 of past years [4,5]. What all these studies have in common is that they do not take account of the evolution of the electricity mix over time. This leads to a distorted picture, given the long lifetime of a transformer and the steady decarbonisation of the electricity grid, which is ongoing and can be assumed to continue. A recent study has recognised this and has conducted a comparative LCA of distribution transformers for the Polish electricity grid, predicting the evolution of the Polish electricity mix based on a linear extrapolation [3].

The study presented in this paper will refine this dynamic approach and will make use of the figures for the evolution of the electricity mix in the EU-27 presented in the impact assessment of the EU Green Deal, published in 2020 [11]. These figures follow directly from EU policies and their targets, making it a more realistic prediction than one that is based on extrapolation.

Making use of these figures, this study will investigate the life cycle environmental impact of enhancing the energy performance of a liquid-immersed, three-phase, 50 Hz, 630 kVA power transformer (MV $U_m \leq 24$ kV, LV $U_m \leq 1.1$ kV, short-circuit impedance 4%).

The functional unit adopted for the transformers under investigation is based on one unit of transmitted electrical power, referring to:

- Rated power as defined in EN 60076-1 [12];
- A load factor equal to 30% (RMS), subsequently changed to 20% (RMS) and 40% (RMS) in the sensitivity analysis;
- A reference service life (RSL) of 40 years.

The assessment will be made by calculating the difference in life cycle environmental impacts between the enhanced transformer model and the base case unit. The starting points of the calculations are the Bill of Material (BOM) and the annual energy losses of the transformer models under scrutiny. For the manufacturing and end-of-life phases, the individual life cycle impacts of each material in the BOM are added up. For the use phase, the life cycle impact of the electricity losses is calculated using the dynamic electricity mix, as mentioned before. As the study is comparative in nature, only the difference in energy losses between the highly efficient models and the base case units will be calculated—no absolute impact figures will be produced.

In a future investigation, a similar exercise could be carried out for transformers with different power ratings.

2. Input Data and Methodology

All the unit designs—both those for the base case and those with enhanced energy performance—were made by the authors, cross-checked by two different European transformer manufacturers, and finetuned based on their feedback (compared to just one manufacturer that was consulted for the LCA in [3]). The bills of material (BOM) were derived from these design exercises. In a future investigation, it would be useful to gather a broader view of manufacturer design methodologies and assess to what extent they influence the results presented in this study.

The base case unit conformed to the current EU Ecodesign energy performance thresholds [13]. This unit was then compared with a transformer demonstrating a reduction of around 10% in both load losses and no-load losses (see Table 1), hereafter referred to as the "Upgraded Energy Performance" (UEP) unit.

Table 1. Nameplate transformer losses (W) and annual energy losses (kWh/y) at an RMS load of 30% for the four selected transformer designs.

Energy Performance	Al/Al Windings		Cu/Cu Windings	
	Base Case	UEP Unit	Base Case	UEP Unit
No-load losses (W)	540	480	540	480
Load losses (W)	4600	4140	4600	4140
Annual energy losses, based on a 30% RMS load (kWh/y)	8357	7469	8357	7469
Additional energy losses compared to UEP unit (kWh/y)	888	0	888	0

For each of the two units, two different transformer designs were developed, one with aluminium conductor material in both the high-voltage and low-voltage windings, and one with copper conductor material in both windings. This resulted in a total of four different designs, each with a distinct BOM, as shown in Table 2.

Table 2. Bills of material of the four transformer designs developed for the case study.

Bill-of-Material (kg)	Al/Al Windings		Cu/Cu Windings	
	Base Case	UEP Unit	Base Case	UEP Unit
Aluminium	426	465	0	0
Copper	0	0	631	735
Steel core (GOES M070)	1106	1370	633	1020
Oil	366	435	262	300
Structural steel	298	345	264	270
Total mass	2196	2615	1790	2325
Mass of metals	1830	2180	1528	2025

Note that the designs of the UEP units use M070 grain-oriented electrical steel (GOES). While this is considered to be the best type of GOES available in large quantities on the European market, further consultations with transformer manufacturers and steel suppliers revealed that a general market move to M070 GOES might be challenging, since large-scale supply of this high-end material could be compromised. The present study should, therefore, be seen as an investigation of a particular case, and not as a proposal for a large-scale, general roll-out of this high-end material technology.

The embedded life cycle impacts for copper, aluminium, electrical steel, structural steel, and oil were retrieved from the GaBi LCA input database, content version 2023.2, developed by Sphera Solutions GmbH [14]. The references of the database values (proxy

dataset, UID code, and geography), as well as a reference for the allocation rules, are given in Appendix A.

An average root mean square (RMS) load of 30% was assumed for the transformer, the same figure that was used in [9,15,16]. This results in annual energy losses, as shown in Table 1. A sensitivity analysis on the RMS load was carried out to reveal whether additional efforts to estimate the future load with greater accuracy would be useful.

There is no difference in the power losses and annual energy losses between the models with two aluminium windings and the ones with two copper windings, because both base cases are based on the Ecodesign MEPS, and both UEP units are based on a 10% improvement in load and no-load losses.

The electricity mix is evolving over time. The transformer lifetime was assumed to be 40 years, as assumed in other studies [9,15], with the starting point set in 2025 and the end-of-life in 2065. The projected electricity mix for the years between 2025 and 2050 was taken from predictions in the study "2030 Climate Target Plan Impact Assessment" related to the EU Green Deal (Commission Communication COM (2020) 562 final) [11]—see Appendix B, Table A2. The electricity mix was assumed to be stable between 2050 and 2065.

The LCA impact of the various types of electricity generation that are present in the electricity mix was determined in accordance with the United Nations Economic Commission for Europe (UNECE) document "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" [17]. In Table 14 (pp. 76–77), this document provides LCA impact figures for the EU-28 in 2020 for 1 kWh of electricity produced by multiple sources of electricity. Note that the figures for the electricity mix are for the EU-27 (excluding the UK), while the LCA impact figures for the various types of electricity generation predate Brexit and are consequently given for the EU-28 (including the UK). More recent, publicly available LCA impact figures for the EU could not be found. The authors assume that the LCA impact figures of wind and solar PV electricity generation—which are predicted to strongly dominate the marginal additions to the electricity mix in the studied time frame [11]—do not differ significantly between the UK and the EU-27 Note also that these impact figures were necessarily treated as constant over time, as no publicly available future forecasts for these figures were found. A similar assumption was made in other cradle-to-grave LCA assessments of distribution transformers that can be found in the literature [3–5,9,10].

For each five-year period over the transformer lifetime (2025–2065), the impact of 1 kWh of electricity losses was calculated by a weighted summation of the generation technology impacts (Table 14, pp. 76–77 of [17]), proportionally to their contribution to the electricity mix in that period (Appendix B, Table A2 and [11]).

3. Results

For each of the four transformer designs under scrutiny, nine major LCA impact categories were calculated: acidification, climate change, freshwater eutrophication, land use, ozone depletion, particulate matter, photochemical ozone formation, fossil fuel resource use, and water use. The LCAs for the material use in the manufacturing phase, for the difference in energy losses during the use phase, and for the end-of-life phase of the distribution transformer were calculated and subsequently aggregated.

For the manufacturing phase, only material use was taken into account, not the impact of the transformer manufacturing process. According to input from transformer manufacturers, industrial processes at the manufacturing plant account for only 4% to 7% of the total LCA impact of the manufacturing phase; differences in this respect between models with different conductor materials or different energy efficiency levels are negligible. Since this LCA study is purely comparative, the impact of the manufacturing processes can

be disregarded; the manufacturing phase impact calculations can be limited to material use alone.

Regarding the use phase, the comparative character or the LCA study enables us to only take the difference in energy use compared to the base case into account, instead of total energy use values.

The comparative character of the LCA analysis means that the end results can only be used for comparing the environmental impacts of the different models under study, and not for other purposes.

3.1. LCA of the Material Use During the Manufacturing Phase

The results of the LCA for material use in the transformer manufacturing phase are shown in Table 3.

Table 3. LCA of the manufacturing phase (material use only).

LCA Impact of Material Use	Al/Al Windings		Cu/Cu Windings	
	Base Case	UEP Unit	Base Case	UEP Unit
EF3.0 Acidification [mole of $H+_{eq}$.]	6.09×10^{1}	7.26×10^{1}	4.90×10^{1}	6.72×10^{1}
EF3.0 Climate change [kg CO_{2eq}]	1.06×10^{4}	1.25×10^{4}	6.62×10^{3}	9.08×10^{3}
EF3.0 Eutrophication freshwater [kg P_{eq}]	1.07×10^{-2}	1.28×10^{-2}	1.91×10^{-2}	2.39×10^{-2}
EF3.0 Land use [P_t]	1.20×10^{4}	1.42×10^{4}	6.37×10^{3}	9.22×10^{3}
EF3.0 Ozone depletion [kg $CFC\text{-}11_{eq}$]	6.12×10^{-9}	6.77×10^{-9}	7.27×10^{-8}	8.46×10^{-8}
EF3.0 Particulate matter [disease ind.]	1.14×10^{-3}	1.39×10^{-3}	1.20×10^{-3}	1.63×10^{-3}
EF3.0 Photochemical ozone formation, human health [kg $NMVOC_{eq}$]	2.91×10^{1}	3.48×10^{1}	2.22×10^{1}	3.06×10^{1}
EF3.0 Resource use, fossils [MJ]	1.48×10^{5}	1.75×10^{5}	8.49×10^{4}	1.16×10^{5}
EF3.0 Water use [m^3 world equiv.]	3.06×10^{3}	3.70×10^{3}	3.30×10^{3}	4.48×10^{3}

3.2. Comparative LCA of the Transformer Use Phase

The results of the comparative LCA for the transformer use phase are shown in Table 4. Designs with copper windings and with aluminium windings have the same energy performance, as both must comply with Ecodesign standards (see Table 1). Consequently, their use phase impact is the same.

Table 4. Comparative LCA of the use phase.

Comparative LCA Impact of Use Phase (Difference from the UEP Unit)	Al/Al Windings		Cu/Cu Windings	
	Base Case	UEP Unit	Base Case	UEP Unit
EF3.0 Acidification [mole of $H+_{eq}$.]	7.87×10^{0}	0	7.87×10^{0}	0
EF3.0 Climate change [kg CO_{2eq}]	4.58×10^{3}	0	4.58×10^{3}	0
EF3.0 Eutrophication freshwater [kg P_{eq}]	1.14×10^{0}	0	1.14×10^{0}	0
EF3.0 Land use [P_t]	1.66×10^{4}	0	1.66×10^{4}	0
EF3.0 Ozone depletion [kg $CFC\text{-}11_{eq}$]	5.20×10^{-4}	0	5.20×10^{-4}	0
EF3.0 Particulate matter [disease ind.]	9.29×10^{-5}	0	9.29×10^{-5}	0
EF3.0 Photochemical ozone formation, human health [kg $NMVOC_{eq}$]	5.47×10^{0}	0	5.47×10^{0}	0
EF3.0 Resource use, fossils [MJ]	1.69×10^{5}	0	1.69×10^{5}	0
EF3.0 Water use [m^3 world equiv.]	1.47×10^{3}	0	1.47×10^{3}	0

Since the aim was a comparative analysis, only the difference in energy losses between the base case and the UEP unit was taken into account.

3.3. LCA for the End-of-Life Phases of the Transformers

The results of the LCA for the end-of-life phase of the transformers under scrutiny are shown in Table 5. A recycling rate of 90% was assumed for all metals (structural steel, magnetic steel, copper, and aluminium). For oil, the assumption was 90% recovery and a 70% recycling rate (i.e., 63% net recycling rate), based on [18].

Table 5. LCA of the end-of-life phase.

LCA Impact of End-of-Life Phase	Al/Al Windings		Cu/Cu Windings	
	Base Case	UEP Unit	Base Case	UEP Unit
EF3.0 Acidification [mole of $H+_{eq}$.]	-4.10×10^{1}	-4.91×10^{1}	-4.49×10^{1}	-5.64×10^{1}
EF3.0 Climate change [kg CO_{2eq}]	-8.43×10^{3}	-9.94×10^{3}	-4.61×10^{3}	-6.34×10^{3}
EF3.0 Eutrophication freshwater [kg P_{eq}]	-8.50×10^{-3}	-1.03×10^{-2}	-6.97×10^{-3}	-9.51×10^{-3}
EF3.0 Land use [P_t]	-9.08×10^{3}	-1.11×10^{4}	-6.31×10^{3}	-9.13×10^{3}
EF3.0 Ozone depletion [kg CFC-11_{eq}]	-2.28×10^{-9}	-2.48×10^{-9}	-4.94×10^{-9}	-5.23×10^{-9}
EF3.0 Particulate matter [disease ind.]	7.44×10^{-4}	9.03×10^{-4}	5.38×10^{-4}	8.10×10^{-4}
EF3.0 Photochemical ozone formation, human health [kg $NMVOC_{eq}$]	-1.91×10^{1}	-2.28×10^{1}	-1.31×10^{1}	-1.78×10^{1}
EF3.0 Resource use, fossils [MJ]	-1.14×10^{5}	-1.34×10^{5}	-5.73×10^{4}	-7.91×10^{4}
EF3.0 Water use [m^3 world equiv.]	-2.11×10^{3}	-2.58×10^{3}	-2.08×10^{3}	-2.79×10^{3}

Recovered materials were modelled using the avoided-burden (substitution) approach: after accounting for the end-of-life treatment processes, an environmental credit was assigned for the production of the corresponding amount of primary materials displaced by the recovered secondary materials, in accordance with the GaBi datasets and allocation rules. The high recycling rates explain the fact that the end-of-life impact figures are negative.

3.4. Consolidated LCA

The results of the consolidated, comparative LCA (material use in manufacturing phase + difference in energy losses + end-of-life phase) are shown in Table 6. A graphical representation of the numbers is presented in Appendix C, Figure A1.

Table 6. Consolidated comparative LCA.

Consolidated Comparative LCA	Al/Al Windings		Cu/Cu Windings	
	Base Case	UEP Unit	Base Case	UEP Unit
EF3.0 Acidification [mole of $H+_{eq}$.]	2.77×10^{1}	2.35×10^{1}	1.19×10^{1}	1.09×10^{1}
EF3.0 Climate change [kg CO_{2eq}]	6.77×10^{3}	2.57×10^{3}	6.60×10^{3}	2.74×10^{3}
EF3.0 Eutrophication freshwater [kg P_{eq}]	1.14×10^{0}	2.48×10^{-3}	1.15×10^{0}	1.44×10^{-2}
EF3.0 Land use [P_t]	1.95×10^{4}	3.15×10^{3}	1.67×10^{4}	8.38×10^{1}
EF3.0 Ozone depletion [kg CFC-11_{eq}]	5.20×10^{-4}	4.28×10^{-9}	5.20×10^{-4}	7.94×10^{-8}
EF3.0 Particulate matter [disease ind.]	4.94×10^{-4}	4.85×10^{-4}	7.08×10^{-4}	8.19×10^{-4}
EF3.0 Photochemical ozone formation, human health [kg $NMVOC_{eq}$]	1.54×10^{1}	1.20×10^{1}	1.46×10^{1}	1.28×10^{1}
EF3.0 Resource use, fossils [MJ]	2.03×10^{5}	4.03×10^{4}	1.97×10^{5}	3.72×10^{4}
EF3.0 Water use [m^3 world equiv.]	2.42×10^{3}	1.12×10^{3}	2.69×10^{3}	1.68×10^{3}

3.5. Sensitivity of the Climate Change Impact to the Average RMS Load

A sensitivity analysis on the average RMS load was carried out.

Here, we will present the results of the sensitivity analysis for the climate change impact category—an important criterion in EU policymaking. In many LCA studies of transformers, it is the only impact category that is taken into account [3–7]. The results of the sensitivity analysis show that the level of RMS load has an influence on the impact figures, but without changing the fundamental nature of the conclusions.

The sensitivity analysis on the RMS load for the other impact categories can be found in Appendix D. These results lead to a similar outcome: the RMS load influences the impact figures without changing the fundamental nature of the conclusions, with two exceptions, which are discussed in Section 4 and Appendix D.

Note that, in this study, we assumed that the RMS load could vary according to the circumstances but could not be influenced by engineering decisions. In reality, however, some grid and transformer design choices might influence the average RMS load. The design options affecting the load factor, and how this influences the electricity system's environmental impacts, is a study beyond the scope of this paper.

4. Discussion

Table 6 shows that the transformers with enhanced energy performance—both the one with two aluminium windings and the one with two copper windings—have a lower impact compared to the base case in every impact category except for particulate matter in the case of the transformer with copper windings, which sees a moderate increase when switching to the UEP unit. The sensitivity analysis in Appendix D shows that this exception remains true for a high RMS load (40%). For a low RMS load (20%), the same becomes true for a transformer with aluminium windings. At such a low load, the aggregated acidification impact of the UEP unit with copper windings also becomes slightly larger than that of the base case. Note that these increases in a few impact categories remain small compared to most of the gains that are achieved by the UEP unit in other impact categories.

Transformers with copper windings score better in some categories while those with aluminium windings score better in others, largely balancing each other out.

In the context of the EU Green Deal, the climate change and fossil fuel use impact categories deserve special attention. In these categories, both transformer types with enhanced energy performance score better than the base cases.

Land use is a further environmental concern requiring particular attention in the context of the energy transition. Generating electricity from renewable energy sources requires more land than generating it from fossil fuels, putting pressure on land used for nature protection, agriculture, and forestry [19]. In this regard, an additional challenge not taken into account by the LCA impact calculation on land use should be considered: the renewable energy capacity needed for the energy transition in its later stages will be the most difficult to achieve, since the low-hanging fruit will have already been picked, meaning that the more difficult and controversial locations will then need to be exploited. Better energy efficiency can reduce the need to seek this additional capacity.

As can be seen in Table 7, switching from the base case to the unit with enhanced energy performance reduces the impact on climate change by between 2.83 and 5.65 tonnes of CO_2-eq. emissions over the life cycle of the unit, depending on the RMS load and the choice of winding material. The advantage, in terms of greenhouse gas emissions, of switching to a high-performance transformer becomes less prominent with a lower RMS load, but it nonetheless remains significant.

In the sensitivity analysis presented in Section 3.5 and Appendix D, the comparison between the UEP unit with copper windings and the base case with aluminium windings is also made explicit. We see that the UEP unit scores better in eight out of nine impact categories, the exception being particulate matter, which sees a moderate increase in the life cycle impact.

Table 7. LCA impact in the climate change category: comparing the UEP unit with the base case for varying RMS loads.

EF3.0 Climate Change—Total [kg CO_{2eq}]	Al/Al	Cu/Cu	
	Al/Al UEP Unit Compared to Base Case with Al/Al Windings	**Cu/Cu UEP Unit Compared to Base Case with Cu/Cu Windings**	**Cu/Cu UEP Unit Compared to Base Case with Al/Al Windings**
Manufacturing phase	1.90×10^3	2.46×10^3	-1.53×10^3
Use phase, RMS 20%	-3.55×10^3	-3.55×10^3	-3.55×10^3
End-of-life phase	-1.51×10^3	-1.74×10^3	2.09×10^3
Total difference	$\mathbf{-3.16 \times 10^3}$	$\mathbf{-2.83 \times 10^3}$	$\mathbf{-2.99 \times 10^3}$
Manufacturing phase	1.90×10^3	2.46×10^3	-1.53×10^3
Use phase, RMS 30%	-4.58×10^3	-4.58×10^3	-4.58×10^3
End-of-life phase	-1.51×10^3	-1.74×10^3	2.09×10^3
Total difference	$\mathbf{-4.19 \times 10^3}$	$\mathbf{-3.87 \times 10^3}$	$\mathbf{-4.03 \times 10^3}$
Manufacturing phase	1.90×10^3	2.46×10^3	-1.53×10^3
Use phase, RMS 40%	-6.04×10^3	-6.04×10^3	-6.04×10^3
End-of-life phase	-1.51×10^3	-1.74×10^3	2.09×10^3
Total difference	$\mathbf{-5.65 \times 10^3}$	$\mathbf{-5.32 \times 10^3}$	$\mathbf{-5.48 \times 10^3}$

5. Conclusions

This paper compared cradle-to-grave LCAs of liquid-immersed 630 kVA distribution transformers of various energy performance levels. By including the use phase, the LCA can be of guidance for the trade-off between greater material use in the transformer and higher energy losses during its operation. To take the decarbonisation of the electricity supply over the lifetime of the transformer into account, the LCA was calculated with a dynamic electricity mix. It is the first analysis of this kind that calculates using figures for the evolution of the electricity mix in the EU-27 presented in the impact assessment of the EU Green Deal.

The comparative character of the LCA analysis means that the end results can only be used for comparing the environmental impacts of the different models under study, and not for other purposes. The results demonstrate that the use phase is still predominant in the total impact of the unit, despite the ongoing decarbonisation of the grid. This is mainly because renewable energy power plants require substantial amounts of materials. As a result, for all but one of the studied LCA impact categories, using higher energy performance transformers is more optimal than using those currently prescribed by mandatory EU Ecodesign energy performance standards. This is particularly the case in the climate change impact category, which merits particular attention in view of the ambitions of the EU Green Deal. Varying assumptions for the transformer RMS load alter the relative significance of this conclusion, without changing its nature fundamentally. At the projected RMS load of 30%, particulate matter in the case of the transformer with copper windings is the only impact category for which the switch to the UEP unit increases the impact.

In a future investigation, it would be useful to gather a broader view of manufacturer design methodologies and assess to what extent they influence the results presented in this study. It would also be useful to further investigate the assumption that, for a comparative study between units of different energy performance levels, the impact of the manufacturing phase can be limited to the material use. Finally, a similar exercise could be carried out for transformers with different power ratings and energy performance levels.

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Data Availability Statement: The embedded life cycle impacts for copper, aluminium, electrical steel, structural steel, and oil were retrieved from the GaBi LCA modelling software, content version 2023.2, developed by Sphera Solutions GmbH (Leinfelden-Echterdingen, Germany) [14]. This software contains those figures as input values. All other relevant data can be found in the paper itself.

Conflicts of Interest: The International Copper Association Europe supervised the creation of this paper, but had no role in designing the study, nor in collecting, analysing, or interpreting the data.

Abbreviations

The following abbreviations are used in this manuscript:

BOM	Bill Of Materials
GHG	Greenhouse Gas
GOES	Grain-Oriented Electrical Steel
LCA	Life Cycle Assessment
MEPS	Minimum Energy Performance Standard
RMS	Root Mean Square
UEP	Upgraded Energy Performance
UNECE	United Nations Economic Commission for Europe

Appendix A

Table A1. References of the GaBi data sets, developed by Sphera [14].

Name	Proxy Dataset	UID	Geography
Magnetic steel	Stainless steel cold rolled coil (430)	{1FC27F09-4535-4398-A157-8AE2ECCB5D73}	RER
Structural steel	Steel sheet 1.5 mm EG (0.01 mm Zn; 1 side)	{8FE98D45-B509-4A30-BE82-A1904F3DC6B2}	DE
Copper wire	Copper Wire Mix	{35A4B3F7-6E52-4E31-9894-E09D72BC0367}	RER
Oil	Lubricants at refinery	{BDFAC21C-7415-46AF-ACBC-8916CB95B9B8}	RER
Aluminium wire	Aluminium extrusion profile	{AEE496C2-7854-4178-915F-A9F59926D1E7}	RER

The GaBi database follows the allocation rules specified in 'Harmonized calculation methods for product carbon footprints and life cycle assessments in the mining and metals industry', published in the *International Journal of Life Cycle Assessment* [20].

Appendix B

Table A2. The EU electricity mix between 2000 and 2050 in TWh, as predicted by [11].

Year	Coal	Oil	Natural Gas	Nuclear	Hydro	Wind Onshore	Wind Off-shore	Solar	Bioenergy	Other Renewables
2000	814	173	363	860	379	21	0	0	42	5
2005	826	137	550	916	341	68	0	1	73	6
2010	722	82	623	854	401	129	11	23	129	6
2015	719	63	430	787	363	223	41	101	169	7
2020	496	34	619	735	373	325	48	138	153	24

Table A2. *Cont.*

Year	Coal	Oil	Natural Gas	Nuclear	Hydro	Wind Onshore	Wind Off-shore	Solar	Bioenergy	Other Renewables
2025	396	13	533	665	366	479	108	238	156	23
2030	288	10	458	585	370	680	160	369	174	21
2035	180	11	630	556	371	784	210	391	162	30
2040	36	8	607	551	370	919	242	473	152	68
2045	27	7	526	512	372	1049	279	541	149	83
2050	23	4	544	500	370	1121	285	561	150	99

As can be observed from Table A2, the marginal additions to the EU electricity mix between 2025 and 2050 are largely dominated by solar energy and wind energy (both onshore and offshore).

Appendix C

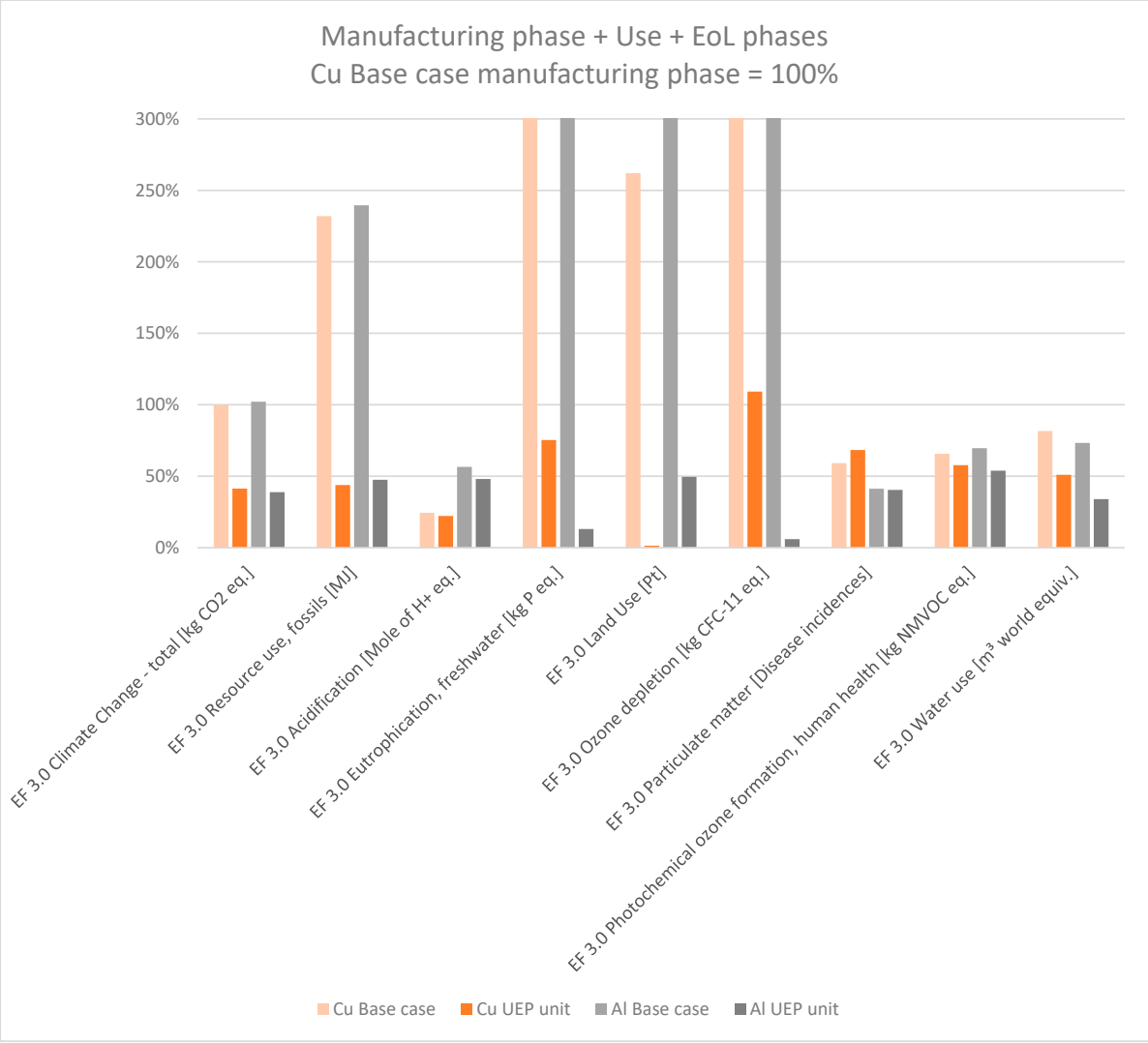


Figure A1. Graphical representation of the relative consolidated LCA. For the manufacturing phase, only the material use was taken into account. For the use phase, only the difference in energy losses between the base case and the highly efficient unit was taken into account. The impact of the manufacturing phase of the copper base case design was assumed to be 100%.

Appendix D

The following tables show the outcomes of the sensitivity analyses on the average RMS load for the other eight impact categories—the analysis for the climate change impact category was already given in Section 3.5.

It can be observed that variations in the RMS load have an impact on the figures without changing the fundamental nature of the conclusions, with two exceptions. The first exception is the impact category of particulate matter for the transformer with aluminium windings, where a low RMS load (20%) makes the aggregated impact of the UEP unit larger than that of the base case, which is not the case at higher RMS loads. The second exception is the impact category of acidification for the transformer with copper windings, where a low RMS load (20%) makes the aggregated impact of the UEP unit slightly higher than that of the base case.

Tables A3–A10 also make the comparison between the UEP unit with copper windings and the base case with aluminium windings. We see that the UEP unit scores better in eight out of nine impact categories, with the exception being particulate matter, which sees a moderate increase in the life cycle impact.

Table A3. LCA impact in the acidification impact category: comparing the UEP unit with the base case for varying RMS loads.

EF3.0 Acidification [Mole of H+ eq.]	**Al/Al**	**Cu/Cu**	
	Al/Al UEP Unit Compared to Base Case with Al/Al Windings	**Cu/Cu UEP Unit Compared to Base Case with Cu/Cu Windings**	**Cu/Cu UEP Unit Compared to Base Case with Al/Al Windings**
Manufacturing phase	1.18×10^{1}	1.83×10^{1}	6.38×10^{0}
Use phase, RMS 20%	-6.09×10^{0}	-6.09×10^{0}	-6.09×10^{0}
End-of-life phase	-8.07×10^{0}	-1.15×10^{1}	-1.53×10^{1}
Total difference	$\mathbf{-2.37 \times 10^{0}}$	$\mathbf{7.15 \times 10^{-1}}$	$\mathbf{-1.50 \times 10^{1}}$
Manufacturing phase	1.18×10^{1}	1.83×10^{1}	6.38×10^{0}
Use phase, RMS 30%	-7.87×10^{0}	-7.87×10^{0}	-7.87×10^{0}
End-of-life phase	-8.07×10^{0}	-1.15×10^{1}	-1.53×10^{1}
Total difference	$\mathbf{-4.15 \times 10^{0}}$	$\mathbf{-1.07 \times 10^{0}}$	$\mathbf{-1.68 \times 10^{01}}$
Manufacturing phase	1.18×10^{1}	1.83×10^{1}	6.38×10^{0}
Use phase, RMS 40%	-1.04×10^{1}	-1.04×10^{1}	-1.04×10^{1}
End-of-life phase	-8.07×10^{0}	-1.15×10^{1}	-1.53×10^{1}
Total difference	$\mathbf{-6.65 \times 10^{0}}$	$\mathbf{-3.56 \times 10^{0}}$	$\mathbf{-1.93 \times 10^{0}}$

Table A4. LCA impact in the freshwater eutrification impact category: comparing the UEP unit with the base case for varying RMS loads.

EF3.0 Eutrophication Freshwater [kg P_{eq}]	**Al/Al**	**Cu/Cu**	
	Al/Al UEP Unit Compared to Base Case with Al/Al Windings	**Cu/Cu UEP Unit Compared to Base Case with Cu/Cu Windings**	**Cu/Cu UEP Unit Compared to Base Case with Al/Al Windings**
Manufacturing phase	2.13×10^{-3}	4.80×10^{-3}	1.32×10^{-2}
Use phase, RMS 20%	-8.80×10^{-1}	-8.80×10^{-1}	-8.80×10^{-1}
End-of-life phase	-1.83×10^{-3}	-2.54×10^{-3}	-1.01×10^{-3}
Total difference	$\mathbf{-8.79 \times 10^{-1}}$	$\mathbf{-8.77 \times 10^{-1}}$	$\mathbf{-8.67 \times 10^{-1}}$
Manufacturing phase	2.13×10^{-3}	4.80×10^{-3}	1.32×10^{-2}
Use phase, RMS 30%	-1.14×10^{0}	-1.14×10^{0}	-1.14×10^{0}
End-of-life phase	-1.83×10^{-3}	-2.54×10^{-3}	-1.01×10^{-3}
Total difference	$\mathbf{-1.14 \times 10^{0}}$	$\mathbf{-1.13 \times 10^{0}}$	$\mathbf{-1.12 \times 10^{0}}$
Manufacturing phase	2.13×10^{-3}	4.80×10^{-3}	1.32×10^{-2}
Use phase, RMS 40%	-1.50×10^{0}	-1.50×10^{0}	-1.50×10^{0}
End-of-life phase	-1.83×10^{-3}	-2.54×10^{-3}	-1.01×10^{-3}
Total difference	$\mathbf{-1.50 \times 10^{0}}$	$\mathbf{-1.50 \times 10^{0}}$	$\mathbf{-1.49 \times 10^{0}}$

Table A5. LCA impact in the land use impact category: comparing the UEP unit with the base case for varying RMS loads.

EF3.0 Land Use [P_t]	Al/Al	Cu/Cu	
	Al/Al UEP Unit Compared to Base Case with Al/Al Windings	Cu/Cu UEP Unit Compared to Base Case with Cu/Cu Windings	Cu/Cu UEP Unit Compared to Base Case with Al/Al Windings
Manufacturing phase	2.22×10^{3}	2.85×10^{3}	-2.78×10^{3}
Use phase, RMS 20%	-1.29×10^{4}	-1.29×10^{4}	-1.29×10^{4}
End-of-life phase	-1.99×10^{3}	-2.82×10^{3}	-5.15×10^{1}
Total difference	$\mathbf{-1.26 \times 10^{4}}$	$\mathbf{-1.28 \times 10^{4}}$	$\mathbf{-1.57 \times 10^{4}}$
Manufacturing phase	2.22×10^{3}	2.85×10^{3}	-2.78×10^{3}
Use phase, RMS 30%	-1.66×10^{4}	-1.66×10^{4}	-1.66×10^{4}
End-of-life phase	-1.99×10^{3}	-2.82×10^{3}	-5.15×10^{1}
Total difference	$\mathbf{-1.64 \times 10^{4}}$	$\mathbf{-1.66 \times 10^{4}}$	$\mathbf{-1.95 \times 10^{4}}$
Manufacturing phase	2.22×10^{3}	2.85×10^{3}	-2.78×10^{3}
Use phase, RMS 40%	-2.19×10^{4}	-2.19×10^{4}	-2.19×10^{4}
End-of-life phase	-1.99×10^{3}	-2.82×10^{3}	-5.15×10^{1}
Total difference	$\mathbf{-2.17 \times 10^{4}}$	$\mathbf{-2.19 \times 10^{4}}$	$\mathbf{-2.47 \times 10^{4}}$

Table A6. LCA impact in the ozone depletion impact category: comparing the UEP unit with the base case for varying RMS loads.

EF3.0 Ozone Depletion [kg $CFC^{-11}{}_{eq}$]	Al/Al	Cu/Cu	
	Al/Al UEP Unit Compared to Base Case with Al/Al Windings	Cu/Cu UEP Unit Compared to Base Case with Cu/Cu Windings	Cu/Cu UEP Unit Compared to Base Case with Al/Al Windings
Manufacturing phase	6.50×10^{-1}	1.19×10^{-8}	7.85×10^{-8}
Use phase, RMS 20%	-4.02×10^{-4}	-4.02×10^{-4}	-4.02×10^{-4}
End-of-life phase	-2.01×10^{-1}	-2.92×10^{-1}	-2.95×10^{-9}
Total difference	$\mathbf{-4.02 \times 10^{-4}}$	$\mathbf{-4.02 \times 10^{-4}}$	$\mathbf{-4.02 \times 10^{-4}}$
Manufacturing phase	6.50×10^{-1}	1.19×10^{-8}	7.85×10^{-8}
Use phase, RMS 30%	-5.20×10^{-4}	-5.20×10^{-4}	-5.20×10^{-4}
End-of-life phase	-2.01×10^{-1}	-2.92×10^{-1}	-2.95×10^{-9}
Total difference	$\mathbf{-5.20 \times 10^{-4}}$	$\mathbf{-5.20 \times 10^{-4}}$	$\mathbf{-5.20 \times 10^{-4}}$
Manufacturing phase	6.50×10^{-1}	1.19×10^{-8}	7.85×10^{-8}
Use phase, RMS 40%	-6.85×10^{-4}	-6.85×10^{-4}	-6.85×10^{-4}
End-of-life phase	-2.01×10^{-1}	-2.92×10^{-1}	-2.95×10^{-9}
Total difference	$\mathbf{-6.85 \times 10^{-4}}$	$\mathbf{-6.85 \times 10^{-4}}$	$\mathbf{-6.85 \times 10^{-4}}$

Table A7. LCA impact in the particulate matter impact category: comparing the UEP unit with the base case for varying RMS loads.

EF3.0 Particulate Matter [disease ind.]	Al/Al	Cu/Cu	
	Al/Al UEP Unit Compared to Base Case with Al/Al Windings	Cu/Cu UEP Unit Compared to Base Case with Cu/Cu Windings	Cu/Cu UEP Unit Compared to Base Case with Al/Al Windings
Manufacturing phase	2.43×10^{-4}	4.30×10^{-4}	4.84×10^{-4}
Use phase, RMS 20%	-7.19×10^{-5}	-7.19×10^{-5}	-7.19×10^{-5}
End-of-life phase	-1.59×10^{-4}	-2.27×10^{-4}	-6.67×10^{-5}
Total difference	$\mathbf{1.13 \times 10^{-5}}$	$\mathbf{1.31 \times 10^{-4}}$	$\mathbf{3.45 \times 10^{-4}}$
Manufacturing phase	2.43×10^{-4}	4.30×10^{-4}	4.84×10^{-4}
Use phase, RMS 30%	-9.29×10^{-5}	-9.29×10^{-5}	-9.29×10^{-5}
End-of-life phase	-1.59×10^{-4}	-2.27×10^{-4}	-6.67×10^{-5}
Total difference	$\mathbf{-9.69 \times 10^{-6}}$	$\mathbf{1.10 \times 10^{-4}}$	$\mathbf{3.24 \times 10^{-4}}$
Manufacturing phase	2.43×10^{-4}	4.30×10^{-4}	4.84×10^{-4}
Use phase, RMS 40%	-1.22×10^{-4}	-1.22×10^{-4}	-1.22×10^{-4}
End-of-life phase	-1.59×10^{-4}	-2.27×10^{-4}	-6.67×10^{-5}
Total difference	$\mathbf{-3.92 \times 10^{-5}}$	$\mathbf{8.07 \times 10^{-5}}$	$\mathbf{2.95 \times 10^{-4}}$

Table A8. LCA impact in the photochemical ozone formation impact category: comparing the UEP unit with the base case for varying RMS loads.

EF3.0 Photochemical Ozone Formation, Human Health [kg $NMVOC_{eq}$]	**Al/Al**	**Cu/Cu**	
	Al/Al UEP Unit Compared to Base Case with Al/Al Windings	**Cu/Cu UEP Unit Compared to Base Case with Cu/Cu Windings**	**Cu/Cu UEP Unit Compared to Base Case with Al/Al Windings**
Manufacturing phase	5.68×10^{0}	8.40×10^{0}	1.48×10^{0}
Use phase, RMS 20%	-4.23×10^{0}	-4.23×10^{0}	-4.23×10^{0}
End-of-life phase	-3.68×10^{0}	-4.68×10^{0}	1.36×10^{0}
Total difference	$\mathbf{-2.24 \times 10^{0}}$	$\mathbf{-5.17 \times 10^{-1}}$	$\mathbf{-1.40 \times 10^{0}}$
Manufacturing phase	5.68×10^{0}	8.40×10^{0}	1.48×10^{0}
Use phase, RMS 30%	-5.47×10^{0}	-5.47×10^{0}	-5.47×10^{0}
End-of-life phase	-3.68×10^{0}	-4.68×10^{0}	1.36×10^{0}
Total difference	$\mathbf{-3.48 \times 10^{0}}$	$\mathbf{-1.76 \times 10^{0}}$	$\mathbf{-2.64 \times 10^{0}}$
Manufacturing phase	5.68×10^{0}	8.40×10^{0}	1.48×10^{0}
Use phase, RMS 40%	-7.21×10^{0}	-7.21×10^{0}	-7.21×10^{0}
End-of-life phase	-3.68×10^{0}	-4.68×10^{0}	1.36×10^{0}
Total difference	$\mathbf{-5.22 \times 10^{0}}$	$\mathbf{-3.49 \times 10^{0}}$	$\mathbf{-4.37 \times 10^{0}}$

Table A9. LCA impact in the resource use (fossil) impact category: comparing the UEP unit with the base case for varying RMS loads.

EF3.0 Resource Use, Fossils [MJ]	**Al/Al**	**Cu/Cu**	
	Al/Al UEP Unit Compared to Base Case with Al/Al Windings	**Cu/Cu UEP Unit Compared to Base Case with Cu/Cu Windings**	**Cu/Cu UEP Unit Compared to Base Case with Al/Al Windings**
Manufacturing phase	2.65×10^{4}	3.14×10^{4}	-3.21×10^{4}
Use phase, RMS 20%	-1.31×10^{5}	-1.31×10^{5}	-1.31×10^{5}
End-of-life phase	-2.02×10^{4}	-2.18×10^{4}	3.52×10^{4}
Total difference	$\mathbf{-1.25 \times 10^{5}}$	$\mathbf{-1.21 \times 10^{5}}$	$\mathbf{-1.28 \times 10^{5}}$
Manufacturing phase	2.65×10^{4}	3.14×10^{4}	-3.21×10^{4}
Use phase, RMS 30%	-1.69×10^{5}	-1.69×10^{5}	-1.69×10^{5}
End-of-life phase	-2.02×10^{4}	-2.18×10^{4}	3.52×10^{4}
Total difference	$\mathbf{-1.63 \times 10^{5}}$	$\mathbf{-1.60 \times 10^{5}}$	$\mathbf{-1.66 \times 10^{5}}$
Manufacturing phase	2.65×10^{4}	3.14×10^{4}	-3.21×10^{4}
Use phase, RMS 40%	-2.23×10^{5}	-2.23×10^{5}	-2.23×10^{5}
End-of-life phase	-2.02×10^{4}	-2.18×10^{4}	3.52×10^{4}
Total difference	$\mathbf{-2.17 \times 10^{5}}$	$\mathbf{-2.13 \times 10^{5}}$	$\mathbf{-2.20 \times 10^{5}}$

Table A10. LCA impact in the water use impact category: comparing the UEP unit with the base case for varying RMS loads.

EF3.0 Water Use [m^3 World Equiv.]	**Al/Al**	**Cu/Cu**	
	Al/Al UEP Unit Compared to Base Case with Al/Al Windings	**Cu/Cu UEP Unit Compared to Base Case with Cu/Cu Windings**	**Cu/Cu UEP Unit Compared to Base Case with Al/Al Windings**
Manufacturing phase	6.46×10^{2}	1.18×10^{3}	1.42×10^{3}
Use phase, RMS 20%	-1.14×10^{3}	-1.14×10^{3}	-1.14×10^{3}
End-of-life phase	-4.73×10^{2}	-7.13×10^{2}	-6.81×10^{2}
Total difference	$\mathbf{-9.66 \times 10^{2}}$	$\mathbf{-6.76 \times 10^{2}}$	$\mathbf{-4.02 \times 10^{2}}$
Manufacturing phase	6.46×10^{2}	1.18×10^{3}	1.42×10^{3}
Use phase, RMS 30%	-1.47×10^{3}	-1.47×10^{3}	-1.47×10^{3}
End-of-life phase	-4.73×10^{2}	-7.13×10^{2}	-6.81×10^{2}
Total difference	$\mathbf{-1.30 \times 10^{3}}$	$\mathbf{-1.01 \times 10^{3}}$	$\mathbf{-7.34 \times 10^{2}}$
Manufacturing phase	6.46×10^{2}	1.18×10^{3}	1.42×10^{3}
Use phase, RMS 40%	-1.94×10^{3}	-1.94×10^{3}	-1.94×10^{3}
End-of-life phase	-4.73×10^{2}	-7.13×10^{2}	-6.81×10^{2}
Total difference	$\mathbf{-1.77 \times 10^{3}}$	$\mathbf{-1.48 \times 10^{3}}$	$\mathbf{-1.20 \times 10^{3}}$

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