Master Thesis

Development of a Tool for the Life Cycle Assessment of a Medium Voltage Transformer for the Distribution Grid.

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Abstract: Tackling climate change is one of the greatest challenge humanity is going to face and it demands a transition towards a more sustainable energy sector. A Life Cycle Analysis (LCA) of transformers from 1980, 2022, and 2050 is conducted, following the established legislative framework within the European Union (EU) to integrate environmental criteria for green procurement. Transformers play a key role in the electrical grid, and as the economy increasingly embraces electrification, it becomes imperative to comprehend and improve their environmental impact. The performed LCA of the three transformers reveals the most significant stages: manufacturing and operation, as well as the major impact categories: climate change, acidification, resource use - fossil, and resource use - minerals and metals. Transformers have undergone advancements towards sustainability, resulting in a general reduction of their environmental impacts. The information extracted from LCA is crucial for continuing making informed decisions at the mitigating of environmental impacts related with life cycle of transformers. This project develops a simplified tool to integrate environmental criteria in purchasing processes. The user-friendly interface enables the development of LCA without the need of extensive expertise, promoting the consideration of environmental factors when making purchasing decisions and thereby fostering more sustainable practices.

Keywords: Life Cycle Assessment; Distribution transformer; Green procurement; Sustainability.

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1. Introduction.

During the past years, an increase in the concentration of greenhouse gases in the atmosphere and in the number of extreme weather events is causing significant impacts on the development of human activity. The effects of climate change are manifested in material losses and population migrations [1], generating an increasing concern in the society that has given rise to a socio-cultural movement towards sustainable development.

During the last decades, scientists have studied climate change and how human activities impact on the Earth. In 2009, Johan Rockström led a team of scientists to identify planetary boundaries, which are critical thresholds for the stability and resilience of the Earth system [2]. In this study, they determined that exceeding planetary boundaries could lead to significant and non-reversible environmental consequences. During 2022 several limits were already exceeded, threatening the integrity of the biosphere and biochemical cycles, which could trigger serious consequences for the Earth's equilibrium [3].

Humanity is therefore facing one of its greatest challenges in history: climate change. In this context, this project aims to promote the integration of sustainable initiatives in companies through the adoption of green purchasing criteria.

Sustainability has become a fundamental concept, the first time it was defined was in 1987 by the United Nations Brundtland Commission as *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*[4]. To face climate change, sustainability is considered indispensable for businesses, governments, and educational institutions. It is crucial that they analyze their environmental impact and implement different strategies to improve their performance to achieve a more balanced and responsible future.

Integrating environmental criteria into purchasing processes involves selecting products with a lower environmental impact. It is an important opportunity for companies to make a positive contribution to reducing their environmental impacts as they are promoting the most sustainable product. In addition, the evaluation of the environmental performance of a product also favors the analysis and complete knowledge of this product, as for example it offers the opportunity to improve its functional characteristics.

There are different environmental assessment methods. For this project the one selected is the Life Cycle Assessment (LCA), a science-based method that evaluates the inputs, outputs, and potential environmental impacts of a product throughout its entire life cycle, from the extraction of raw materials to the end-of-life of the product.

The EU has made a major commitment to promote sustainable development, creating a regulatory framework that favors activities that have an appropriate environmental performance. Under this framework, the Product Environmental Footprint (PEF) Guide[5] has been published. It establishes a common framework for performing LCAs in the EU to facilitate the comparison between different EU products. The PEF Guide enables a transparent and reliable comparison.

The most relevant impact category the energy transition aims to achieve is climate change. The objective of the energy transition is to electrify the economy, which implies an increase in the development of electricity grids. But this development must be sustainable. For this reason, manufacturers, distributors, and regulators are increasingly focusing on studying the environmental impact of electrical products. Among these initiatives, it is worth highlighting the regulation of the transformer as a key part of the network: In 2014 after an analysis on the environmental and economic aspects of transformers, "*Regulation (EU) No. 548/2014 on implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to small, medium, and large power transformers"* [6] was published. This Directive establishes minimum energy efficiency requirements around the operation phase of the transformers, as it was identified as the most significant phase of the environmental performance.

After the Regulation (EU) No. 548/2014 was published, similar research and studies have been carried out. As an example, several papers were presented at the International Conference on Electrical Distribution. In these papers the LCA enable the comparison between transformers with amorphous metal cores and grain-oriented magnetic steel [7,8] or transformers with different smart technologies implemented[9]. The studies have compared the different types of transformers and evaluate their sustainability in all the stages of the life cycle. In addition, it was also analyzed the impact of transformers related to the integration of renewable energies into the electrical grid. The importance of the LCA lies in the essential information it provides, enabling the company to reduce the environmental impact of any product by focusing on the changes that will make the most significant environmental improvements.

According to these papers, the most significant environmental stage of the transformer's life cycle are the electrical losses that occur during voltage transformation in the operation. However, this impact is directly related to the electrical generation mix, therefore, an evolution towards more sustainable mixes will result in a reduction of the environmental impact of this stage compared to other phases of the life cycle.

2. State of the Art.

2.1. History of the Life Cycle Assessment (LCA) [10].

Life Cycle Assessment (LCA) is a science-based method which requires the study of all the life cycle of a product from the extraction of raw materials to its end of life. LCA is a quantitative, transparent, and replicable method, these characteristics makes it a powerful tool.

LCA has experienced notable development since the first time it was used in 1963 to analyse by-products of a Nuclear Power Plant. Coca-Cola also used it to study in 1969 the impacts of their containers. Also, in 1974, the US Environmental Protection Agency published the first public LCA study comparing nine container alternatives[11].

Developing an LCA is complex and time consuming due to the significant knowledge it requires. Therefore, one of the most significant achievements in LCA history was the development of professional tools in the 1980s. GaBi, the commercial software, was launched in 1984 and became widely used. Additionally, in 1990, the first version of SimaPro was published and it has become one of the most commercial software used for LCA.

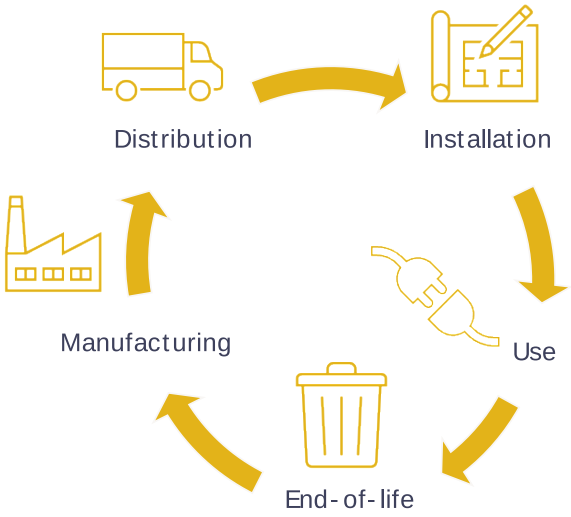


Figure 1: Life Cycle Assessment stages.

The International Organization for Standardization (ISO) published a series of standards between 1997 and 2007 to define a common framework for developing an LCA. These standards include ISO 14040:2006[12] and ISO 14044:2006[13], which establish the principles and guidelines for LCA.

Also, to perform comparable LCA they must be based on the same databases. Therefore, in 2003 the first version of Ecoinvent was published. Ecoinvent is one of the most relevant Life Cycle Inventory databases used all over the world. The database contains the characterization factors which are necessary to obtain the environmental impact of each stage.

The software and the database development have facilitated the use of LCA, establishing it as a reference tool for evaluating environmental performance. Over the following years, updated methodologies, databases, and calculation tools were published, defining flows, relationships, and characterization factors in life cycle assessment. However, there were different methods and approaches which made impossible to compare results between different LCA studies.

The European Union to develop a regulatory framework of LCA and facilitate the comparison between European products published the *"Product Environmental Footprint (PEF) Guide"* [5] in 2012. The PEF guide establishes more specific requirements and the minimum contents for LCA studies in the UE. Also, it indicates that more specific standards should be develop for the different categories of products. These standards are known as Product Category Rules (PCRs). Once an LCA is performed following an PCR and audit, the product will have an Environmental Product Declarations (EPDs). An EPD is a standardized document that provides transparent and comprehensive information about the environmental impact of a product throughout its entire life cycle. The data it should contain is declared in the PCR. EPDs serve as valuable tools for consumers, purchasers, and policymakers to make informed decisions and compare the environmental performance of different products. The development of this comprehensive framework has solidified LCA as the primary method for assessing and comparing the environmental impact of products.

2.2. Distribution Network - The Transformer as a Key Component.

The policies and laws that promote the energy transition aims to integrate a larger capacity of Distributed Energy Resources (DER). This new energy paradigm presents significant challenges for the existing distribution network. The integration of renewable energies into the electrical grid is an important challenge. In the article titled *"Radical change in the Spanish grid: Renewable energy generation profile and electric energy excess"* [14] it is analysed how the installation of renewable energies can exceed expectations and might end up altering the grid.

The energy transition implies a significant change, especially in the end-users such as small industries, businesses, and households, who now can reduce their energy consumption by installing photovoltaic solar energy systems for self-consumption.

The electrical system consists of infrastructures that enable the transportation and distribution of electricity from power generation plants to consumption points. The infrastructure is classified based on the different voltage levels: very high, high, medium, and low voltage. Before the energy transition, the development of the grid was focused on the infrastructure of very high and high voltage. But now, a development and expansion of low and medium voltage networks are required to enable greater connections of DER. In LV and MV transformers play a key role as it is the responsible of modifying the voltage level to adapt to consumption or generation requirements.

The transformer has a high efficiency. It operates through electromagnetic induction. By applying alternating current to the primary winding, a variable magnetic field is generated around the transformer core, inducing a current in the secondary winding. However, there are losses that occur during the normal operation of the transformer due to the resistance of electrical and magnetic circuits. These losses are divided into no-load losses, associated with the magnetic circuit, and load losses, related to electrical resistance.

In summary, to achieve energy transition goals it is necessary to modernize the distribution network to provide it with greater flexibility and capacity. However, it is important to consider environmental aspects in the development of the network to achieve a more sustainable and environmentally friendly energy model [15].

2.3. Life Cycle Assessment of a Transformer for Green Purchasing.

In the article *"Integrating Sustainability in asset management decision making: a case study on streamlined Life Cycle Assessment in asset procurement"* [16] it is described how distributors have an important responsibility in the product procurement processes. That's why incorporating environmental criteria for green purchasing can make significant changes in manufacturing processes. For this reason, the Dutch distribution company *Liander* conducts a study on how to integrate environmental criteria for green purchasing. Thanks to the standardization through ISO[12,13], LCA has become a transparent and reliable method. But at the same time, LCA method is complex, time-consuming and requires significant knowledge. Therefore, the distributor has chosen to simplify the method, focusing only on the most impactful stages and environmental categories. Thanks to the simplification of the LCA, it was possible to be used by all manufacturers and *Liander* could integrate environmental criteria with other criteria such as cost, performance, and compliance of technical requirements.

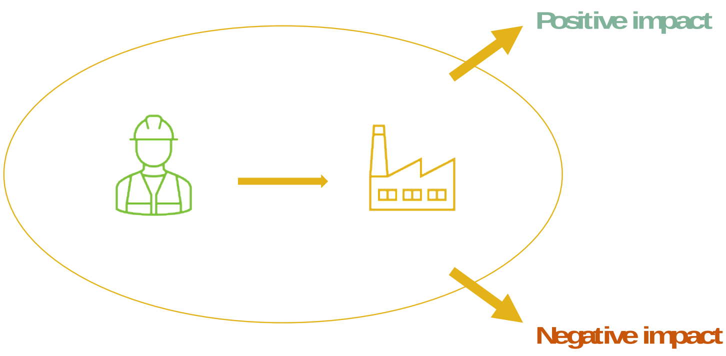


Figure 2: Green Procurement.

Green purchasing involves the acquisition of goods and services that meet environmental, social, and economic criteria to reduce the impact of commercial activities and promote sustainable development. Integrating green purchasing criteria is complex because the company must be able to weigh these criteria against more traditional aspects by which it evaluates the product. In the article, *Liander* also monetizes the environmental criteria to compare them with the other requirements. To do this, they employ the life cycle cost analysis method, which assigns an economic value to environmental impacts.

Moreover, various studies have been published regarding transformers environmental evaluation in recent decades. Among them, in 2009 and 2011, the articles *"Comparative Life Cycle Assessment of a MV/LV transformer with an amorphous metal core and a mv/lv transformer with a grain-oriented magnetic silicon steel core"* [8] and *"Life Cycle Assessment of dry-type and oil-immersed distribution transformers with amorphous metal core"* [7] were presented at International Conference on Electricity Distribution (CIRED). These articles perform an LCA of different transformers to compare the materials used by manufacturers. The functional unit of the papers was a transformer with a lifespan of 30 years. The results indicate that using materials that reduce transformer energy losses, although generating greater impacts in the manufacturing phase, compensates for the operation phase and improves its environmental performance throughout its complete life cycle.

Similarly, the article *"Sustainability assessment of novel transformer technologies in distribution grid applications"* [9] carries out a sustainability analysis of different technologies integrated into transformers: LFT, LFT and OLTC, SST, and HT. To carry out this study, they used a simulation of a typical distribution network in Switzerland. Different generation scenarios were taken into account, first the current electricity mix in Switzerland, secondly the sustainable development objectives for 2050 (ES2050) and, thirdly the Swissolar objectives, which have a more ambitious targets for renewable energy penetration. Their LCA includes a simulation of how each of the transformers would behave according to the integration of renewable energies. The consumption-generation curves vary with the integration of renewables, compared to a more traditional electricity mix, which could increase energy losses in the grid due to voltage variations.

The results of the article indicate that in a traditional electricity mix, the LFT transformer has the best environmental performance. However, if the operation of the transformer to expand the grid capacity and integrate renewable energy sources is considered, it is possible to compensate the negative environmental impact of the manufacturing stage and improve the total environmental performance. Therefore, other transformers, such as the hybrid LFT and OLTC transformer, could achieve better environmental performance in an electricity mix with a high penetration of renewables, where congestion situations may arise.

2.4. Software Used.

The LCA is usually carried out using one of the available software packages, as these software packages include the main databases for the different stages of a multitude of products and for different countries. Some of the available software are SimaPro, Open LCA, GaBi, Eco-it, Air.e LCA, TEAM and Umberto. The results that can be obtained from the different available software can vary and depending on the LCA application it is important to choose the most suitable software. In the article *"Why using different Life Cycle Assessment software tools can generate different results for the same product system? A cause–effect analysis of the problem"* [17], a comparison of the LCA of a product in Brazil was carried out for two modelling scenarios: cradle-to-grave and cradle-to-gate. The results of the characterised and normalised impacts were obtained for five impact categories, which makes it possible to show the different results depending on the software and database used.

The comparative study between the different available software's has been a common practice, and the most relevant ones are described in the article. But the general trend is that SimaPro and GaBi are the most widely used programs in the industry. This is because they are the most comprehensive, offering better data management, ease of analysis of results and transparency of results. In this study, SimaPro will be used since it is not only a renowned program but also the one used at the university.

3. Objectives.

The objective of this project is to develop a Life Cycle Assessment (LCA) tool that facilitates the study of the environmental impact of a medium-voltage transformer to integrate green procurement criteria. The tool will enable a simple and efficient comparison of the environmental impact of transformers from different manufacturers.

The project is divided into the following specific objectives:

a) Modelling the LCA of a 2022 standard transformer.

b) Evaluating the LCA of transformers from the past (1980), present (2022), and future (2050), with the aim of understanding the most relevant environmental impacts and stages of the life cycle.

c) Developing a simplified tool based on the previous LCA models, which allows for an easy comparison of the environmental impact of transformers from different manufacturers.

By carrying out this project, the aim is to provide a practical and effective tool that facilitates decision-making in the acquisition of transformers, considering their environmental impact and promoting green procurement.

4. Methodology.

The implementation of this LCA project for a transformer is based on a set of regulations that establish a framework to ensure that the study is properly executed. The following regulations are presented in greater detail, from the most generic to the most specific.

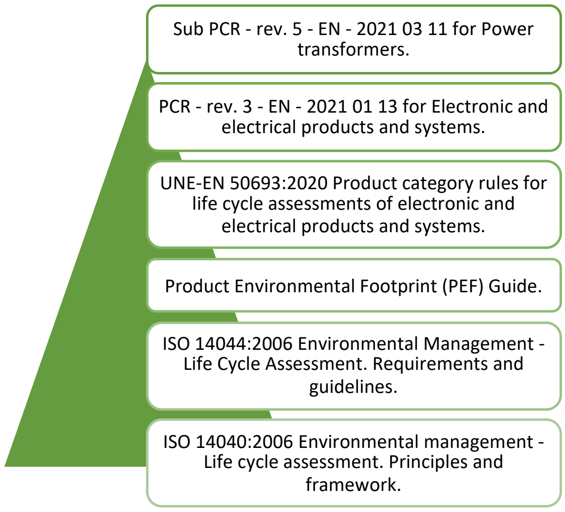


Figure 3: Regulation on the LCA of a transformer.

The principles of conducting an LCA are detailed in the *"ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework"* [12], and *"ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines*" [13]. According to these standards, LCA implementation is divided into four steps:

a) **Definition of the objective and scope:** in this step the goal and scope will be determine, by the study boundaries, the functional unit, the public objective, …

b) **Inventory analysis:** this step will include the collection of the data for the inputs and outputs associated with all life cycle stages, including manufacturing, use, final treatment, and disposal.

c) **Environmental impact assessment:** in this step the results of the category impacts will be analyzed. Those results will be obtained from the inventory and characterization factors.

d) **Interpretation of results:** finally, a summary of the results will be done to draw conclusions and make recommendations based on the initially defined objective.

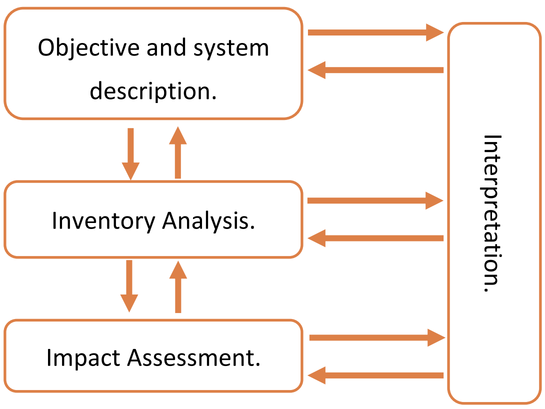


Figure 4: Life Cycle Assessment stages.

The main characteristics of LCA implementation are also defined in these standards. According to the ISO when conducting an LCA the entire life cycle of the product, from raw material acquisition to final disposal, must be considered. LCA is an iterative process for which different methodologies exist, allowing for adaptation to the specific application.

The implementation of this project has followed the framework established by the European Union through the *"Product Environmental Footprint (PEF) Guide"* [5] and the *"UNE-EN 50693 PCR for the life cycle assessment of electrical and electronic products and systems"* [18], which provides specific guidelines and requirements for conducting the LCA of electrical products, including transformers. In addition, the *"PCR - rev. 3 - EN - 2021 01 13 for electrical and electronic products and systems*" [19], as well as the *"Sub-PCR - rev. 5 - EN - 2021 03 11 for Power Transformers*" [20], have been considered, which provide specific considerations for conducting an LCA of the transformer.

The adoption of this set of specific rules for transformer analysis ensures that the results are of an appropriate quality. Furthermore, it facilitates data comparison and aggregation in larger-scale studies and lays the foundation for the development of an Environmental Product Declaration (EPD).

4.1. Objective and System Description.

The objective of this work is to quantify the environmental impact of the transformer. The application of this LCA will be for integrating the results as environmental criteria for the procurement process. Therefore, the objective of the study is not to publish the results externally but to generate an internal tool that allows the comparison between different transformers.

The functional unit considered for the LCA is a 630kVA transformer with a primary voltage of 20kW and a secondary low voltage (LV). The transformer is assumed to have a 35-year lifespan. The LCA considers two possible operating scenarios during the operation phase: 40% and 70% load index. The *"Sub-PCR - rev. 5 - EN - 2021 03 11 for Power Transformers*" [20] defines that the load index to be considered corresponds to 70% of the nominal power. However, usually to ensure supply safety and avoid potential risks, electrical infrastructure is oversized. Therefore, distribution network transformers often operate at lower load indexes. This is the reason why in this study also is compared the environmental impact of the transformer operating at 40%.

Regarding the location, the transformer is assumed to be manufactured, installed, and operated in Spain. Therefore, the energy losses during operation will be associated with Spain's energy mix based on the year of the LCA study.

The scope of the LCA considers the product's life cycle from raw material extraction to end-of-life, following a cradle-to-grave approach. The different stages are categorized into the following modules specified by the *"Sub-PCR - rev. 5 - EN - 2021 03 11 for Power Transformers*" [20]:

<u>Upstream:</u>

This module includes raw material extraction and processing, energy consumption during manufacturing and distribution from suppliers to the transformer assembly factory. The raw materials considered for the transformer include silicon steel, aluminum, insulation paper, glass fabric, steel, mineral bases, vegetable esters, and resin. The steel and aluminum working processes are also considered in this module.

<u>Core:</u>

This module includes the transformer's assembly process, including the energy consumed, transportation, and waste management at the factory.

<u>Downstream:</u>

This module covers the stages of distribution, operation, and end-of-life. Different scenarios are considered in this stage, which will be detailed in the inventory analysis.

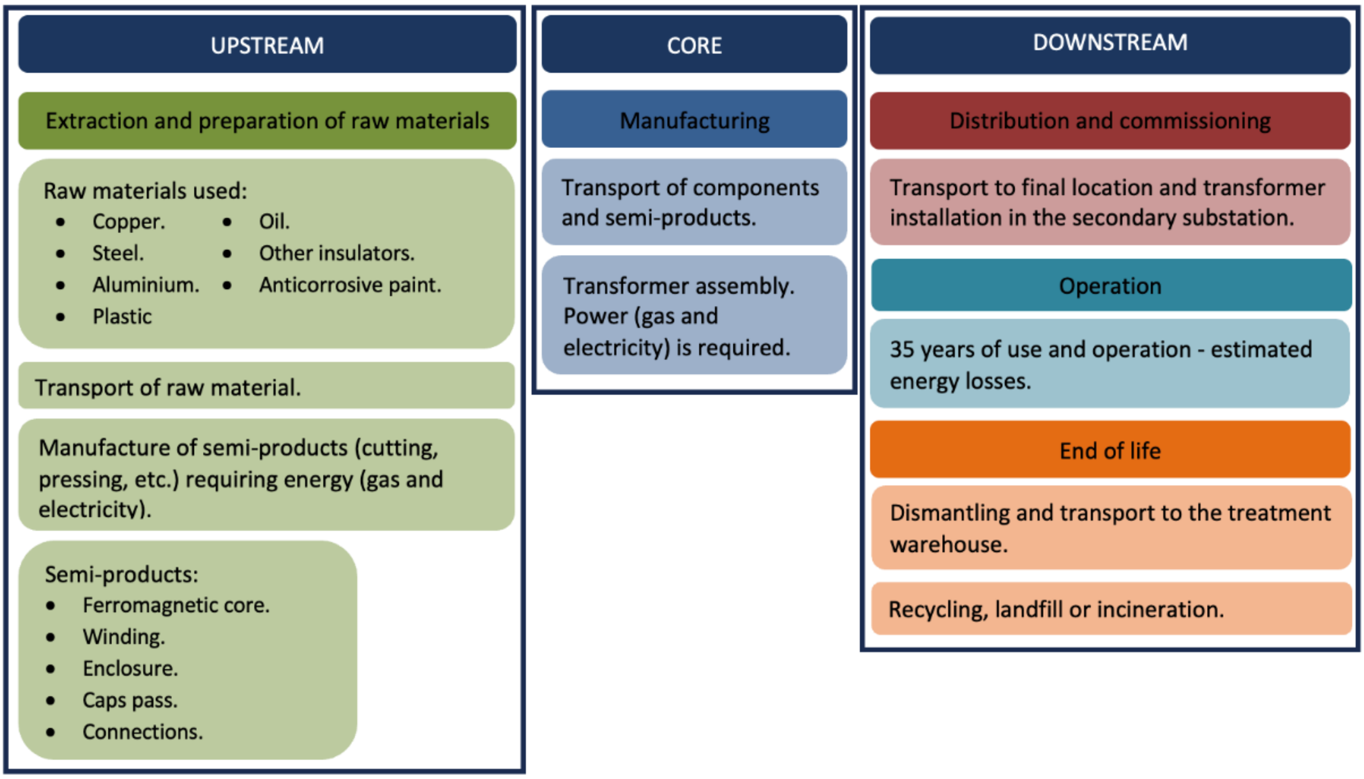


Figure 5: Transformer LCA scheme.

The life cycle inventory was conducted using the Ecoinvent 3.8 database, which is widely recognized at the European level for its considerable size and quality. Ecoinvent was chosen because is the one included in SimaPro and it contains the characterization factors for the study location and the various technologies considered. The modeling was performed using the software of SimaPro, version 9.3.0.3.

According to EN 50693 [18], the cut off rules state that a maximum of 5% of the total environmental impact of the analyzed product system can be excluded. The *"Sub-PCR - rev. 5 - EN - 2021 03 11 for Power Transformers"* [20] specifies that *"materials composing the transformer itself, whose total mass does not exceed 1% of the total weight of the device"* [19,20], can be excluded.

4.1.1. Environmental impacts.

The environmental impacts used in this study correspond to the categories recommended by EN 50693:2020 [18]. These categories include:

- Climate change (kg CO_2 eq.).
- Ozone depletion (kg CFC 11 eq.).
- Acidification (mol H^+ eq.).
- Eutrophication, freshwater (kg P eq.).
- Photochemical ozone formation (kg NMVOC eq.).
- Resource use, minerals and metals (kg Sb eq.).
- Resource use, fossils (MJ).
- Water use (m^3 deprive).

The methodology used for normalization and weighted values is based on the EN 15804 + A2:2019 standard [21] that is align with the EF 3.0 method. The normalization values from the EF 3.0 method published in November 2019 were used. It should be noted that the implementation of this method in SimaPro has been adapted to better fit the substances used in SimaPro data libraries [22]. The normalization and weighting values used by SimaPro are:

Table 1. SimaPro normalization and weighting values.

Impact category	Normalization	Weighting
Climate change – total (GWP)	0,0001235	0,2106
Ozone depletion (ODP)	18,64	0,0631
Acidification (AC)	0,018	0,062
Eutrophication, freshwater (EP-freshwater).	0,6223	0,028
Photochemical ozone formation (POF)	0,02463	0,0478
Resource use, minerals and metals (ADP-minerals&metals)	15,71	0,0755
Resource use, fossils (ADP-fossil)	0,00001538	0,0832
Water use (WDP)	0,00001538	0,0851

The development of weighting factors is essential for establishing an environmental performance value and ensure reliable and comparable environmental information for consumers, stakeholders, and policymakers. In the "*Development of a weighting approach for the Environmental Footprint"* [23] the JRC's objective is to develop a method for weighting EF impact categories based on the environmental problems. To define the most suitable weighting factors, different approaches were considered: single item, distance-to-target, panel-based, monetary valuation, and meta-models. After the evaluation and integration of the different approaches, the JRC proposed two weighting values, considering impacts related to toxicity and excluding these impacts. SimaPro uses weighting values that include toxicity-related impact categories. However, in this present study, the weighting values used exclude toxicity-related impact categories. According to the JRC document, the robustness of these impacts categories is low, and therefore, excluding them may be advisable when studying environmental performance [23]. Below are the percentage values used.

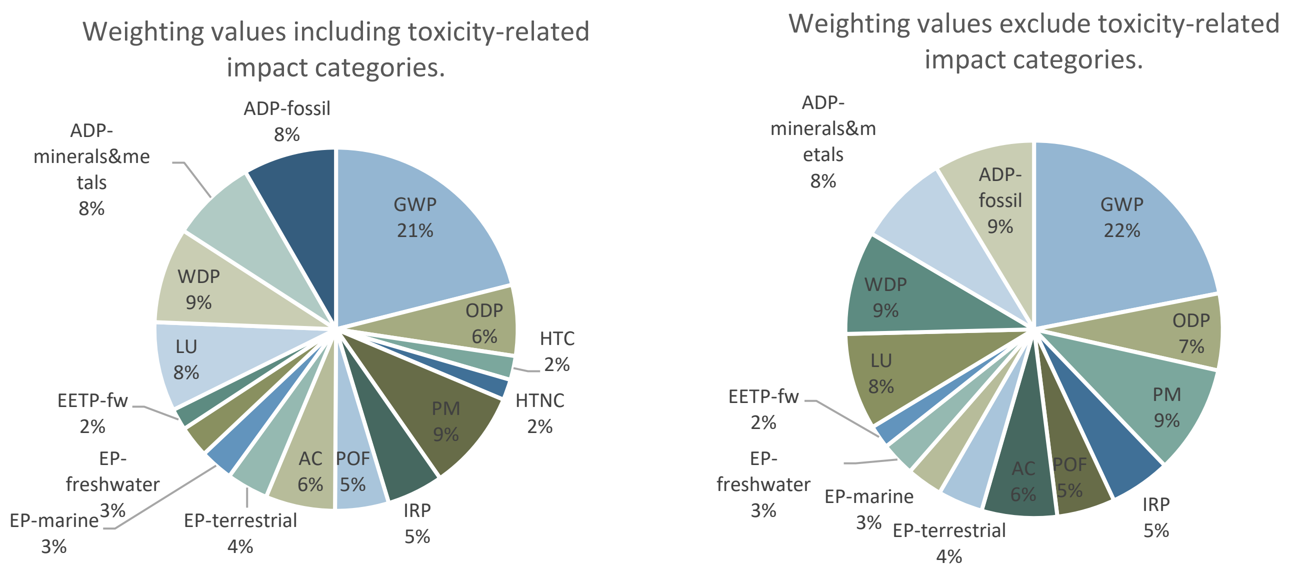


Figure 6: The recommended weighting factors including and excluding toxicity-related impact categories according to the JRC Technical Reports: "*Development of a weighting approach for the Environmental Footprint"* [23].

This representation of the weighting factors includes more impact categories than those set as mandatory in the *"Sub-PCR - rev. 5 - EN - 2021 03 11 for Power Transformers*" [20]. Because of this, in the green procurement tool, where only mandatory impact categories will be shown, these proportional weighting factors will be used for these categories. These values are shown below:

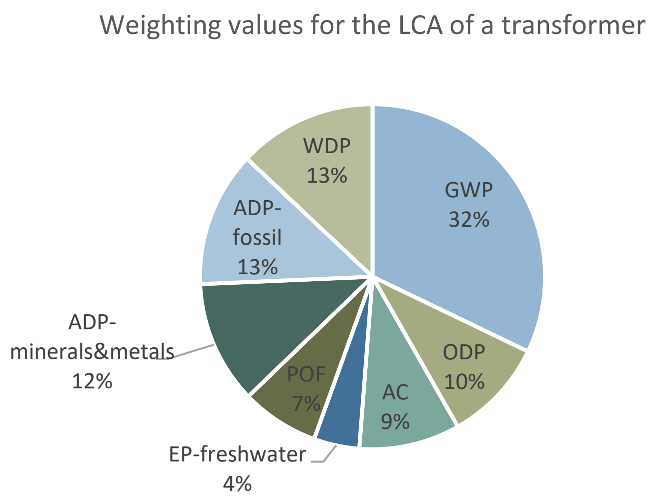


Figure 7: Weighting values for the LCA of a transformer.

4.2. Life Cycle Inventory Analysis.

The data used for each process in the transformer's life cycle modeling have been obtained from measurements of manufacturers during the year 2021. In the following chapters the inventory analysis performed for each stage will be developed.

4.2.1. Upstream and Core.

Necessary raw material data has not been allocated by the manufacturers for the products and co-products. However, they have allocated the consumption of secondary materials, energy consumption, maintenance of facilities and the use of machinery. The remaining data considered in the downstream stages has been gathered from various sources and has been detailed below.

For the manufacturing process, the following raw materials are used in the modeling of the base transformer used for the tool.

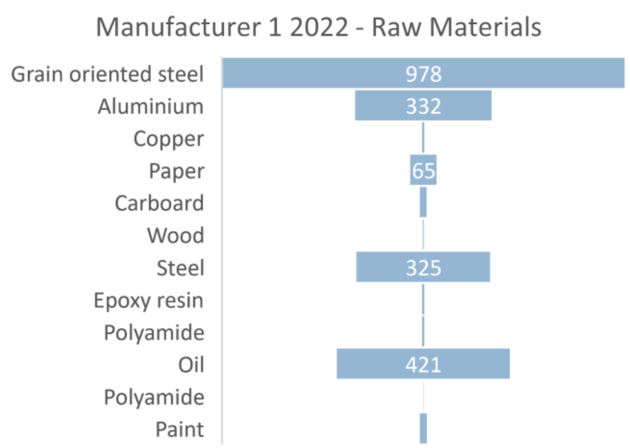


Figure 8: Raw materials (kg) for manufacturer 1 transformer 2022.

In addition, the LCA of transformers from the 1970s-1980s and 2050 has also been analyzed. Obtaining the raw material consumption in the manufacturing process during the 1970s-1980s for these transformers has been a challenge, hence factsheets indicating the main raw materials and total weight have been considered and a similar distribution to that of current transformers has been considered for the remaining unspecified raw materials such as resin, stainless steel, or paint. Moreover, an equal distribution of raw materials has been assumed for the 2050 transformers as for the base transformer in 2022, considering that 50% of these materials are recycled, 20% reused and 30% extracted raw materials. Nevertheless, the characterization factors for recycled materials available in SimaPro for the employed methodologies are limited. For this reason, this assumption has been used only for steel, aluminum, copper, paper, cardboard, and wood materials. For the rest of the materials, it has been considered that 80% comes from raw materials extracted from nature, and 20% comes from reused materials from transformers whose useful life has ended. For reused materials, it has been considered that they require an additional transport distance of 100 km and do not have any impact associated with raw materials since their impact is accounted for in the transformer they originated from. The environmental impact associated with this transport distance has been calculated using trucks from Ecoinvent 3.8 database EURO 5 [24].

4.2.2. Downstream - Distribution and Commissioning.

The distribution phase is complex as the target audience of this study is the distributors. Therefore, after the transformer is manufactured, the transport distance to its final location may vary depending on the position in the grid where it will be installed. For this reason, an average distance of 400km overland has been considered. Also, this was the distance used in the development of other tools. The environmental impact associated with this transport has been calculated using trucks from the Ecoinvent 3.8 database, EURO 5, to reflect the most realistic scenario possible [24].

4.2.3. Downstream - Operation.

The operation stage includes the impacts related to the energy consumed by the transformer during its defined service life. This energy consumed includes, in addition to any possible associated consumption, the different losses that occur during the electricity transformation.

The transformers used for this study do not have auxiliary consumption for cooling or digitization. Therefore, the energy consumption associated with these stages corresponds only to the energy losses.

The Sub-PCR on power transformers [20] defines how these losses should be calculated, following the technical standard IEC 60076-1 [25], which distinguishes two types of losses:

- **Load losses:** caused by the winding impedance and dependent on the transformer's load. It will be calculated at nominal frequency and temperature.
- **No-load losses:** represent the active power absorbed by the transformer when the machine is energized, and the secondary circuit is open. It is independent of the transformer's load.

According to the Sub-PCR on power transformers [20], the total consumed energy ($E_d[kWh]$) will be calculated using the following formula:

$$E_d[kWh] = [P_{load} * k_{load}^2 + P_{no\ load}] * t_{year} * RSL + P_{aux} * f_{aux} * t_{year} * RSL \qquad \text{I}$$

Where:

- P_{load} are the load losses of the transformer.
- k_{load} is the average load index of the transformer.
- $P_{no\ load}$ are the no-load losses of the transformer.
- P_{auxd} are the losses associated with auxiliary consumption.
- f_{aux} is the fraction of time that auxiliary services are operating.
- t_{year} is the total number of hours that the equipment will be operating.
- RSL is the reference service life, which for this study is 35 years.

The total energy consumption was calculated for two different scenarios: a 40% and 70% load index. The energy losses for the transformers manufactured between 1980 and 2022 is the standard. But for the transformers in 2050, it is not possible to know the load and no-load losses. Therefore, a 10% improvement for energy losses has been considered compared to the current losses of the transformers.

The following table summarizes the results obtained for each transformer.

Table 2. Operation of 1970-1980 transformers.

Variables	Units	Value
Power	kW	630
Energy RSL years	kWh*RSL	135.210.600
Losses RSL years	kWh*RSL	1.656.345
Energy 1 year	kWh	3.863.160
Losses 1 year	kWh	47.324
Efficiency	-	0,987750
Efficiency'	-	0,012250
Load losses	kWh	35498,148
No load losses	kWh	11826
Aux losses	kWh	0
Pload	kW	8,27
kload	-	0,7
Pnoload	kW	1,35
Paux	kW	0
faux	-	0
tyear	h	8760
RSL	year	35

Variables	Units	Value
Power	kW	630
Energy RSL years	kWh*RSL	77.263.200
Losses RSL years	kWh*RSL	819.603
Energy 1 year	kWh	2.207.520
Losses 1 year	kWh	23.417
Efficiency	-	0,989392
Efficiency'	-	0,010608
Load losses	kWh	11591,232
No load losses	kWh	11826
Aux losses	kWh	0
Pload	kW	8,27
kload	-	0,4
Pnoload	kW	1,35
Paux	kW	0
faux	-	0
tyear	h	8760
RSL	year	35

Table 3. Operation of 2022 transformers.

Variables	Units	Value
Power	kW	630
Energy RSL years	kWh*RSL	135.210.600
Losses RSL years	kWh*RSL	856.640
Energy 1 year	kWh	3.863.160
Losses 1 year	kWh	24.475
Efficiency	-	0,993664
Efficiency'	-	0,006336
Load losses	kWh	19745,04
No load losses	kWh	4730,4
Aux losses	kWh	0
Pload	kW	4,6
kload	-	0,7
Pnoload	kW	0,54
Paux	kW	0
faux	-	0
tyear	h	8760
RSL	year	35

Variables	Units	Value
Power	kW	630
Energy RSL years	kWh*RSL	77.263.200
Losses RSL years	kWh*RSL	391.222
Energy 1 year	kWh	2.207.520
Losses 1 year	kWh	11.178
Efficiency	-	0,994937
Efficiency'	-	0,005063
Load losses	kWh	6447,36
No load losses	kWh	4730,4
Aux losses	kWh	0
Pload	kW	4,6
kload	-	0,4
Pnoload	kW	0,54
Paux	kW	0
faux	-	0
tyear	h	8760
RSL	year	35

Table 4. Operation of 2050 transformers.

Variables	Units	Value
Power	kW	630
Energy RSL years	kWh*RSL	135.210.600
Losses RSL years	kWh*RSL	770.976
Energy 1 year	kWh	3.863.160
Losses 1 year	kWh	22.028
Efficiency	-	0,994298
Efficiency'	-	0,005702
Load losses	kWh	17770,536
No load losses	kWh	4257,36
Aux losses	kWh	0
Pload	kW	4,14
kload	-	0,7
Pnoload	kW	0,486
Paux	kW	0
faux	-	0
tyear	h	8760
RSL	year	35

Variables	Units	Value
Power	kW	630
Energy RSL years	kWh*RSL	77.263.200
Losses RSL years	kWh*RSL	352.099
Energy 1 year	kWh	2.207.520
Losses 1 year	kWh	10.060
Efficiency	-	0,995443
Efficiency'	-	0,004557
Load losses	kWh	5802,624
No load losses	kWh	4257,36
Aux losses	kWh	0
Pload	kW	4,14
kload	-	0,4
Pnoload	kW	0,486
Paux	kW	0
faux	-	0
tyear	h	8760
RSL	year	35

The location of the study is Spain, so the impact associated with transformer losses will depend on the environmental impact of the generation mix at any given time.

For the base case, which is a transformer from 2022, the data of the generation mix has been obtained from the API of the operator of the electrical system of Spain, REE (Red Eléctrica de España) [26]. On the website it is published the generation data for each year. The generation data for the year 2022 has been extracted and uploaded to SimaPro.

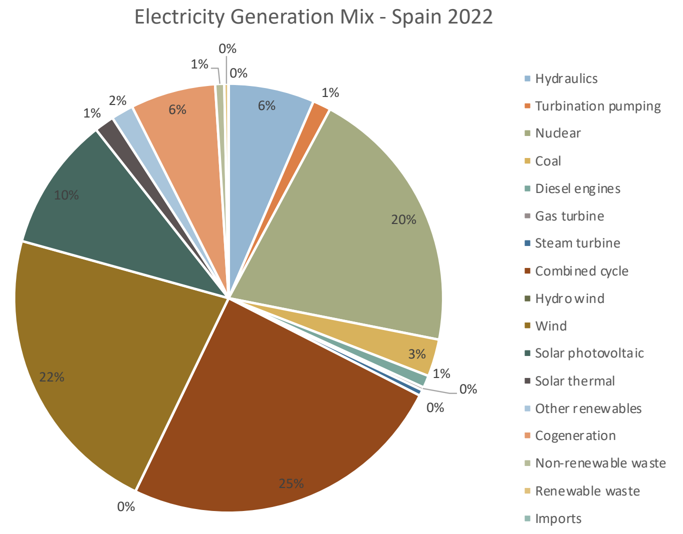


Figure 9: Generation Mix for Spain in 2022.

The energy mix of Spain in 1980 was not available in the REE database. Nevertheless, it was obtained from the UNESA Electric Statistical Report, 1986 [27].

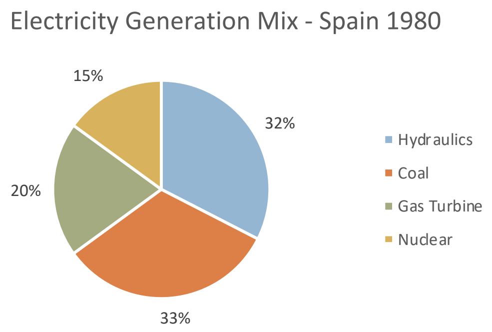


Figure 10: Generation Mix for Spain in 1980.

Lastly, the generation mix for 2050 has been obtained through a combination of the energy policies established in the PNIEC (National Integrated Energy and Climate Plan) [28] and the forecast made by the International Energy Agency in their document Net Zero by 2050: A Roadmap for the Global Energy Sector [29].

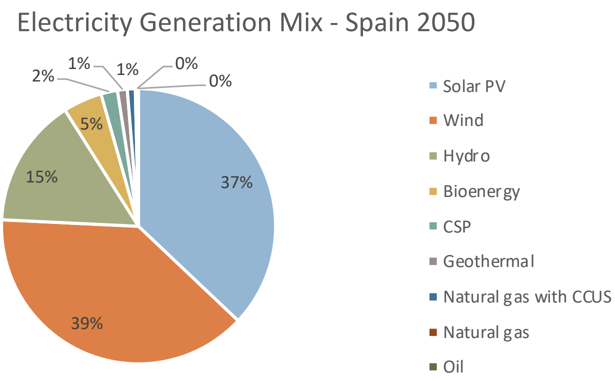


Figure 11: Generation Mix for Spain in 2050.

4.2.4. Downstream – End of life.

A recycling scenario has been considered, in which the transformer is transported to the waste management plant over a 100 km distance. Regarding end-of-life materials, three possible waste treatments have been considered: recycling, incineration, and landfill. Information on the percentage of each material subjected to each process for transformers in the year 2022 has been obtained from the INE (National Statistics Institute) [30]. No waste management data was found for the year 1980; therefore, the latest available data from the INE which was year 2002, has been used. Lastly, for the transformer in the year 2050, considering the increase in raw material costs, it is assumed that all materials will be recycled.

Table 5. End of life of 2050 transformers.

	Recycling			Landfill			Incineration		
Type of waste	**2022**	**1980**	**2050**	**2022**	**1980**	**2050**	**2022**	**1980**	**2050**
Metallic waste	99,63%	99,45%	100%	0,31%	0,23%	0%	0,06%	0,32%	0%
Copper waste	99,63%	99,51%	100%	0,31%	0,05%	0%	0,06%	0,44%	0%
Oil waste	99,23%	58,44%	100%	0,55%	7,10%	0%	0,22%	34,46%	0%
Chemical waste	77,78%	0,00%	100%	11,07%	15,72%	0%	11,14%	84,28%	0%
Wood waste	87,49%	80,89%	100%	3,36%	8,14%	0%	9,15%	10,97%	0%

4.3. Simplified Tool for LCA of Transformers.

To integrate green procurement criteria, a simplified tool has been developed to improve time efficiency in the LCA calculation by focusing on the most relevant aspects.

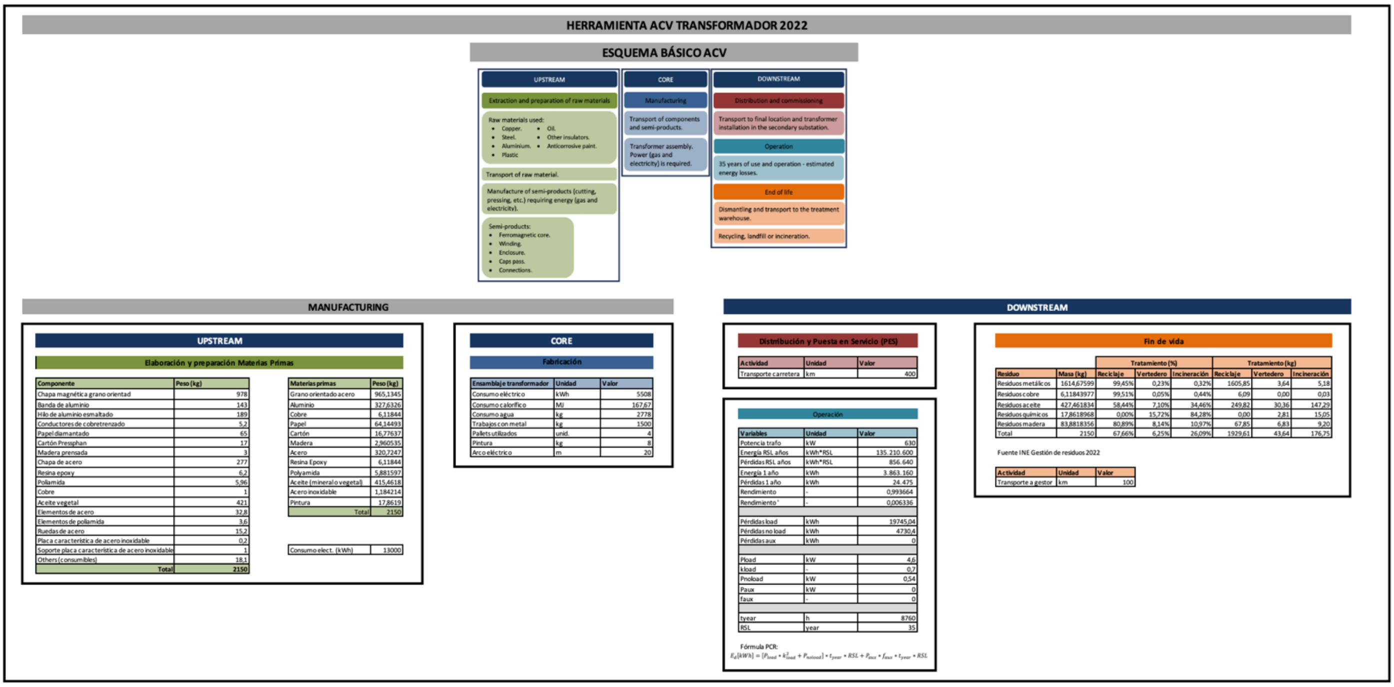
The tool consists of three parts:

a) **Data Input:** All necessary data is entered, focusing on a user-friendly layout that will ensure autonomous use by manufacturers. The tool is divided into the different stages of the transformer's life cycle.

b) **Characterization Factors:** Characterization factors for each stage have been extracted from SimaPro according to the scope and objective defined previously.

c) **Summary of Results:** Environmental impact is presented for each impact category through various graphs. Additionally, a summary table of normalized and weighted results is provided for comparison across impact categories and to identify the most significant ones.

Schematic captures of each part of the tool are included for reference:



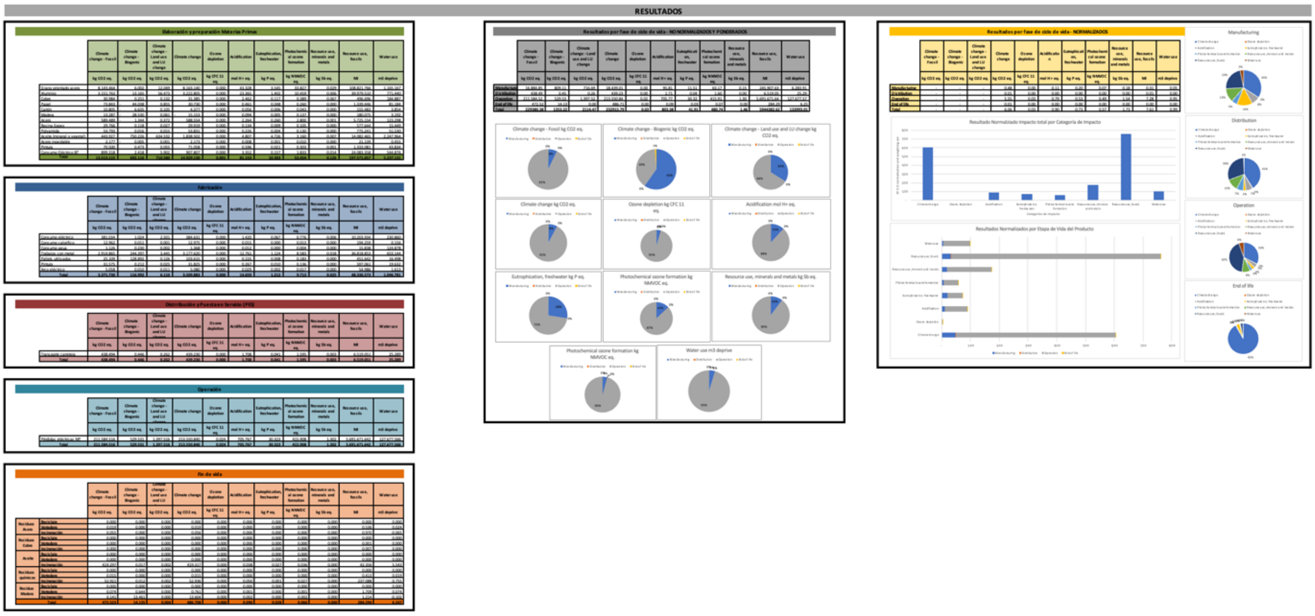


Figure 12: The simplified tool for the LCA of a Transformer.

Green procurement implies integrating environmental criteria with common characteristics evaluated such as performance and costs. Different methods were considered, such as defining a minimum environmental performance a transformer should meet. The method used for this study was assigning a mark based on the environmental performance. When deciding between different transformers that have traditional requirements, the environmental performance score will be considered. The overall score will be obtained after normalizing and weighting all the environmental impacts.

5. Results and Discussion.

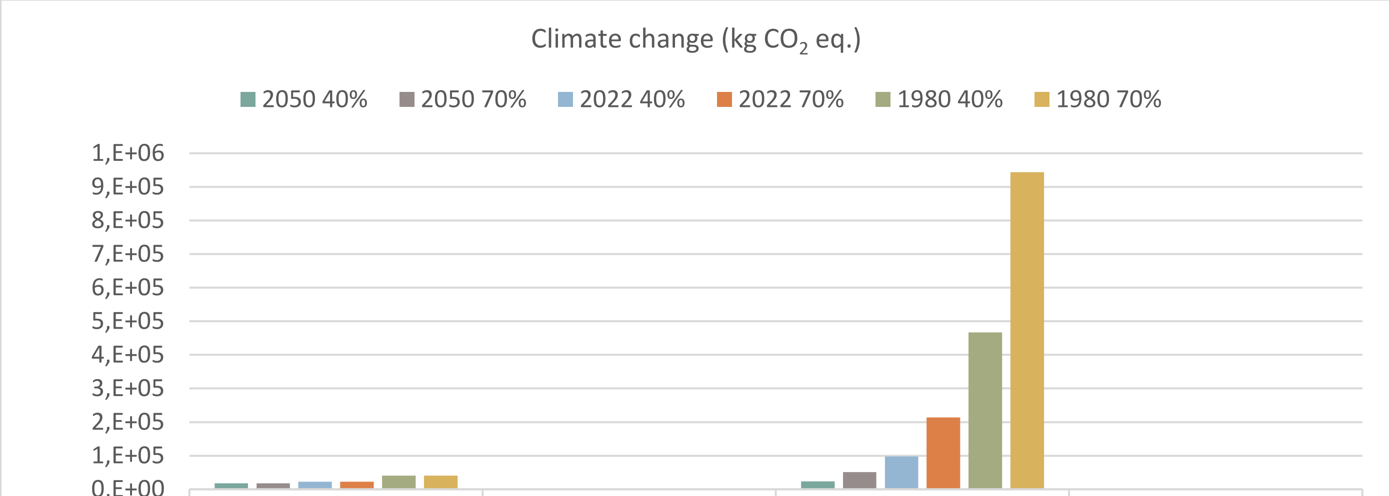
5.1. Main environmental impacts of the transformer LCA results.

Firstly, the results obtained for the LCA conducted for the three different transformers (Transformer 1 from 1980, Transformer 1 from 2022, and Transformer 1 from 2050) will be presented for the four main impact categories across the four stages of the transformer's life cycle. The results are presented in absolute values to provide a visual representation of the significant environmental impacts.

Here, it can be observed that although the impact of climate change has been significantly reduced, the absolute value remains high. This is particularly important considering the large number of transformers installed in the grid and their crucial role. The development of distributed energy resources also requires an increase in the number of transformers in the electrical grid, making it important to minimize the impact generated by these machines.

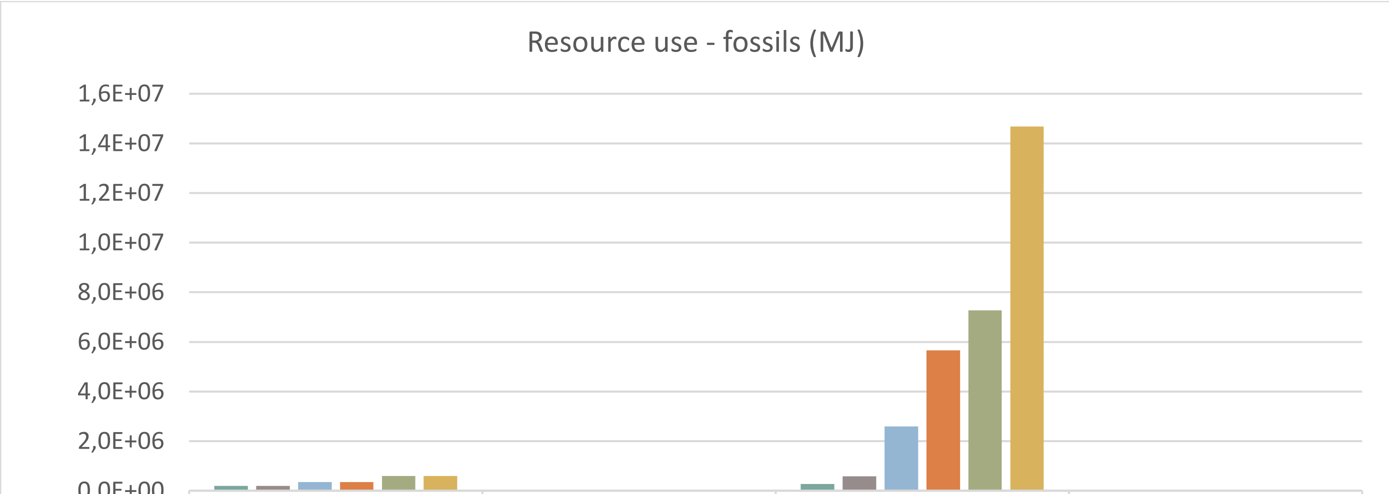
In the paper "*The greenhouse gas emissions of power transformers based on life cycle analysis*"[31] the life cycle of a transformer installed in France during the year 2022 is studied. The characteristics of the transformer studied in that paper do not match with those of this study; the transformers in the paper have higher power, making their results not directly comparable. However, the impact of the operational phase on climate change accounts for 96% of the total. Similarly, in this present study, the operational phase is also the most significant phase. In this study, for a transformer operating in 2022 at 40% of its load, the operational phase accounts for 81% of the total impact. However, if the load of the transformer increases to 70%, the operational phase's contribution rises to 91% of the total impact in the climate change category. These findings highlight the critical role of the operational phase in determining the environmental impact of transformers, especially concerning climate change.

The environmental impact of resource use - fossil is closely linked to climate change. As a result, it exhibits a similar behavior to climate change impact. As time passes, it decreases dramatically.



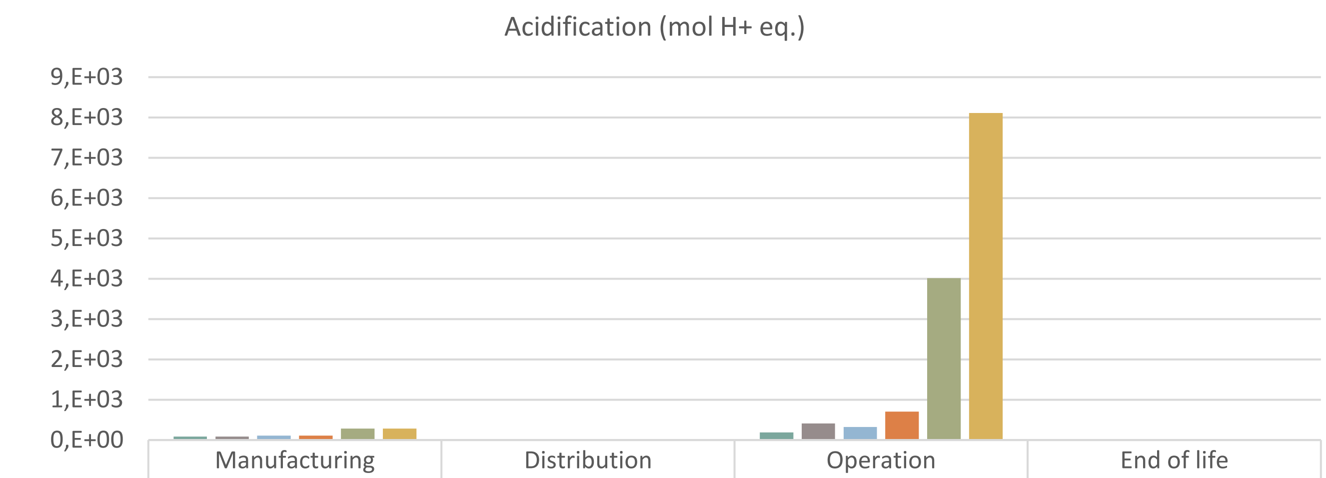
	Manufacturing	Distribution	Operation	End of life
2050 40%	17.710,64	663,70	23.292,06	111,27
2050 70%	17.710,64	663,70	50.989,72	111,27
2022 40%	22.699,10	663,70	97.520,24	132,95
2022 70%	22.699,10	663,70	213.535,37	132,95
1980 40%	40.468,71	663,70	466.734,40	621,84
1980 70%	40.468,71	663,70	943.228,85	621,84

Figure 13: Transformer LCA climate change impact (kg CO_2 eq.).



	Manufacturing	Distribution	Operation	End of life
2050 40%	189.667,95	8.512,29	268.058,45	1.651,49
2050 70%	189.667,95	8.512,29	586.819,00	1.651,49
2022 40%	344.972,53	8.512,29	2.585.828,90	1.686,50
2022 70%	344.972,53	8.512,29	5.662.065,20	1.686,50
1980 40%	598.694,89	8.512,29	7.265.504,30	1.935,09
1980 70%	598.694,89	8.512,29	14.682.940,00	1.935,09

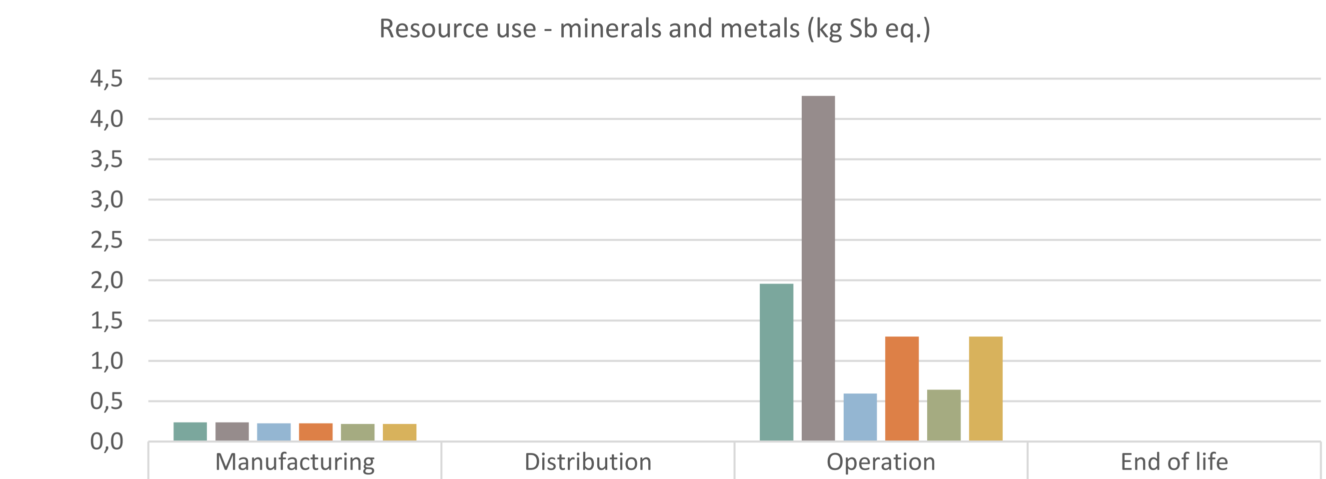
Figure 14: Transformer LCA resource use - fossils (MJ) impact.



	Manufacturing	Distribution	Operation	End of life
2050 40%	87,48	2,62	187,59	0,43
2050 70%	87,48	2,62	410,66	0,43
2022 40%	113,46	2,62	322,26	0,44
2022 70%	113,46	2,62	705,64	0,44
1980 40%	281,69	2,62	4.014,71	0,52
1980 70%	281,69	2,62	8.113,38	0,52

Figure 15: Transformer LCA acidification (mol H+ eq.) impact.

Regarding acidification, a significant reduction is observed. This impact is due to the use of coal-based generation technologies that released significant amounts of gases and particulate pollutants such as sulfur oxides and nitrogen oxides. These gases can react with atmospheric water to form acids, potentially impacting soil, and water. The reduction of this technology and the improvement of technologies for capturing and reducing these emissions result in a significant reduction of this impact [32,33].



	Manufacturing	Distribution	Operation	End of life
2050 40%	0,239	0,005	1,958	0,000690
2050 70%	0,239	0,005	4,287	0,000690
2022 40%	0,227	0,005	0,594	0,000695
2022 70%	0,227	0,005	1,301	0,000695
1980 40%	0,218	0,005	0,644	0,000745
1980 70%	0,218	0,005	1,302	0,000745

Figure 16: Transformer LCA resource use - minerals and metals (kg Sb eq.) impact.

Regarding the resources use, minerals and metals, an increase is observed compared to 1980, which is due to a variation in the generation mix. The use of more sustainable technologies for generation requires a more intensive use of resources, resulting in an increase in this impact.

5.2. Transformer LCA results normalised and weighted.

In the following tables, the results shown are normalized and weighted following the methods described in the previous sections. The intention of this analysis is to understand the evolution of the environmental performance of a transformer over the time, allowing for the identification of the most relevant life cycle stages and potential environmental impacts that should be the focus of attention.

Table 6. Transformer LCA results normalized and weighted.

Scenario	Stage	Climate change	Ozone depletion	Acidification	Eutrophication, freshwater	Photochemical ozone formation	Resource use, minerals and metals	Resource use, fossils	Water use
2022 40%	Manufacturing	9,01E-01	2,90E-03	1,93E-01	3,41E-01	1,31E-01	4,11E-01	6,74E-01	9,77E-02
	Distribution	2,63E-02	2,09E-04	4,47E-03	2,06E-03	4,33E-03	8,36E-03	1,66E-02	1,00E-03
	Operation	3,87E+00	1,99E-02	5,49E-01	3,68E-01	3,41E-01	1,08E+00	5,05E+00	6,58E-01
	End of life	5,28E-03	4,45E-05	7,52E-04	2,83E-04	7,37E-04	1,26E-03	3,29E-03	7,38E-05
	Total	4,80E+00	2,30E-02	7,47E-01	7,11E-01	4,78E-01	1,50E+00	5,74E+00	7,56E-01
2022 70%	Manufacturing	9,01E-01	2,90E-03	1,93E-01	3,41E-01	1,31E-01	4,11E-01	6,74E-01	9,77E-02
	Distribution	2,63E-02	2,09E-04	4,47E-03	2,06E-03	4,33E-03	8,36E-03	1,66E-02	1,00E-03
	Operation	8,48E+00	4,35E-02	1,20E+00	8,06E-01	7,47E-01	2,36E+00	1,11E+01	1,44E+00
	End of life	5,28E-03	4,45E-05	7,52E-04	2,83E-04	7,37E-04	1,26E-03	3,29E-03	7,38E-05
	Total	9,41E+00	4,67E-02	1,40E+00	1,15E+00	8,83E-01	2,78E+00	1,17E+01	1,54E+00
1980 40%	Manufacturing	1,61E+00	4,61E-03	4,80E-01	4,54E-01	2,74E-01	3,95E-01	1,17E+00	1,72E-01
	Distribution	2,63E-02	2,09E-04	4,47E-03	2,06E-03	4,33E-03	8,36E-03	1,66E-02	1,00E-03
	Operation	1,85E+01	3,94E-02	6,84E+00	5,05E+00	3,02E+00	1,17E+00	1,42E+01	3,31E+00
	End of life	2,47E-02	5,15E-05	8,93E-04	1,06E-03	8,48E-04	1,35E-03	3,78E-03	1,47E-04
	Total	2,02E+01	4,43E-02	7,32E+00	5,50E+00	3,30E+00	1,57E+00	1,54E+01	3,48E+00
1980 70%	Manufacturing	1,61E+00	4,61E-03	4,80E-01	4,54E-01	2,74E-01	3,95E-01	1,17E+00	1,72E-01
	Distribution	2,63E-02	2,09E-04	4,47E-03	2,06E-03	4,33E-03	8,36E-03	1,66E-02	1,00E-03
	Operation	3,74E+01	7,96E-02	1,38E+01	1,02E+01	6,11E+00	2,36E+00	2,87E+01	6,68E+00
	End of life	2,47E-02	5,15E-05	8,93E-04	1,06E-03	8,48E-04	1,35E-03	3,78E-03	1,47E-04
	Total	3,91E+01	8,45E-02	1,43E+01	1,07E+01	6,39E+00	2,76E+00	2,99E+01	6,86E+00
2050 40%	Manufacturing	7,03E-01	1,56E-03	1,49E-01	4,14E-01	1,06E-01	4,33E-01	3,70E-01	1,13E-01
	Distribution	2,63E-02	2,09E-04	4,47E-03	2,06E-03	4,33E-03	8,36E-03	1,66E-02	1,00E-03
	Operation	9,24E-01	3,78E-03	3,19E-01	3,01E-01	1,78E-01	3,54E+00	5,23E-01	6,12E-01
	End of life	4,42E-03	4,35E-05	7,37E-04	2,74E-04	7,26E-04	1,25E-03	3,22E-03	7,25E-05
	Total	1,66E+00	5,59E-03	4,74E-01	7,18E-01	2,89E-01	3,99E+00	9,14E-01	7,25E-01
2050 70%	Manufacturing	7,03E-01	1,56E-03	1,49E-01	4,14E-01	1,06E-01	4,33E-01	3,70E-01	1,13E-01
	Distribution	2,63E-02	2,09E-04	4,47E-03	2,06E-03	4,33E-03	8,36E-03	1,66E-02	1,00E-03
	Operation	2,02E+00	8,27E-03	6,99E-01	6,59E-01	3,89E-01	7,76E+00	1,15E+00	1,34E+00
	End of life	4,42E-03	4,35E-05	7,37E-04	2,74E-04	7,26E-04	1,25E-03	3,22E-03	7,25E-05
	Total	2,76E+00	1,01E-02	8,54E-01	1,08E+00	5,01E-01	8,20E+00	1,54E+00	1,45E+00

The most relevant stages for transformers from the past, present, and future correspond to operation and manufacturing. According to the paper titled *"Sustainability assessment of novel transformer technologies in distribution grid applications"* [9], it has been recognized that the operational stage plays a crucial role in improving the environmental performance of transformers. The paper highlights that transformers have a long lifespan and operate continuously, resulting in significant cumulative energy losses over time. Therefore, it is essential to focus on reducing the environmental impact during the operational stage.

However, transformers have evolved throughout the years and other stages are gaining potential for reduction, such as manufacturing. The findings of the same paper [9] emphasize the need for a comprehensive sustainability assessment of transformer technologies, considering the entire life cycle and the impact of different stages. This approach ensures the integration of environmental considerations in distribution grid applications. Consequently, the environmental performance of all the life cycle were considered. Regarding environmental impacts, the most significant are related to climate change, acidification, the use of mineral and metal resources, and the use of fossil fuels. However, the significance of these impacts varies over time. Below is a summarized graph illustrating the overall impact of transformers, showing the evolution of each impact category.

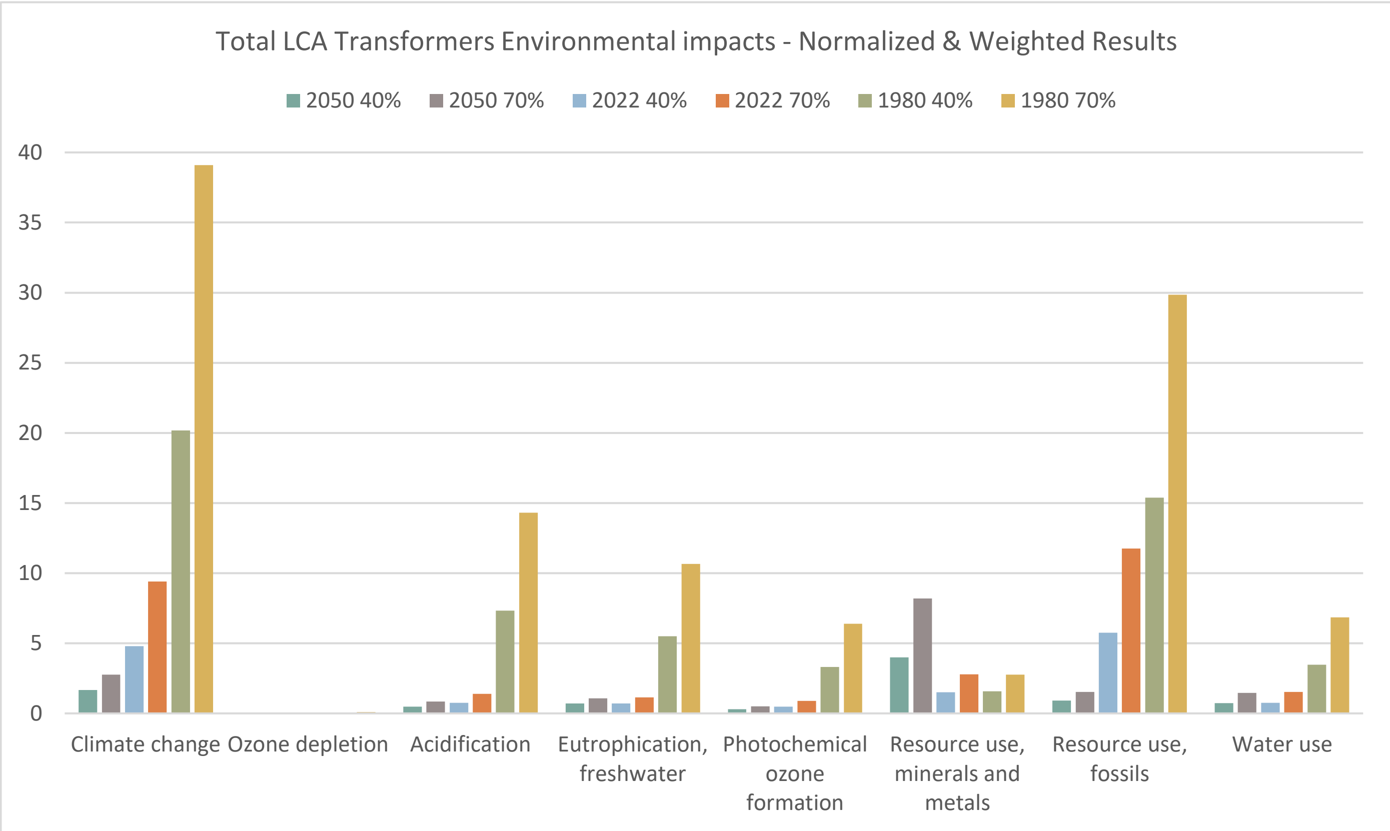


Figure 17: Transformer LCA total results normalized and weighted.

As shown in the graph, climate change mitigation policies are having an effect, and over the years, the climate change and resource use - fossils impacts of transformers are being reduced. This is mainly due to two reasons: Firstly, energy policies have aimed to decrease the use of high-impact climate change generation technologies. The percentage of technologies with such characteristics has been decreasing thanks to the transition to a more sustainable generation mix. Secondly, in response to the initially high impact of transformers, the EU implemented significant regulations to establish minimum energy efficiency standards during transformers operation, such as the *“Commission Regulation (EU) No 548/2014 on implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to small, medium and large power transformers”* [6]. The efforts made by regulators, manufacturers, and system operators to achieve transformers with better environmental performance during the operation stage have resulted in a decrease in climate change related environmental impacts.

To enable a better visualization of the results, a similar summary graph has been presented for the operation and manufacturing stages.

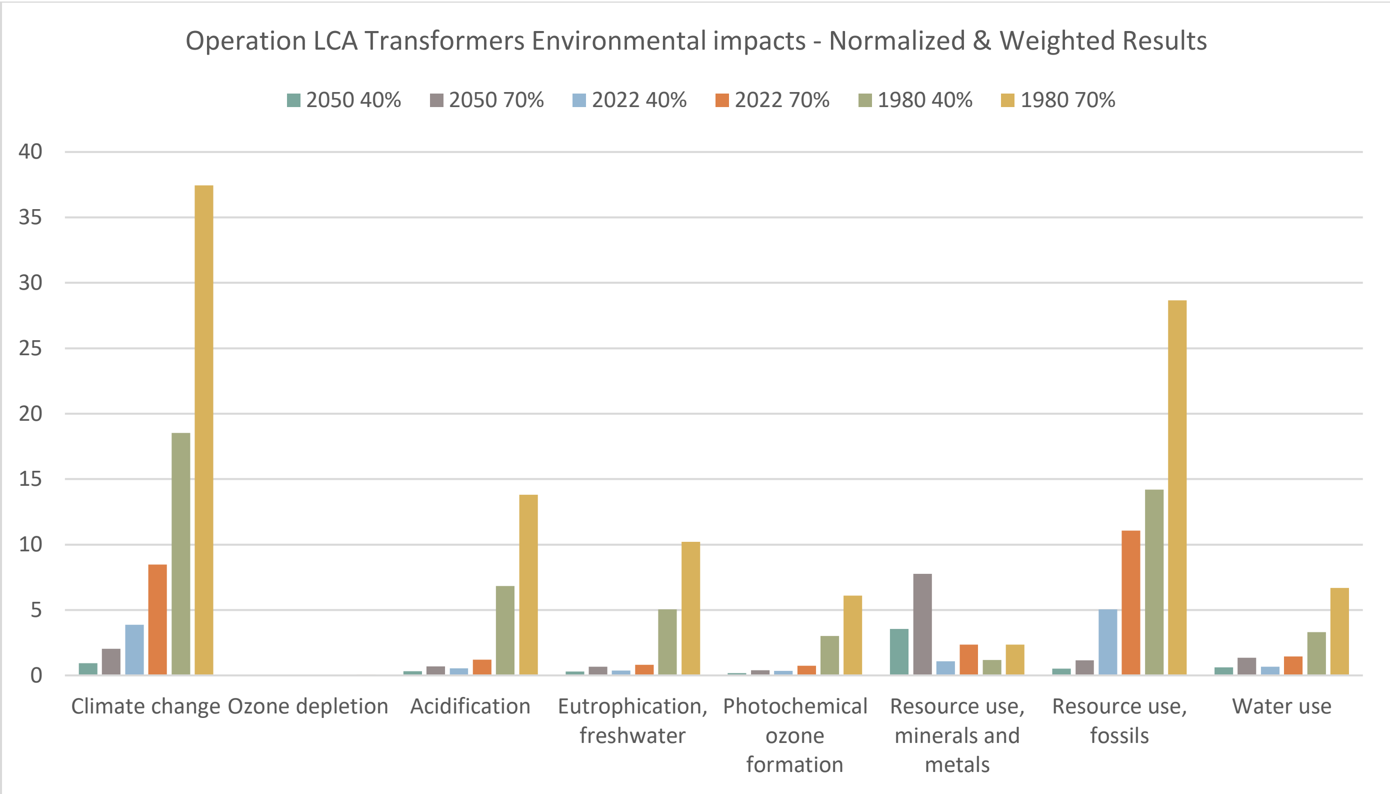


Figure 18: Transformer LCA operation results normalized and weighted.

Since the publication of Regulation (EU) No. 548/2014 [6], which analyzed the life cycle of transformers, it was determined that the focus of action should lie in the operational stage. The lifespan of a transformer is high, around 40 years, and it operates continuously throughout the year. The environmental impact of operation is directly dependent on the generation mix under which the transformer operates. Therefore, transitioning to more sustainable generation mixes leads to a reduction in the impacts and the influence on the LCA. As depicted in the graph, the environmental impact related to climate change has drastically decreased, while impacts such as the use of mineral and metal resources have increased. The increase in this impact is due to the growing utilization of electronic generation technologies, which require a significant amount of these materials. The report presented by the International Energy Agency: "*Critical Minerals Market Review"* [34] highlights how the increased of renewables energies (solar PV and wind) has led to a significant growth in the mineral demand (lithium, nickel, cobalt and neodymium). As the installed capacity of clean energy continues to grow, there will be a corresponding increase in the demand for these metals. The report emphasizes the necessity for countries and businesses to develop strategies that focus on diversifying supplies and adopting more sustainable practices in mineral acquisition. This highlights the importance of conducting a comprehensive LCA and considering the overall evolution. Improving one stage may worsen another or reducing one impact may lead to an increase in another.

The paper titled *"Sustainability assessment of novel transformer technologies in distribution grid applications"* [9] emphasizes the importance of considering the generation mix under which transformers operate. It notes that transitioning to more sustainable generation mixes can result in a reduction in environmental impact and influence the outcomes of the LCA. Additionally, the paper highlights that while the impact related to climate change has decreased, the use of mineral and metal resources has increased due to the growing utilization of electronic generation technologies.

The Regulation (EU) No. 548/2014 [6] established maximum energy loss requirements that transformers marketed in the EU must comply with. These values have been updated over time as technology advances. To improve performance, better manufacturing techniques and more robust raw materials have been used. The current achieved efficiencies for the analyzed transformer are around 99.44% [35]. Enhancing this value presents a significant challenge for manufacturers, so it is essential to assess the impact of such improvement and explore other options for reducing environmental impact that may have greater potential.

Furthermore, the study of sustainability assessment of novel transformer technologies [9] also highlights the evolving focus from the operational stage to the manufacturing stage of transformers. With the energy transition, the significance of the operational phase can be reduced, allowing for a dedicated examination and improvement of the manufacturing phase itself.

At this stage, the analysis of the manufacturing stage begins. Up until now, improving the environmental performance of the transformer often meant compromising the manufacturing stage to enhance operation. However, with the energy transition, the significance of the operational phase can be reduced, shifting the focus towards the manufacturing stage. This allows for an exclusive examination and improvement of the manufacturing phase itself, rather than studying it solely to enhance the operational phase of the transformer's life cycle.

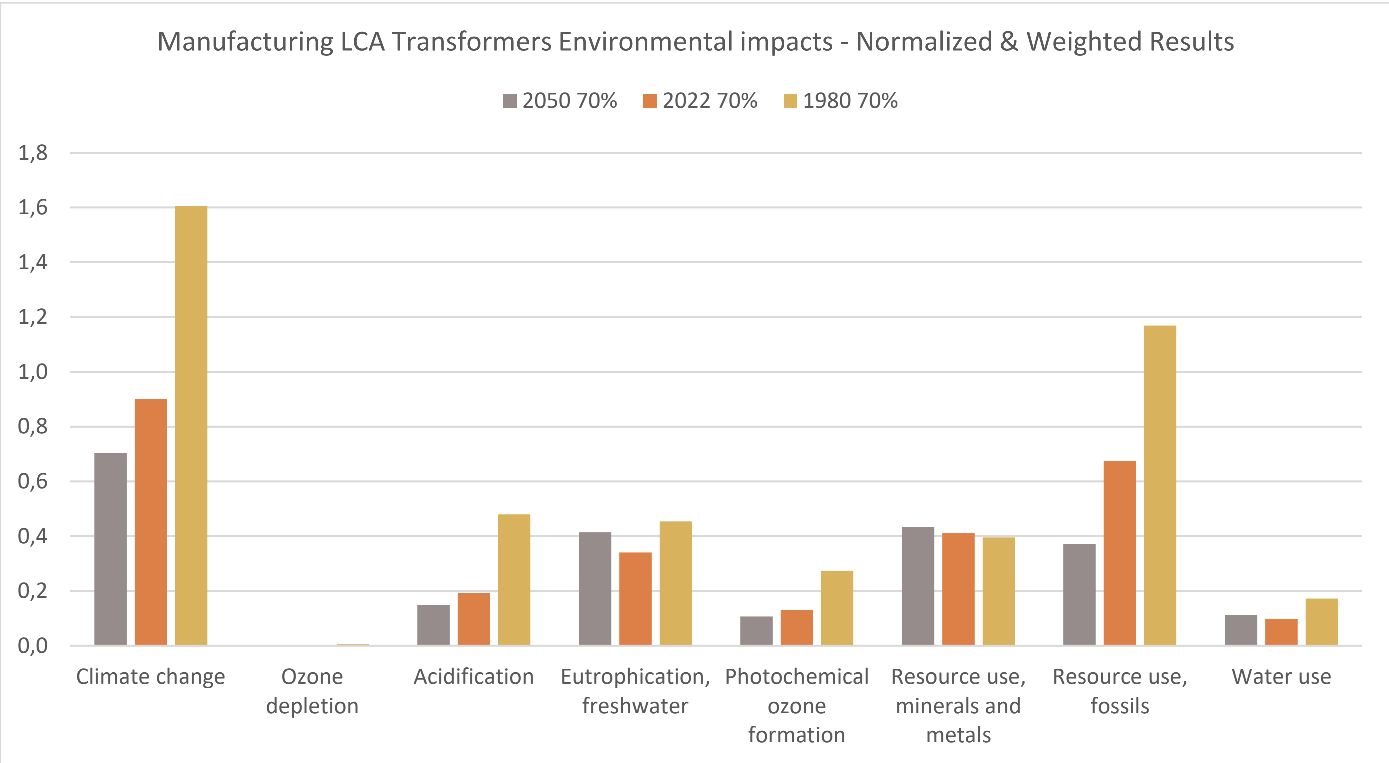


Figure 19: Transformer LCA manufacturing results normalized and weighted.

The environmental impact of this stage is attributed to the energy consumption involved in component preparation and transformer assembly, to the raw material used, and to the transport. Reducing the consumption of raw materials in the 2050 transformer (with 20% being reused) and an electricity consumption of a more sustainable generation mix results in a decrease in most of the environmental impacts. However, the use of mineral and metal resources increases due to the energy consumption associated with the generation mix. Also, the impact: eutrophication, freshwater also increases from 2022 due to the influence in the environment of the recycling techniques. To mitigate the environmental impact of this stage, efforts should be made to decrease energy consumption in manufacturing processes and minimize the transportation of raw materials and subcomponents. Also, improving the percentage of reused materials could also reduce significant impacts by an eco-design of the transformer.

5.3. Environmental impact of the generation mixes.

As observed in the previous analyses, the operational phase has been identified as having the highest impact, which depends directly on the generation mix at the time. To further illustrate this, the exclusive evolution of the generation mix for each year is depicted below, based on the defined percentage allocations in the inventory.

Through the provided graph and table, a clear trend emerges regarding the reduction in climate change and acidification impacts from 1980 to 2050. While the impact of fossil resource use has indeed declined from 1980 to 2022, it has done so to a lesser extent when compared to the other impacts. Notably, the impact of mineral and metal resource use in transformers has exhibited an increase parallel to the growing utilization of technologies such as photovoltaics.

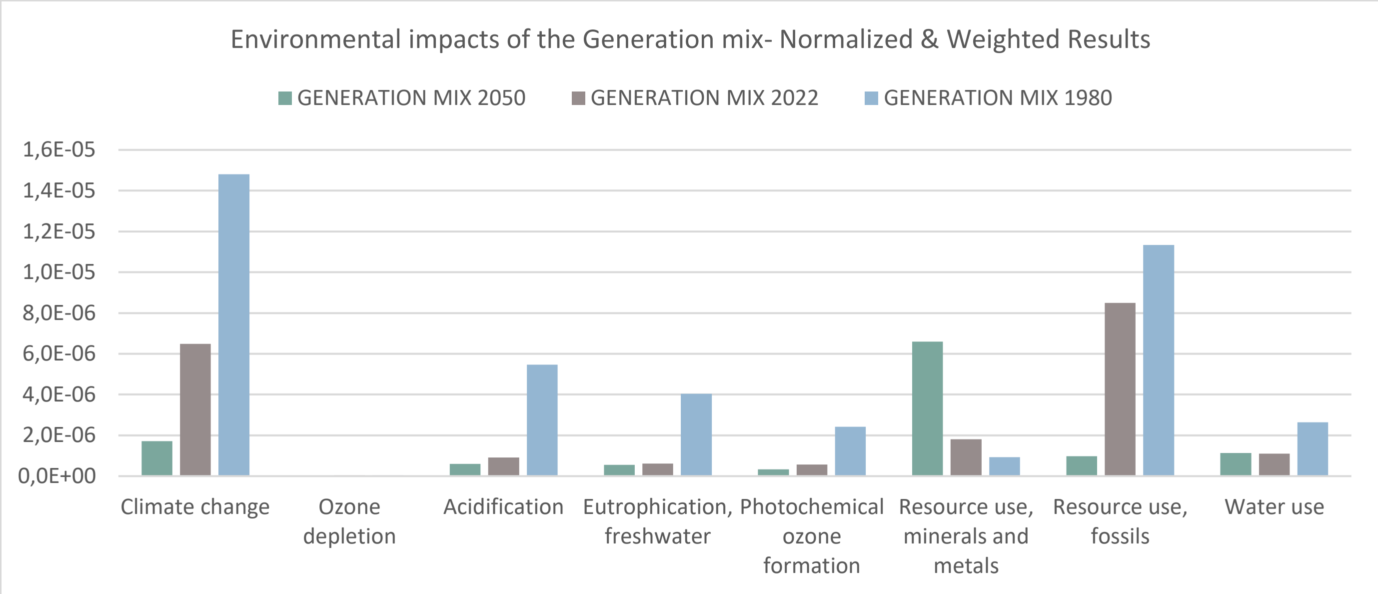


Figure 20: Generation mix environmental impacts.

5.4. Reduction of the environmental impact of transformer LCA.

In this sub-section, a summary table has been created to showcase the reduction of the environmental impact of the transformer over time. The data presented will mean a reduction if the percentage is positive and an increase if it is negative.

Table 7. Reduction of the environmental impact of transformers.

		Climate change	Ozone depletion	Acidification	Eutrophication, freshwater	Photochemical ozone formation	Resource use, minerals and metals	Resource use, fossils	Water use
		kg CO2 eq.	kg CFC 11 eq.	mol H+ eq.	kg P eq.	kg NMVOC eq.	kg Sb eq.	MJ	m3 deprive
Operation 40%-70%		54,33%	54,33%	54,33%	54,33%	54,33%	54,33%	54,33%	54,33%
1980-2022	**Manufacturing**	43,91%	37,10%	59,72%	24,93%	52,04%	-3,85%	42,38%	43,32%
	Operation 40%	79,11%	49,55%	91,97%	92,71%	88,71%	7,78%	64,41%	80,12%
	Operation 70%	77,36%	45,34%	91,30%	92,10%	87,77%	0,08%	61,44%	78,46%
	End of life	78,62%	13,66%	15,76%	73,18%	13,02%	6,78%	12,85%	49,68%
	Total 40%	76,20%	47,98%	89,79%	87,08%	85,54%	4,81%	62,65%	78,27%
	Total 70%	75,94%	44,76%	90,21%	89,22%	86,17%	-0,48%	60,65%	77,56%
2022-2050	**Manufacturing**	21,98%	46,31%	22,90%	-21,66%	18,98%	-5,39%	45,02%	-15,28%
	Operation 40%	76,12%	81,01%	41,79%	18,20%	47,88%	-229,48%	89,63%	6,98%
	Operation 70%	76,12%	81,01%	41,80%	18,21%	47,90%	-229,41%	89,64%	7,00%
	End of life	16,31%	2,26%	2,00%	3,05%	1,51%	0,65%	2,08%	1,77%
	Total 40%	65,48%	75,75%	36,62%	-0,95%	39,43%	-166,49%	84,09%	4,09%
	Total 70%	70,69%	78,42%	39,04%	6,36%	43,32%	-195,47%	86,93%	5,58%
1980-2050	**Manufacturing**	56,24%	66,23%	68,94%	8,68%	61,14%	-9,45%	68,32%	34,66%
	Operation 40%	95,01%	90,42%	95,33%	94,03%	94,12%	-203,85%	96,31%	81,50%
	Operation 70%	94,59%	89,62%	94,94%	93,54%	93,63%	-229,15%	96,00%	79,96%
	End of life	82,11%	15,61%	17,45%	74,00%	14,33%	7,38%	14,66%	50,57%
	Total 40%	91,78%	87,39%	93,53%	86,96%	91,24%	-153,67%	94,06%	79,16%
	Total 70%	92,95%	88,08%	94,03%	89,91%	92,16%	-196,89%	94,86%	78,81%

The analysis of the table reveals significant trends. Through the table, it is evident that the general trend over the years is a reduction in the environmental impact. However, there is an exception with the impact categories of resource use – minerals and metals, which have worsened with the evolution of the generation mix.

The impacts associated with end of life show that the reuse and recycling of transformer materials significantly reduce the impacts associated with this stage. For the 2050 transformer, it has been assumed that all its components were reused and recycled, resulting in a minimal end of life impact. Therefore, any comparison with the other LCA (Life Cycle Assessment) studies implies an almost 100% improvement in impact.

The percentage reduction has also been represented to compare the operational phase considering load factors of 40% and 70%. The percentage reduction remains at 54% in all stages.

5.5. Green Procurement results.

After selecting the main environmental impacts through LCA for a 630kVA, 20kV to low voltage transformer and developing a simplified tool, the data of three transformer from different manufacturers was collected to assess the impacts. After normalizing and weighting the impacts, the sum of the results represents their final score. In the table shown below, the score for each transformer is presented.

Table 8. Environmental absolute performance.

Manufacturer	Single score
Manufacturer 1	28,43
Manufacturer 2	36,05
Manufacturer 3	25,85

The findings demonstrate a high level of similarity, indicating minimal variations in the manufacturing processes of these three transformers as all of them follow the regulatory standards. According to this table, the transformer from manufacturer 3 has the best environmental performance, followed by transformer 2. Conducting this analysis using a common tool for all three transformers implies that the analysis performed is the same for all three transformers which is highly beneficial as it is going to be used to integrate it for green procurement. A graph is presented with the total normalized and weighted environmental impact values for each of the transformers to gain a better understanding of the differences.

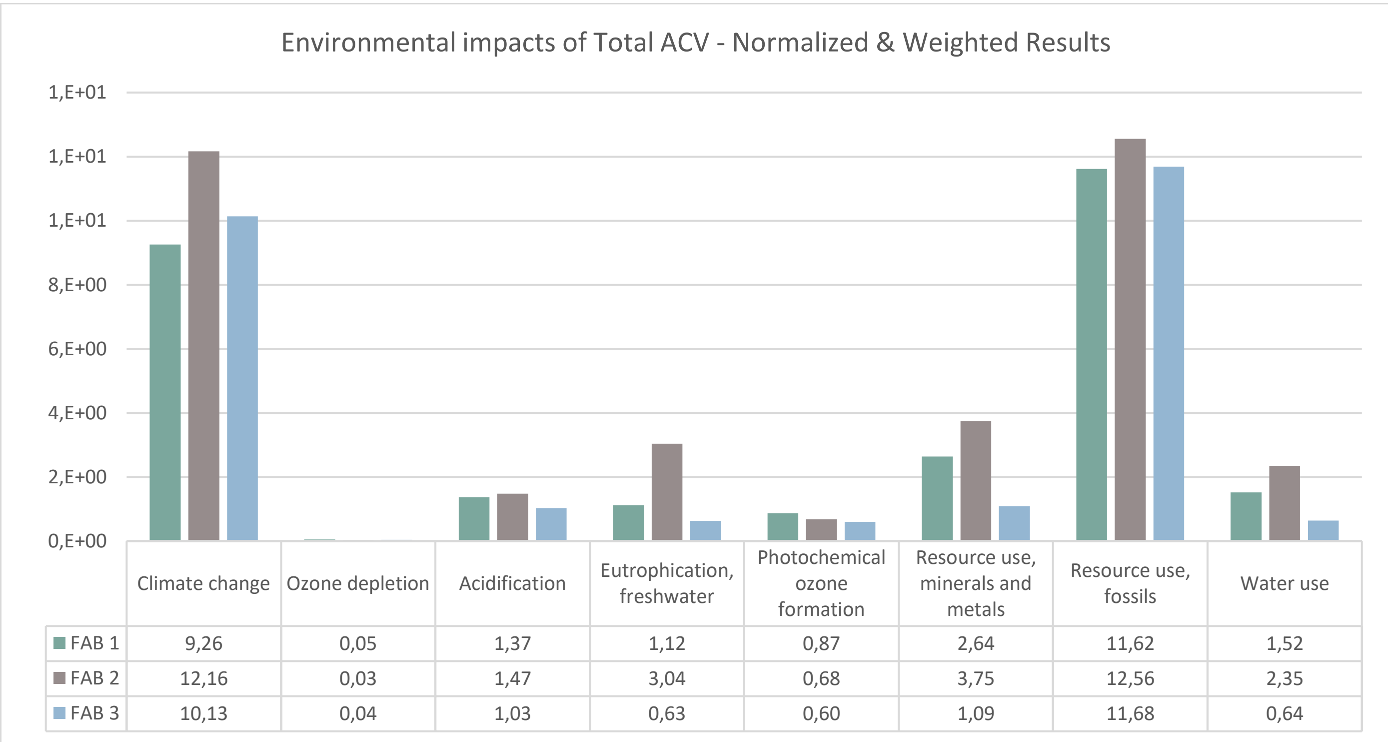


Figure 21: Green procurement comparison – category impacts.

Through the graph, it can be observed that the transformer from manufacturer 2 has worse results in all environmental impacts. The higher impact of this transformer is mainly attributed to the operational stage. This transformer has larger energy losses than the other transformers. However, the results show a high level of similarity, as the variations in the manufacturing processes of these three transformers are not significant. Also, the distribution of raw material mass is related.

6. Conclusions.

The LCA conducted in this project has provided relevant information on the environmental impact of transformers through its different stages and impact categories. It allows the identification of areas with a higher potential for reduction in the transformer's life cycle.

Table 9. Environmental performance of each stage.

	Classification of the LCA of the transformer						
	(%) - 2022 40%	(%) - 2022 70%	(%) - 1980 40%	(%) - 1980 70%	(%) - 2050 40%	(%) - 2050 70%	Average
Manufacturing	18,641%	9,502%	8,021%	4,141%	26,110%	13,973%	13,398%
Distribution	0,430%	0,219%	0,112%	0,058%	0,723%	0,387%	0,321%
Operation	80,850%	90,239%	91,809%	95,772%	73,044%	85,574%	86,215%
End of life	0,079%	0,040%	0,058%	0,030%	0,123%	0,066%	0,066%

The operation and manufacturing stages have been identified as the most significant in environmental performance as they represent 86,46% and 13,4% of the total single score obtained after normalizing and weighting the impacts. The Energy Transition promotion of more sustainable generation mixes and the current high efficiency of transformers implies a significant challenge for manufacturers in reducing the environmental impact during the operation stage. Therefore, during the next years the goal of reducing the environmental impact will be focused on improving the manufacturing stage. Also, improving the manufacturing stage will result in benefits in the acquisition of raw material, a problem that industries are starting to struggle with. Some of the evaluated alternatives for the manufacturing stage included increasing the proportion of recycled materials, evolving the transformer towards an eco-friendlier product for proper dismantling and reuse of subcomponents, and optimizing manufacturing processes with lower energy consumption.

The main impact categories analyzed for transformers are climate change, acidification, resource use - fossils, and resource use - minerals and metals. The evolution of transformers has decreased all environmental impacts, except for resource use - minerals and metals, which increases for transformers in the year 2050 due to the growth of resource-intensive generation technologies.

The development of this analysis has been carried out with the objective of gaining sufficient knowledge about transformers to determine the most relevant impacts and data for the development of a simplified tool. With the information acquired, it was possible to generate a user-friendly and accessible tool for LCA transformers comparison between different manufacturers.

In conclusion, this project has demonstrated the importance of conducting a complete LCA of transformers to evaluate all stages and impact categories. Working towards reducing impacts and promoting the adoption of green procurement criteria are key actions in advancing towards a more sustainable energy sector.

Appendix A

The development of a tool for the life cycle analysis of a medium-voltage transformer for the distribution grid aligns with several Sustainable Development Goals (SDGs) established by the United Nations. The tool contributes to SDG 7: Affordable and Clean Energy by promoting cleaner and more efficient energy solutions. It also aligns with SDG 9: Industry, Innovation, and Infrastructure by fostering innovation in the electrical industry and improving energy distribution infrastructure. Additionally, the project addresses SDG 13: Climate Action by quantifying and reducing greenhouse gas emissions associated with medium-voltage transformers. Overall, the tool supports the adoption of sustainable technologies, encourages industry innovation, and contributes to global climate change mitigation efforts.

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