University of Padova

Department of Industrial Engineering

Master Thesis in Electrical Engineering

Methods and Strategies for Assessing and Improving the Environmental Impact of Power Transformers

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Per tutta la gente che c'è dall'inizio
E per tutti quelli che ho incontrato lungo il cammino
È stato un lungo viaggio

A tutta la mia famiglia
A mia mamma Paola e a mia nonna Bianca
i miei due angeli custodi

Hitachi Energy

Hitachi Energy is a global leader in the energy market carrying on a legacy in power industry that dates back from the 19th century like its ancient predecessors ASEA and BBC (founded in 1883 and 1891, respectively) and during the 20th century as ABB. It plays an important role in the struggle to accelerate the transition to a sustainable future, providing innovative technologies that enable the integration of renewable sources of energy, modernize grid infrastructure and support the international efforts and goals of decarbonization around the world. In Italy, the Monselice factory unit is specialized in the production of high-performance power transformers and exemplifies the commitment of Hitachi with safety, innovation, quality and sustainability. Its *Research&Development* sector contributes to Hitachi Energy's global effort to create modern solutions to tackle the increasing need to save resources and achieve more sustainable energy alternatives.

Abstract

ENG

Nowadays, the trend of environmental sustainability is becoming a fundamental priority for companies worldwide. This thesis aims to explore methods and strategies to assess and improve the environmental impact of Power Transformers.

In the first part, the concept of circularity and Life Cycle Assessment (LCA) is introduced, addressing regulatory aspects and delving into the Environmental Product Declaration (EPD). Examines how these practices can help to understand and document the overall environmental impact during the life cycle of the power transformer.

The second part of the thesis focuses on a specific project that I am working on during my internship in Hitachi Energy. The project, called "CO_2 Calculation in EDS", aims to develop a software specification so that, in the internal electrical design tool, a calculation for estimating CO_2 emissions from construction to dismantling of the transformer can be integrated already during the electrical design phase.

The goal is not only to provide reliable data on the environmental impact, giving the client more detailed documentation during the project phase, but also to address current issues that Hitachi Energy is facing, such as long delivery times for the transformer to the client and the ongoing scarcity of raw materials.

ITA

Al giorno d'oggi, la tendenza alla sostenibilità ambientale sta diventando una priorità fondamentale per le aziende di tutto il mondo. Questa tesi mira a esplorare metodi e strategie per valutare e migliorare l'impatto ambientale dei trasformatori di potenza.

Nella prima parte, viene introdotto il concetto di circolarità e valutazione del ciclo di vita (LCA), affrontando aspetti normativi e approfondendo la dichiarazione ambientale di prodotto (EPD). Si esamina come queste pratiche possano aiutare a comprendere e documentare l'impatto ambientale complessivo durante il ciclo di vita del trasformatore di potenza.

La seconda parte della tesi si concentra su un progetto specifico su cui sto lavorando durante il mio tirocinio presso Hitachi Energy. Il progetto, chiamato "Calcolo CO2 in EDS", mira a sviluppare una specifica software in modo che, nel tool di progettazione elettrico interno, possa essere integrato un calcolo per stimare le emissioni di CO2 dalla costruzione allo smaltimento del trasformatore già durante la fase di progettazione elettrica.

L'obiettivo non è solo fornire dati affidabili sull'impatto ambientale, dando al cliente una documentazione più dettagliata durante la fase di progetto, ma anche affrontare le problematiche attuali che Hitachi Energy sta affrontando, come i lunghi tempi di consegna del trasformatore al cliente e la continua scarsità di materie prime.

Contents

Listing of figures

Listing of acronyms

CE .... Circular Economy

CB .... Certification Body

EDS .... Electrical Design System

EPD .... Environmental Product Declaration

ESPR .... Ecodesign for Sustainable Product Regulation

GWP .... Gas Warming Potential

ISO .... International Organization for Standardization

LCA .... Life cycle Assessment

LCI .... Life Cycle Inventory

LCIA .... Life Cycle Impact Assessment

LCO .... Life Cycle Optimization

NAB .... National Accreditation Body

PCR .... Product Category Rules

PT .... Power Transformer

R&D .... Research and Development

SGS .... General Society of Surveillance

UNEP .... United Nations Environment Program

1
Overview of a Power Transformer

1.1 Circuital Representation

A Power Transformer is defined as a static electrical machine used in power systems to transfer power between circuits using electromagnetic induction, usually by transforming the voltage and current values between two electrically separated circuits. Fundamentally, it consists of two or more windings and a core of magnetic material, which serves to improve the magnetic coupling between the windings themselves.

It operates by converting electrical energy from the primary circuit into magnetic energy within its core, and then back into electrical energy in the secondary circuit. The simplest model for a real monophasic power transformer is shown in Fig. 1.1 below.

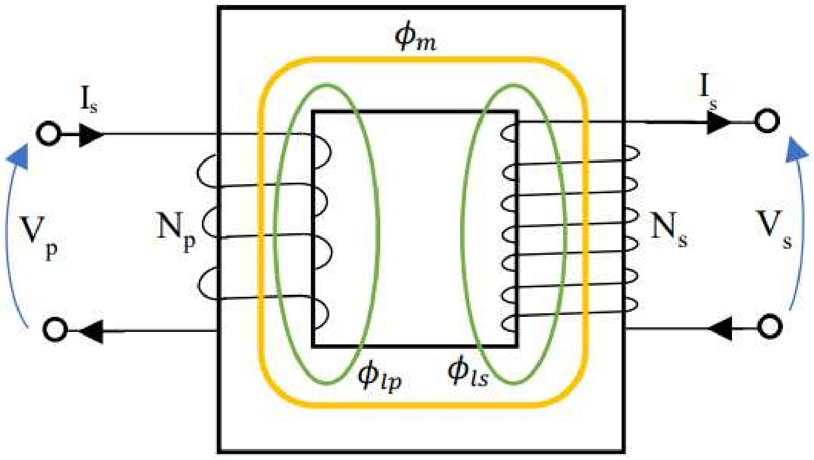


Figure 1.1: Simple Power Transformer Representation: [1] The windings and core are represented in the image: A voltage V_p is applied to the primary side of the transformer, that experiments a current I_p and has N_p turns around the core. A magnetic flux ϕ_m is generated inside the transformer's core, along with leakage fluxes ϕ_{lp} and ϕ_{ls}. An output voltage V_s is generated on the secondary side of the transformer, which has a winding with N_s turns around the core.

A step forward can be done to evaluate the real parameters that can path to the real power transformer: Joules Losses on primary and secondary copper windings can be modeled as series Resistuors R_p and R_s, instead, L_p and L_s are the modeled inductance of primary and secondary windings due to dispersion flux, respectively; inductance due to leads wire leakage flux might also be included.

The model also contains a shunt reactance $(R_{exc} + jX_{exc})$ on the primary side, it models the losses related to the magnetization of the core, across the voltage $V_p^{''}$ that comes after the dispersive flux impedance. A minimum current I_{exc} that runs through this branch is needed to excite the core.

A more complete scheme of a real transformer can be seen in the two Figures below 1.2.

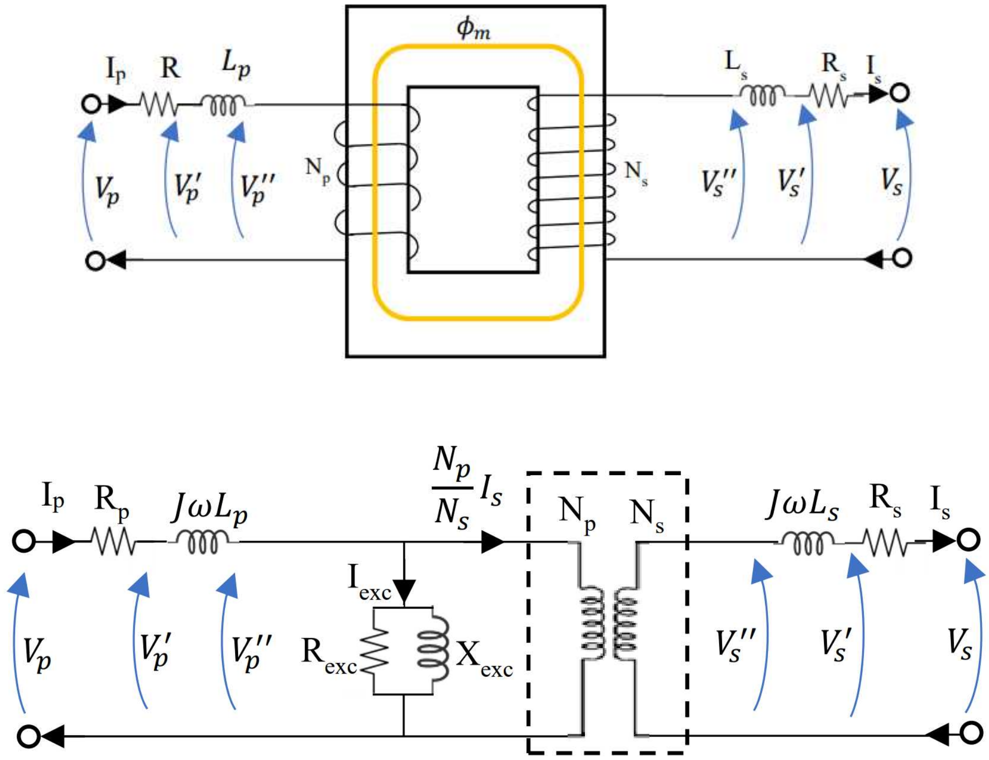


Figure 1.2: Real Power Transformer Representation: [1] Power Transformer model with dispersive flux inductance included

1.2 Generic Transformer Structure

This chapter explores the various components of a Power Transformer. We will analyze the role and function of general modules, to understand how they contribute to the PT structure and reliability. [2]

1.2.1 Core

The core structure and composition are designed to optimize magnetic flux and minimize energy losses. The core is generally made of ferromagnetic materials, with silicon steel being the most commonly used. This material is chosen for its excellent magnetic properties, including high magnetic permeability and low hysteresis losses.

The core is formed from thin laminations, which are layers of magnetic material stacked together. These laminations are insulated from each other to reduce eddy currents, which can cause energy losses and overheating.

Figure 1.3: Metal Laminations

There are different core configurations, including:

- **Three-leg core**: Commonly used in dry-type distribution transformers and larger oil-filled power transformers. This configuration is cost-effective and provides good performance for many standard applications.

- **Five-leg core**: Commonly used for high-capacity transformers with height restrictions, this configuration optimizes magnetic flux management and reduces transformer height, facilitating easier transportation and installation.

Figure 1.4: Three-leg Core

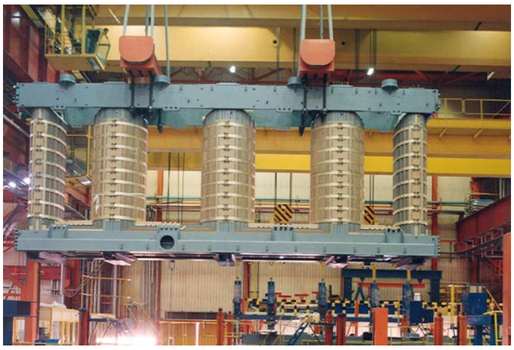


Figure 1.5: Five-leg Core

1.2.2 Tank

The transformer tank serves as a container for the active components and the insulating oil.

During transportation, the tank is subjected to various forces, ensuring the safety and integrity of the transformer. Typically, transformer tanks are constructed from steel sheets, providing durability and strength.

To facilitate access to active parts, the tank is designed with a removable cover that is bolted around the perimeter. This cover allows maintenance and inspection of the internal components. To prevent oil leakage, gaskets are used to create a secure seal between the main cover and the tank, ensuring that the insulating oil remains contained within the tank.

Figure 1.6: Power Transformer Tank

1.2.3 Windings

A special kind of winding conductor is the continuously transposed cable (CTC). This cable is built up of two layers of enamel lacquer insulated strands arranged axially upon each other.

By transposing the outer strand of one layer to the next layer with a regular pitch and applying common outer insulation, a continuous transposed cable is achieved. With an increasing conductor area, the conductor must be divided into two or more parallel conductor elements in order to reduce the losses in the windings and ease the winding work.

At the end, the windings are subjected to a shrinking and seasoning process, so no further shrinkage occurs during service. Adjustable devices are provided to accommodate possible shrinkage in service.

Figure 1.7: Continuously Transposed Cable

1.2.4 Paper insulation

The paper used in transformers is typically kraft paper (thickness 30 to 250 μm), made from unbleached softwood pulp through the sulfate process. This type of paper is chosen for its high dielectric strength and absence of conductive particles.

One of the primary functions of paper insulation is to prevent electrical short circuits between the windings and other conductive parts. By impregnating the paper with oil, a complex structure is created that offers excellent dielectric properties. This combination of paper and oil insulation helps to maintain the transformer's operational integrity and prolong its lifespan.

In addition to electrical insulation, paper insulation also contributes to the thermal management of the transformer. During operation, the core and windings of the transformer generate heat due to power losses. The oil-impregnated paper helps to dissipate this heat, ensuring that the transformer operates within safe temperature limits.

The properties of paper deteriorate under the effects of heat, moisture, oxygen, and impurities; that means that the is subjected to aging. The aging of paper first causes a deterioration of mechanical properties, and a reduction of dielectric strength only afterwards.

Paper aging is one of the main causes of the end-of-life of power transformers.

1.2.5 Mineral Oil & Oil Conservator

The oil in a transformer performs several crucial functions. Its primary role is to provide electrical insulation between the various energized parts. By impregnating paper and cardboard, the oil creates a complex with excellent dielectric properties; additionally, the oil acts as a protective layer to prevent oxidation of metal surfaces inside the equipment.

Another fundamental function of the oil is to improve heat dissipation. The transformer core and windings heat up during operation due to various power losses. The oil absorbs heat from the core and windings through a conduction process, transporting it to the surrounding area where radiators are present to dissipate heat in the atmosphere.

When the oil warms up, it fills the conservator located at the top of the transformer.

Figure 1.8: Conservator

Since the transformer operates at atmospheric pressure, there is a valve that communicates with the outside air. To prevent humidity from entering the transformer, a filter is used to remove moisture from the incoming air.

When the oil heats up and expands, the air is expelled, while when it cools, the air is reinserted inside, filtered for humidity. The transformer is maintained at atmospheric pressure to avoid the risk of overpressure, which could damage the tank over time.

Two oils can be mentioned:

- **Mineral oil**: Mineral oil is the most common type of insulation fluid used in power transformers. It is derived from petroleum and has high dielectric strength, good heat transfer properties, and chemical stability. However, mineral oil is also flammable and can release harmful fumes if it breaks down.
- **Synthetic esters**: Synthetic esters are a type of synthetic oil that is often used in place of mineral oil. They have similar properties to mineral oil, but are less flammable and do not release harmful fumes.

1.2.6 On Load Tap Changer

This device allows for the regulation of transformer voltage without interrupting the energy flow, ensuring a continuous and stable supply of electricity.

The operating principle of the OLTC is based on varying the transformer's turn ratio. This is achieved by selecting different tap points on the transformer's winding side. Each tap point corresponds to a different number of turns, and thus a different output voltage. The ability to change these tap points under load is crucial for maintaining the output voltage within desired limits, despite variations in load or input voltage.

The switching process is designed to minimize interruptions and energy losses. The OLTC uses a system of resistors and switches to manage the current flow during tap changes. In practice, when a tap change is desired, the switch opens the current circuit and inserts a resistor to limit the current flow. Subsequently, the switch closes the new tap circuit and removes the resistor, thus completing the switching process without significant interruptions in the energy flow.

1.2.7 Bushings

Bushings are crucial components in power system networks, primarily responsible for carrying high-voltage current through grounded parts.

The transformer bushing is installed on the top or side of the tank to connect to the external circuit.

There are different types of bushings:

- **Porcelain Insulator Bushings**: Used for transformers up to 11 kV.
- **Oil-Filled Bushings**: Consist of a hollow porcelain cylinder of a specific shape and are used for voltages above 33 kV.
- **Capacitor-Type Bushings**: Covered by porcelain rain sheds and used for voltages above 33 kV.

Figure 1.9: Transformer Bushings

1.3 Peak Efficiency Index

The increasing power of electrical machines has driven a greater demand for efficiency. In addition to this, there is a need to conserve materials and reduce production costs by using efficient materials.

The European Directive 548/2014 [3] outlines the minimum energy efficiency requirements for power transformers with a rated power of at least 1 kVA, used in 50 Hz electricity transmission and distribution networks or for industrial applications. This directive applies to all transformers placed on the market or put into service in the European Union, except those used in special applications, such as safety transformers or those used in industrial environments.

The directive specifies two main requirements:

- Transformers must meet a minimum energy efficiency standard, indicated by the Peak Efficiency Index (PEI). The PEI represents the ratio between the output power and the input power of the transformer, measured at peak efficiency.
- Transformers must be labeled with their energy efficiency rating, denoted PEI. This label must be visible and easily accessible to the user.

Directive 548/2014 is a significant step towards reducing energy consumption and the environmental impact of transformers. It aims to achieve substantial energy savings and reduce air pollution. It is estimated that the directive will result in electricity savings of 16.2 TWh per year by 2025, which corresponds to a reduction of 3.7 million tons of CO_2 emissions.

Rated Power (MVA)	Tier 1 (1 July 2015)	Tier 2 (1 July 2021)
	Minimum Peak Efficiency Index (%)	
≤ 4	99,465	99,532
5	99,483	99,548
6,3	99,510	99,571
8	99,535	99,593
10	99,560	99,615
12,5	99,588	99,640
16	99,615	99,663
20	99,639	99,684
25	99,657	99,700
31,5	99,671	99,712
40	99,684	99,724
50	99,696	99,734
63	99,709	99,745
80	99,723	99,758
≥ 100	99,737	99,770

Figure 1.10: Minimum Peak Efficiency Index requirements for liquid immersed large power transformers

2
Project Presentation

Hitachi Energy is making significant strides towards the sustainability of its products, aligning with the United Nations' Sustainable Development Goals. Their sustainability strategy focuses on achieving carbon neutrality in operations through the "Sustainability 2030" program, which aims to use 100% fossil-free electricity.

In addition, the company is increasingly integrating projects within its research and development departments to follow the sustainability trend. The company has increased investments in R&D to develop innovative technologies that reduce environmental impact and improve energy efficiency. [4]

At the company, I am involved in multiple projects alongside the R&D team. One project, in particular, is the subject of my thesis and can be identified as green, referring to its focus on sustainability.

In the following sections, I will provide a detailed explanation, outlining Its objectives, methodologies, and the results we aim to achieve.

2.1 CO2 Calculation in EDS

The continuous requests from customers for an environmental impact assessment associated with Power Transformer orders are leading Hitachi Energy to reassess its position and interest in tools and methodologies that can meet these demands.

So far, a comprehensive analysis of the environmental impact of a power transformer was not included in the technical specifications of customers and was always very limited, even when requested by major companies. In these cases, such technical specifications were addressed in collaboration with external companies, which, after a very detailed analysis of all life processes (cradle to grave)* of the PT, produced an official document called Environmental Product Declaration (EPD), certified by a Certification Body.

It involves studying the impact of the individual materials used, their transportation, and decommissioning, the emissions during the PT's life related to losses, the energy used in the company for its construction, and much more. The idea for the future is to have complete autonomy in this aspect as well.

This has led Hitachi Energy, with the sustainability team, to develop and refine a tool that allows the calculation of the Life Cycle Assessment (LCA) of a PT in all fields without relying on external companies; its name is EcoSmart.

EcoSmart has not yet received an official status as it is new and constantly evolving; however, it provides an accurate estimate of the LCA as the calculation is based on reliable and certified databases.

The project goal is to integrate a section for calculating CO_2 emissions estimates into the company's internal design tool (EDS) so that the designer can obtain this value in $kgCO_2e$ at any electrical design stages†, divided into macro categories. This would enable the client to obtain a detailed estimate of the overall CO_2 impact of the PT during the quotation phase and so before the official EPD realization. This allows for a critical evaluation of various design alternatives; for instance, opting for a more expensive design with a lower environmental impact would mean a higher initial investment but lower CO_2 emission costs in the long run.

Direct integration of EcoSmart is currently not feasible because, being continuously updated, it would not ensure logistical stability. Therefore, a more direct manual calculation method has been adopted.

In the following chapters, the topics mentioned will be addressed in more detail with examples and results obtained.

*Cradle-to-grave is the full life cycle assessment from resource extraction ('cradle') to the use phase and disposal phase ('grave'). [5]

†The electrical design stages can be seen in 5.1.2

3

Introduction of Main Actors

3.1 Circular Economy

The concept of circular economy (CE) develops along two main lines: the flow of materials and the economic conditions that favor this flow. These ideas, which emerged in the 1960s and 1970s, are closely linked to the environmental movement and have profoundly influenced ecological and industrial thinking.

In the 1970s, a closed industrial system was proposed, where waste was reused as resources, anticipating the modern idea of a circular economy. This regulatory approach emphasized the importance of designing products that facilitate recycling and reuse. A future was envisioned where the concept of waste did not exist, as every material would be reused in a continuous cycle. It also highlights the need to care about sustainable economics for both ethical and practical reasons.

It was anticipated that issues related to pollution and resource depletion were expected to be not just future concerns but require immediate attention. This thinking is the foundation of the concept of sustainable development. [6]

The main goal of CE is to slow down the depletion of scarce natural resources, reduce environmental damage from the extraction and processing of virgin materials, and reduce pollution associated with the processing, use, and end-of-life of materials.

The means to achieve the circular economy and gain substantial economic and environmental benefits are:

- **Increasing resource efficiency and productivity:** Reduced amount of material disposed. [7]
- **New business models:** These must be part of a systemic perspective on resource use, incorporating closed supply chains, regenerative design, and reverse logistics to extend product life and maintain material value for longer periods. [7]
- **Financial sustainability:** Business models must be financially sustainable and supported by public policies and changes in the corporate organization. [7]
- **Importance of indicators:** Indicators are fundamental to guide and review CE policies. The choice of indicators is crucial as it determines the behavior of a system. Indicators have two main purposes: providing guidance and feedback to review performance. Therefore, quantitative indicators are necessary to guide and review CE policies. [7]

The exploratory analysis of the literature on CE identifies and examines key concepts in the field, including closed supply chains, blue economy, and regenerative design.

The blue economy emphasizes local and sustainable solutions, resource optimization, and the creation of multiple revenue streams. It posits that the local environment, with its unique ecological characteristics, should serve as the foundation for sustainable solutions. It aims to protect the global ecosystem while generating new job opportunities and addressing social issues. Regenerative design, grounded in systems theory, seeks to create products and services that can be renewed and revitalized. It focuses on establishing a framework for communities to operate using locally available renewable resources without depleting them, while also minimizing unnecessary transportation efforts. Closed supply chains underscore the importance of circularity through the reuse and recycling of products. This concept explores how governance and coordination mechanisms can facilitate or impede the development of circular systems. Closed supply chains encompass both direct and reverse supply chains, where producers employ a combination of reuse options based on the most profitable alternatives. [8]

Circular economy business models are categorized into two groups: those that promote reuse and life extension through repair, refurbishment, upgrades, and retrofitting; and those that transform old goods into new resources through material recycling. Ownership gives way to stewardship; consumers become users and creators. The repair and refurbishment of old goods, buildings, and infrastructure create skilled jobs in local workshops.

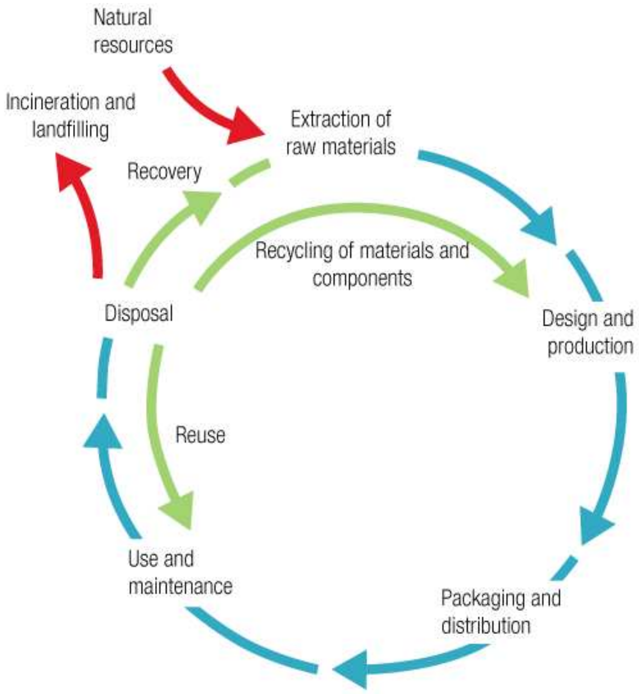


Figure 3.1: Circular Economy Iterative Process.

The concept of CE has been slow to gain traction due to unfamiliarity and fear of the unknown. It also faces challenges from the siloed structures of academia, businesses, and administrations. However, concerns about resource security, ethics, and greenhouse gas reduction are shifting our approach to materials, viewing them as assets to be preserved rather than continuously consumed.

In conclusion, CE represents a formidable yet necessary challenge to transform the competitiveness of a nation. Shifting the focus from environmental protection policies to business models based on full ownership and responsibility could revolutionize the economy, promoting long-term sustainability and resilience. [9]

3.2 Sustainability Emission Levels in the Supply Chain

To better understand how a company impacts in terms of emissions is important face in the first path where they come from and their representation. Firstly, we need to split the CO2 emissions in order to make a clear subdivision:

- **Scope 1 emissions:** are direct greenhouse gas emissions from sources owned or controlled by the company. These include on-site energy use, such as natural gas and fuel, refrigerants, and emissions from combustion in boilers and furnaces owned or controlled by the company. In addition, emissions from fleet vehicles, such as cars and trucks. Process emissions released during industrial processes and on-site production, such as factory fumes and chemicals, are also included. [10]

- **Scope 2 emissions:** are indirect greenhouse gas emissions from purchased or acquired energy consumed by the company. These include electricity, steam, heat, and cooling generated off-site. These emissions are considered indirect because the energy is generated off-site but consumed by the company. [10]

- **Scope 3 emissions:** are all indirect emissions that occur within a company's value chain. These emissions are divided into two main categories: upstream and downstream*. Upstream emissions include indirect emissions related to purchased or acquired goods and services, generated from cradle to gate. These emissions cover purchased goods and services, capital goods, fuel and energy-related activities, upstream transportation and distribution, and waste generated in operations. Downstream emissions include indirect emissions related to goods and services sold and emitted after they have left the company's ownership or control. These emissions cover downstream transportation and distribution, processing of sold products, use of sold products, end-of-life treatment of sold products, downstream leased assets, franchises, and investments. [10]

*Upstream emissions are indirect emissions generated from the company's supply chain activities, such as the production of raw materials and the transportation of fuels. Downstream emissions are indirect emissions that occur after the company's products have left its control, such as the use of sold products and their end-of-life treatment.

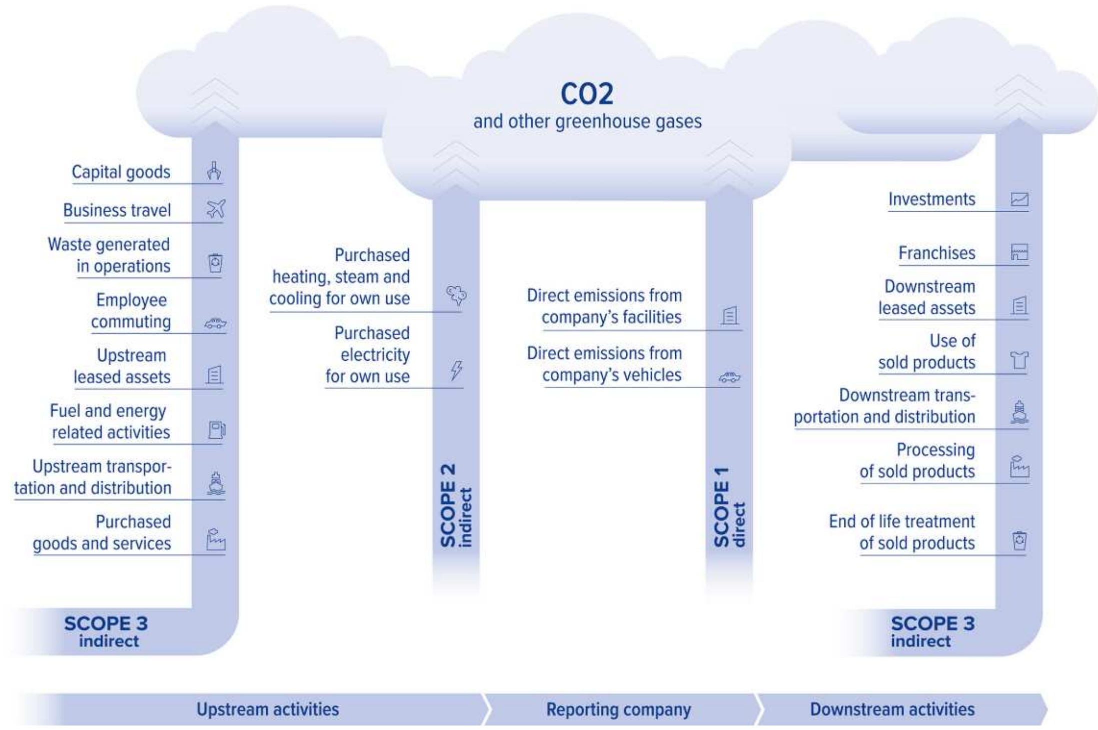


Figure 3.2: Overview of GHG Protocol scopes and emissions across the value chain.

3.3 Eco-design for Sustainable Product Regulation

The Eco-design for Sustainable Products Regulation (ESPR), which came into force on 18 July 2024, represents a significant evolution in European legislation. This regulation replaces Directive 2009/125/EC, significantly expanding the scope and eco-design requirements for products placed on the EU market.

Unlike the previous Directive, which applied exclusively to energy-related products, the ESPR covers almost all physical products, with a few exceptions such as food, feed and medicinal products. This expanded scope is essential to address the overall environmental impact of products.

The Regulation sets out a series of eco-design requirements that products must meet to be placed on the EU market. Products must be designed to last longer and be easily repairable, using fewer natural resources and facilitating recycling. Manufacturers must provide clear and transparent information about the environmental characteristics of their products.

One of the central elements of the Regulation is the introduction of the Digital Product Passport. This informational tool collects and provides key data related to product composition, environmental impacts, repair and recycling options, and traceability. This passport aims to facilitate the transition to a more circular system by improving product lifecycle management and making information accessible to all economic operators.

In the first half of 2025, the European Commission will adopt the first ESPR working plan, setting out which products will be prioritized over the coming years. [11]

4

Environmental Impact Documentation

The increasing use of electrical products has had a significant environmental impact. From production to disposal, electrical products contribute to various forms of pollution and resource consumption. This chapter will explore the main environmental documentation associated with electrical products, analyzing the stages of their life cycle and their ecological implications.

Furthermore, at the end of the chapter, there will be a section dedicated to examples of Environmental Product Declarations carried out in Hitachi Energy Monselice.

4.1 Life Cycle Assessment

Life Cycle Assessment (LCA) evaluates the impacts of a product throughout its life cycle, from raw material extraction to production, distribution, use, maintenance and disposal or recycling. The objective is to identify both the negative and positive aspects of a product or service. LCA is standardized in the ISO 14040 series and comprises four interdependent phases: definition of the objective and scope, inventory analysis, impact assessment, and interpretation of results. [12]

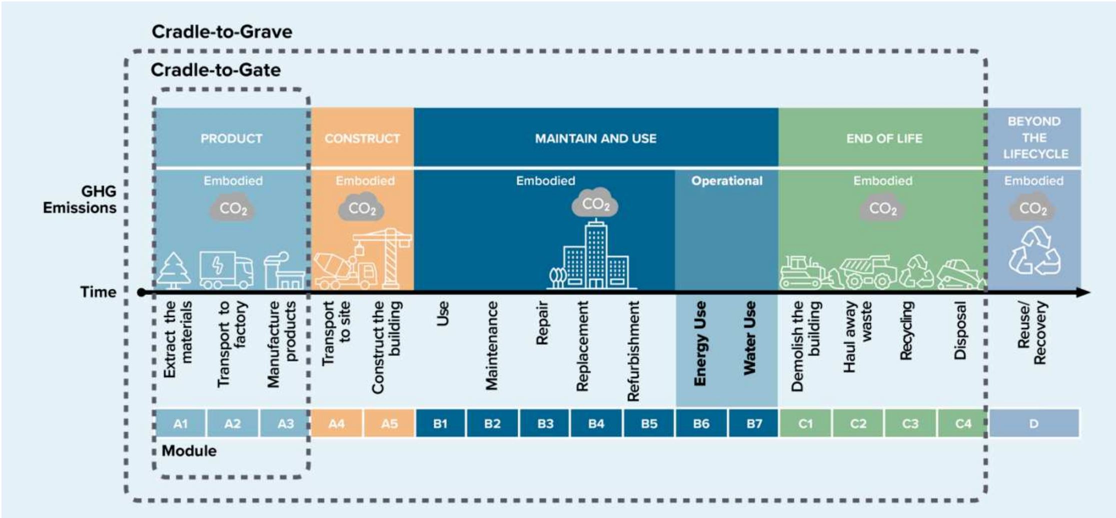


Figure 4.1: Life cycle stages and corresponding information modules for construction materials and products.

4.1.1 History

LCA has its roots in the 1960s and 1970s, when early energy analyzes evolved to include resource requirements, emissions, and waste. During this period, LCA was characterized by divergent approaches and a lack of a common theoretical framework.

In the 1990s, LCA saw a significant growth in scientific and coordination activities. Organizations such as the Society of Environmental Toxicology and Chemistry (SETAC) and the International Organization for Standardization (ISO) played a crucial role in standardizing LCA methodologies. This period led to the definition of a general methodological framework and the production of numerous guides and manuals.

The first decade of the 21st century saw increasing attention towards LCA, with initiatives such as the Life Cycle Initiative launched by UNEP and SETAC in 2002. LCA became a fundamental component of environmental policies worldwide, with applications ranging from building materials to military systems and tourism.

The Life Cycle Initiative aimed primarily to put life cycle thinking into practice and improve support tools through better data and indicators. Life cycle thinking continued to grow in importance in European policy, as evidenced, for example, by the European Commission's Communication on Integrated Product Policy (IPP).

In addition, life cycle thinking was incorporated into thematic strategies on the sustainable use of resources and waste prevention and recycling. [13]

4.1.2 LCI, LCIA, LCO: Key Players for an Effective LCA

A **Life Cycle Inventory (LCI)** involves quantifying the energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases throughout the entire life cycle of a product, process, or activity. This inventory analysis generates a comprehensive list detailing the quantities of pollutants released into the environment (post-treatment or control) and the amounts of energy and materials consumed. The results can be categorized by life cycle stage, environmental medium (air, water, and land), specific processes, or any combination thereof.

During the LCI phase of an LCA, all relevant data are collected and organized. Without an in-depth LCI, there is no foundation for evaluating comparative environmental impacts or identifying potential improvements. The precision and detail of the collected data significantly influence the subsequent phases of the LCA process. [14]

The **Life Cycle Impact Assessment (LCIA)** converts LCI into impacts. This process helps interpret the assessment by translating these emissions and resource extractions into environmental impact scores. The criteria for including life cycle impact categories were chosen based on their relevance to the analyzed systems. There are various LCIA tools (e.g., TRACI, ReCipe, USEtox *), and the choice of environmental categories depends on the LCIA tools used. [16]

Below is a detailed description of the main metrics used:

- **Cumulative Energy Demand (CED)**: This metric measures the total energy consumed over the entire life cycle of a product, including end-of-life waste management. CED considers all energy sources, both renewable and non-renewable, used to produce, distribute, use, and dispose of the product.
- **Cumulative Fossil Energy Demand (CFED)**: CFED is a subset of CED and focuses on fossil fuel-based energy consumed during the product's life cycle. It includes energy derived from coal, oil, and natural gas.

*USEtox is a scientific consensus model endorsed by UNEP's Life Cycle Initiative for characterizing human and ecotoxicological impacts of chemicals. [15]

- **Cumulative Renewable Energy Demand (CRED)**: CRED is another subset of CED and measures the renewable energy used during the product's life cycle. It includes energy sources such as solar, wind, hydroelectric, geothermal, and biomass.
- **Global Warming Potential (GWP)**: Also known as carbon footprint, GWP measures the impact of climate change in terms of greenhouse gas emissions, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). GWP is expressed in CO_2 equivalents.
- **Ozone Depletion Potential (ODP)**: ODP measures the effect of gas emissions that deplete stratospheric ozone, such as chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs). Stratospheric ozone protects life on Earth from harmful ultraviolet (UV) rays.
- **Acidification Potential (AP)**: AP measures the effect of acidic gas emissions, such as sulfur oxides (SOx) and nitrogen oxides (NOx), which can acidify water and soil.
- **Eutrophication Potential (EP)**: Also known as nutrification potential, EP measures the effect of nutrient emissions, such as phosphorus and nitrogen, which can cause excessive algae growth in water bodies.
- **Photochemical Ozone Creation Potential (POCP)**: POCP measures the effect of emissions of volatile organic compounds (VOCs) and nitrogen oxides (NOx) that can form tropospheric ozone (photochemical smog) in the presence of sunlight.
- **Consumptive Water Footprint and Water Emissions Footprint**: These metrics describe the total amount of water required during the product's life cycle, including end-of-life waste management.
- **Eco and Human Toxicity Assessment**: The assessment of environmental and human toxicity uses models such as the USEtox™ model to quantify the environmental fate of chemical emissions and their impact on human health and ecosystems.
- **Direct Land Use Change (LUC)**: This metric evaluates the impact of direct land conversion from its original state (forest, grassland, pasture, cropland, degraded land, etc.) to an altered state for the production of agricultural or forest products.

- **Indirect Land Use Change (ILUC)**: This metric evaluates the impact of indirect land use change, which occurs when a primary land use change displaces a commercial crop, which is then grown in another location, leading to further land changes.

[12]

At the end the **Life Cycle Optimization (LCO)** is a critical methodology to improve system sustainability by integrating environmental, economic, and social considerations into decision-making processes. The primary goal is to minimize environmental impacts while maximizing economic and social benefits. This approach requires a comprehensive understanding of the entire life cycle of a product, from raw material extraction to end-of-life disposal. [17]

LCO has been applied in various sectors to improve sustainability. Some notable applications include:

- **Supply Chain Optimization**: Integrating LCA with supply chain optimization helps create supply chains that are both economically efficient and environmentally sustainable. This integration addresses inconsistencies in scope and data transfer, leading to more accurate and effective decision-making. [18]

- **Energy Systems**: LCO is used to optimize the design and operation of energy systems, including renewable energy sources. By considering the entire life cycle of energy production, from resource extraction to energy generation and distribution, LCO helps minimize environmental impacts and costs. [19]

- **Product Design**: In product design, LCO helps identify materials and processes that reduce environmental impacts while maintaining product performance and cost-effectiveness. This approach is essential for developing sustainable products that meet consumer demands and regulatory requirements. [20]

4.1.3 Uncertainties

Like many decision support tools, uncertainties † are often not considered in Life Cycle Assessment studies, even though they can be significant. However, it is necessary to analyze the uncertainties involved in conducting an LCA study to focus research efforts and support the interpretation of LCA study results.

In LCA, we can distinguish the following sources of uncertainty:

- **Data**: for example, the electricity used in a boiler, CO_2 emissions from a coal power plant, and the GWP of nitrous oxide.
- **Choices**: for example, system boundaries, allocation principles, and the time horizon in impact assessment.
- **Relationships**: for example, the linear dependence of distance traveled on fuel consumption, the linear dependence of acidification on SO_2 emissions, and the discount formula used for long-term impacts.

In Life Cycle Assessment (LCA), we can identify several sources of uncertainty that can impact the results and interpretations of the study.

First, there are uncertainties related to the data. This includes, for example, the amount of electricity consumed by a boiler, the emissions of CO_2 from a coal-fired power plant, and the Global Warming Potential (GWP) of nitrous oxide. These data points are crucial for the accuracy of the LCA, and any variability or errors in these measurements can lead to significant uncertainties in the final results.

Secondly, we have uncertainties arising from choices made during the LCA process. These choices include defining the system boundaries, selecting allocation principles, and determining the time horizon for impact assessment. Each of these decisions can influence the outcome of the LCA, and different choices can lead to different results.

Lastly, there are uncertainties related to relationships within the LCA model. For instance, the relationship between the distance traveled and fuel consumption is often assumed to be linear, as is the relationship between acidification potential and SO_2 emissions.

† Uncertainty can be defined in many ways, but a useful definition in the current context is: ”the discrepancy between a measured or calculated quantity and the true value of that quantity.” [21]

Furthermore, the discount formula used to account for long-term impacts introduces another layer of uncertainty. These relationships are based on assumptions and simplifications that may not always be true in real world scenarios.

Understanding and addressing these sources of uncertainty is essential for improving the reliability and robustness of LCA studies. [22]

In conclusion, to facilitate systematic uncertainty analysis, the standardization of uncertainty information is necessary. The existence of the ISO standard for expressing uncertainties (the Guide to the Expression of Uncertainty in Measurement, or GUM) seems to have escaped the attention of those who designed, for example, the ISO standards for LCA. The reporting of uncertainties in data sources and LCA results is likely to improve significantly if the LCA community adheres to the principles outlined in GUM. [23]

4.2 Environmental Product Declaration

Over the past few years, a large number of environmental labels and certifications have emerged from various sectors. This development aims to provide enterprises with a credible and comprehensive tool to demonstrate their environmental efforts to stakeholders (customers, public institutions, local communities, etc.) and consequently gain a competitive advantage. Indeed, environmental issues are rapidly becoming one of the most important topics for strategic planning due to growing public awareness. [24]

An Environmental Product Declaration (EPD) is a standardized document that provides transparent, objective, and third-party verified information about the environmental impact of a product throughout its life cycle.

EPDs are based on the ISO 14025 standard and are derived from comprehensive Life Cycle Assessments, which evaluate the environmental effects of raw material extraction, production, use, and disposal. These declarations are crucial for businesses aiming to demonstrate their commitment to sustainability and consumers who want to make informed choices. EPDs include data on various environmental indicators such as global warming potential, resource consumption, and emissions. Although EPDs do not certify a product as environmentally superior, they offer a valuable tool for comparing the environmental performance of products within the same category, thus facilitating more sustainable decision-making. [25]

4.2.1 EPD Types

Environmental labels can be categorized into three types: Type I, Type II, and Type III. Each type has distinct characteristics and standards, primarily defined by the ISO (International Organization for Standardization).

Type I: Environmental Labels

Type I environmental labels are governed by ISO standard 14021. This standard outlines the selection of specific products or product categories, the environmental criteria for these products, their functional features, evaluation methods, and certification procedures. To ensure high credibility, these programs must be supported by an independent accredited board and adhere to clear rules.

One of the main strengths of the European Ecolabel is its European dimension, which allows it to be used across the entire European Union, as well as in Norway, Iceland, and Liechtenstein. In addition, the criteria for each category are regularly reviewed to ensure they remain up-to-date and relevant. Another positive aspect is that the Ecolabel has been extended to services, thanks to Regulation 1908/2000.

However, the European Ecolabel also has some weaknesses. The complexity of defining criteria for a product category can take several years, making the process long and laborious. The costs, both direct and indirect, are high, which can be a barrier for many companies. Furthermore, only 20-30% of products manage to obtain the label, limiting access to this recognition. Another issue is the inability to differentiate between two products that have the same label, which can create confusion among consumers. Finally, the bureaucratic structure managing the label is often rigid and cumbersome, making the management process less efficient. [24]

Type II: Self-Declared Environmental Claims

ISO standard 14021 describes self-declared environmental claims as "environmental declarations made without certification from an independent third party, by manufacturers, importers, distributors, retailers, or any other entity able to gain benefit from this declaration".

This standard establishes that the goal of voluntary ecological labeling is to make environmental claims more precise, promote environmental improvements, reduce inaccurate claims, decrease confusion, facilitate international trade, and allow consumers to make well-informed choices.

In this context, there are no minimum environmental values to respect, and each company has the freedom to decide what to communicate and what not to communicate.

However, a product made from recycled material might have a greater environmental impact than another product made from virgin material, due to the energy used to collect, clean, and process the recycled material. In such a case, the product labeled ”made from recycled material” could be worse for the environment. The same could apply to products that use a significant amount of energy during their use phase and carry labels such as ”extended life” or ”designed for disassembly.” In these cases, the most significant life cycle phase might be ignored, and the product could still carry an environmental label.

It is very simple for a company to develop a label; in fact, there are few data to collect and few administrative steps. [24]

Type III: Environmental Declarations

Type III environmental declarations are governed by ISO standard 14025. This standard involves predefined criteria and quantification of potential environmental impacts across a product's life cycle using the Life Cycle Assessment (LCA) method. These impacts are then validated by an independent board to ensure accuracy and reliability.

The main goal of the Environmental Product Declaration (EPD) is to provide verifiable and accurate information about the environmental aspects of products and services. This helps encourage continuous environmental improvement driven by market forces. It also allows for fair comparisons between products based on their environmental performance, reflecting ongoing improvements over time.

Transparency is another crucial principle, with a focus on demonstrating openness throughout the development and operational stages of the EPD. The programs are accessible to all applicants who meet specific data requirements, and they are based on sound scientific and engineering approaches to maintain their scientific character.

Confidentiality is also maintained for all identified confidential information.

Currently, the EPD system has national validity, meaning it is recognized within individual countries. For example, in Italy, the system is managed by an independent body such as ANPA (Agenzia Nazionale per l'Ambiente), which is responsible for providing general guidelines.

The process for companies or organizations preparing an EPD involves several steps. First, they need to define product-specific requirements. Then, they collect and calculate LCA-based information. This information is compiled into an EPD report, which undergoes verification and registration to ensure its accuracy and reliability.

In conclusion, the EPD system provides a structured and reliable way for companies to communicate the environmental performance of their products, fostering transparency and continuous improvement in environmental practices. [24]

4.2.2 Structure

An EPD consists of three main sections. The first section is quite straightforward, providing descriptions of the product and the manufacturer. It may also include the functional unit, which is the unit to which all calculations are referred. This unit reflects the actual function of the product and can be mentioned here or in the second section.

The core of an EPD is found in the second section, which details the environmental performance of the product. This section is based on a LCA, meaning it considers all processes from resource extraction and raw material refining to transportation and final production. Most EPDs present significant air and water emissions both as inventory data and as potential impacts on various environmental categories, such as GWP. Resource consumption is divided into non-renewable and renewable resources, and additionally, EPDs might include information on the environmental impact of typical transportation to the customer.

The third section contains information from the company and the accredited certification body. This includes the name and address of the company contact person and the certification body, the validity period of the certification, and relevant references. [26]

We will be able to see an example of transformer's EPD in the next chapter.

4.2.3 The Role of EPD Databases in Sustainable Development

The concept of sustainable development has received significant attention due to the high rate of global resource utilization, such as energy, water, forests, and raw materials. The electrical sector contributes to environmental emissions and resource usage. Consequently, the shift from green energy to sustainable energy impacts sustainability assessment tools, including EPD databases.

EPD databases are crucial for enhancing the sustainability assessment process, providing high-quality data for informed decision-making and reducing the industry's contribution to climate change. These databases are publicly accessible platforms where every companies can upload and share their certified Environmental Product Declarations. This transparency allows sustainability professionals, engineers, consumers, policymakers, and other stakeholders to make informed decisions based on verified environmental impact assessments. By making EPDs publicly accessible, these platforms facilitate the dissemination of essential environmental information.

Among these platforms, EPDItaly stands out as a key player, offering a unified source of EPDs that cover various sectors across the nation.

4.3 Product Category Rules

Product Category Rules (PCR) are a fundamental element in the process of creating Environmental Product Declarations; they establish the rules and guidelines that must be followed to ensure that EPDs are comparable and transparent.

PCRs are standardized documents that describe how to conduct a life cycle assessment for a specific product category. These documents include detailed instructions on various aspects, such as system boundaries, the declared functional unit, the life cycle stages to be considered, and environmental impact categories to be assessed.

PCRs are essential to ensure that similar products are consistently evaluated. This allows transparent comparison of the environmental performance of different products within the same category. PCRs are an integral part of the ISO 14025 standard, which promotes transparency and comparability among EPDs.

A typical PCR includes:

- **System boundaries**: Defines which processes and life cycle stages of the product must be considered.
- **Functional unit**: Specifies the quantity, weight, and duration of service of the evaluated product.
- **Life cycle stages**: Describes how to define the use phases and end-of-life options of the product.
- **Impact categories**: Lists the environmental impact categories that must be assessed, in addition to those described in the general program instructions (GPI).

By following the guidelines established by PCRs, companies can evaluate and transparently communicate the environmental performance of their products, thus contributing to a more sustainable and informed market. [27]

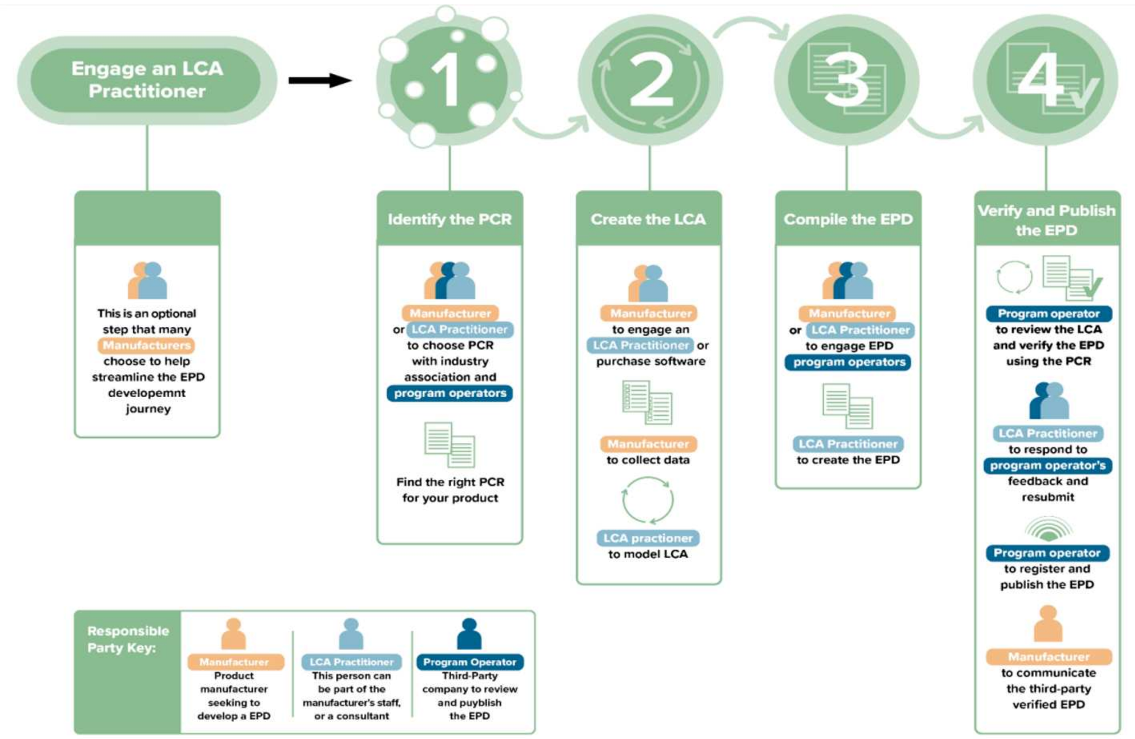


Figure 4.2: Key steps to develop an EPD and the responsible parties involved.

4.4 Hitachi Energy Evaluating EPDs Process

As previously mentioned, the increasing interest in product-related environmental impact documentation in recent years has also affected Hitachi Energy in the field of power transformers. More and more clients, primarily multinational corporations, are becoming increasingly interested in studying their environmental impact, including the products they purchase. This trend has led to a demand for detailed documentation that includes all the key factors necessary for a proper and certified Life Cycle Assessment.

To date, Hitachi Energy has collected two Environmental Product Declarations in 2021 for two groups of four transformers each: ”Mineral oil immersed transformers (25 MVA)” and ”Mineral and vegetable oil immersed transformers (40 MVA)”. These EPDs can be reviewed by anyone on the EPDItaly website.

The process of creating such documentation is highly systematic and requires the involvement of multiple stakeholders, each essential for the proper execution of individual tasks.

For an EPD to be globally recognized, it is mandatory that the document be certified by a third party. Currently, Hitachi Energy does not have the license to create a certifiable LCA and has therefore relied on a consulting firm that specializes in sustainability strategies for businesses called Spinlife.

Spinlife created LCA outputs with Hitachi using SimaPro, a leading software tool for conducting Life Cycle Assessments (LCAs). SimaPro leverages the Ecoinvent database to track life material trends and all related environmental factors.

This comprehensive approach ensures that the LCAs not only follow material trends but also account for various multiplication factors across environmental fields, resulting in accurate and detailed assessments.

After completing the EPD in strict accordance with the procedure, it was certified by a third-party organization called the General Society of Surveillance (SGS), specifically SGS Italy.

SGS Italy is identified as the ”Certification Body” (CB), and conducted inspections to Hitachi Monselice to verify the manufacturing processes and checked all the data given to Spinlife. This process is mandatory to obtain the certification.

It is important to choose a reputable CB with experienced auditors approved by a ”National Accreditation Body” (NAB).

A NAB is designated by a country's government to assess and accredit conformity assessment bodies, such as testing and calibration laboratories, certification bodies, and inspection bodies. NABs ensure these bodies meet international standards and are competent to carry out specific tasks and services. There is an NAB in every European country; in Italy there is Accredia.

In the end, these EPDs, after certification by the third party SGS, have been published in EPDItaly, as mentioned before.

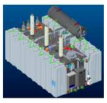
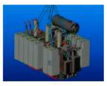
	Mineral and vegetable oil immersed transformers (40 MVA)	Hitachi Energy Italy S.p.A.	EPDITALY0319	Trasformatori	2021
	Mineral oil immersed transformers (25 MVA)	Hitachi Energy Italy S.p.A.	EPDITALY0318	Trasformatori	2021

Figure 4.3: Mineral oil immersed transformers (25 MVA) and Mineral and vegetable oil immersed transformers (40 MVA) in the EPDItaly website.

The public database of EPDItaly is not only used for uploading EPDs related to power transformers but also for a wide range of products and sectors, including ceramics, chemicals, medical devices, photovoltaic modules, and much more. In fact, you can find EPDs for electrical products uploaded by competitors such as Tamini, Getra Power and Siemens Energy.

Table 4.1: Characters definitions

EPDItaly	Is a key program operator in Italy, promoting environmental transparency and sustainability through Environmental Product Declarations (EPDs). It helps companies communicate the environmental performance of their products and supports international visibility. [28]
SpinLife	It offers Life Cycle Assessments to evaluate environmental impacts throughout a product's life cycle and develop EPDs for transparent and comparable information about product environmental impacts. [29]
SimaPro	Is a software tool that provides access to extensive life cycle inventory data and advanced features for comprehensive environmental assessments. It supports studies like product carbon footprint and much more. [30]
Ecoinvent	is a globally recognized database offering comprehensive LCI data. It is essential for LCA to understand the environmental impacts of products and services. The database includes over 20,000 datasets across various sectors, enabling users to trace environmental impacts throughout the supply chain. [31]
SGS Italy	Is a branch of SGS, a global leader in testing, inspection, and certification services across various industries, including agriculture, life sciences, consumer goods, environmental services and much more. It provides laboratory testing to ensure product quality and safety, conducts inspections to verify compliance and condition, and offers certification services recognized worldwide. [32]
Accredia	Is the Italian National Accreditation Body, responsible for accrediting certification, inspection, and verification bodies, as well as testing and calibration laboratories. It ensures the competence, independence, and impartiality of these bodies. Operating under the supervision of the Italian Ministry of Economic Development, Accredia is recognized as the sole NAB in Italy. [33]

5

CO_2 Calculation Integrated into Hitachi Energy Electrical Design System

As previously discussed, I have studied the key elements that connect companies, particularly Hitachi Energy Monselice, to the sustainable practices they aim to adopt in PT.

In this chapter, I will delve into the evolution of this project over the past months. I will begin by analyzing the existing tools, identifying the problems encountered, and presenting the results with illustrative examples. Finally, I will outline the future tasks that need to be addressed to further enhance the project's development.

5.1 Tools Analysis

In the following sections, I will discuss two essential tools developed by Hitachi Energy that have significantly supported the projects I am currently working on. These tools, which are proprietary and not open source, have been instrumental in enhancing efficiency and achieving project milestones.

5.1.1 EcoSmart

EcoSmart is a recently developed tool by Hitachi Energy, reflecting the company's commitment to the growing trend of sustainability. This tool is globally used by the sustainability team to achieve accurate calculations of the Life Cycle Assessment for specific power transformers.

The primary purpose of EcoSmart is to inform product design and tendering processes with a preliminary assessment of the environmental life cycle impacts and eco-efficiency of transformer solutions throughout their life cycle.

For conducting a comprehensive LCA study, a more detailed Bill of Materials and further modeling of the life cycle inventory by a qualified life-cycle analysis expert is required.

EcoSmart is based on life-cycle modeling in accordance with ISO 14040 and ISO 14044 standards on environmental life cycle assessment, as well as the applicable Product Category Rules of the International EPD System.

The tool evaluates energy and resource consumption, as well as environmental emissions, from all life cycle stages of transformer solutions.

These stages include:

- **Upstream processes**: Production and transportation of materials and parts to manufacturing sites.
- **Core processes**: Manufacturing, assembly, and testing.
- **Downstream processes**: Transportation to customer sites, product use and maintenance, and end-of-life.

The impact assessment conducted by EcoSmart is based on life cycle models created with inventory data from the Ecoinvent database and data from the supply chain. This comprehensive approach ensures that all aspects of the transformer life cycle are considered, providing a thorough understanding of its environmental impact.

In addition to its primary functions, EcoSmart also offers several advanced features:

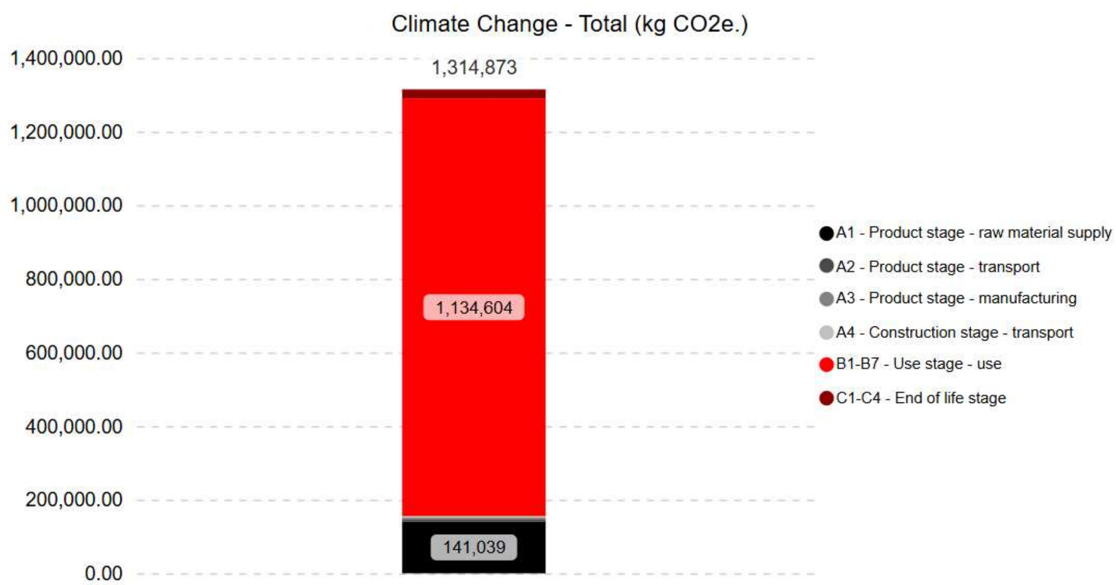
- **Scenario Analysis**: Allows users to compare different design and operational scenarios to identify the most sustainable options.

- **Real-Time Data Integration**: Incorporates real-time data from the supply chain and manufacturing processes to enhance the accuracy of the LCA.

- **User-Friendly Interface**: Designed with an intuitive interface that makes it accessible to both experts and non-experts in life cycle assessment.

By using these features, EcoSmart not only supports Hitachi Energy's sustainability goals but also empowers other stakeholders in the industry to make informed decisions that contribute to a more sustainable future.

As we can see in Fig. 5.1 most of the parameters present in an official LCA can be found.



Environmental Impact Categories	Material Supply (A1-A2)	Manufacturing Stage (A3)	Distribution to Customer (A4)	Use & Maintenance (B1-B7)	End of Life (C3-C4)	Total
Abiotic Depletion (ADP elements) (kg Sb eq.)	6.64E+001		1.47E-002	0.00E+000	0.00E+000	6.64E+001
Abiotic Depletion (ADP fossil) (MJ)	2.23E+006		6.57E+004	0.00E+000	1.63E+004	2.31E+006
Acidification Potential (kg SO2 eq)	5.50E+003		2.18E+001	0.00E+000	1.48E+001	5.54E+003
Climate Change - Biogenic (kg CO2 eq.)	5.44E+003		5.64E+001	0.00E+000	8.13E+002	6.31E+003
Climate Change - Fossil (kg CO2 eq.)	1.42E+005	3.38E+003	4.67E+003	1.13E+006	2.38E+004	1.31E+006
Climate Change - Land Use and Land Use Changes (kg CO2 eq.)	2.07E+002		1.67E+001	0.00E+000	5.64E-001	2.25E+002
Climate Change - Total (kg CO2 eq.)	1.48E+005	3.38E+003	4.74E+003	1.13E+006	2.46E+004	1.31E+006
Eutrophication, Freshwater (kg PO4 eq.)	4.44E+002		3.85E-001	0.00E+000	1.32E+000	4.45E+002
Eutrophication, Marine (kg N eq.)	3.78E+002		8.39E+000	0.00E+000	4.52E+000	3.91E+002
Eutrophication, Terrestrial (Mole of N eq.)	4.27E+003		8.85E+001	0.00E+000	7.18E+001	4.43E+003
Non Renewable Primary Energy Resources (MJ)	2.40E+006		6.68E+004	0.00E+000	1.53E+004	2.49E+006
Ozone Depletion Potential (kg R11 eq.)	2.50E-003		8.12E-005	0.00E+000	-2.31E+000	-2.31E+000
Photochemical Ozone Formation Potential (kg NMVOC eq.)	1.55E+003		3.02E+001	0.00E+000	2.09E+001	1.60E+003
Renewable Primary Energy Resources (MJ)	2.87E+005		1.02E+003	0.00E+000	-2.51E+002	2.88E+005
Water Use (m3 world eq.)	4.53E+007		1.63E+005	0.00E+000	4.31E+004	4.55E+007

Figure 5.1: Example of EcoSmart output interface of a transformer: 36MVA, Load losses 176kW, France electricity mix during operation, Lifetime 40 years, Average load during life-time 40%.

5.1.2 Electrical Design System (EDS)

In the context of PT design and production, Hitachi Energy has developed an advanced calculation tool called EDS (Electrical Design System). This tool is essential to ensure that transformers not only meet the technical specifications required by customers but also comply with international standards (IEC 60076) and Hitachi Energy's internal standards. The EDS tool is divided into two main areas: electrical design and verification through simulation of the required tests.

Electrical Design:

The electrical design phase of the EDS tool includes all the necessary aspects for the design of windings, the active part, and the main insulation of transformers.

During the design process, various parameters are considered, including:

- **Windings**: The design of the windings is essential to determine the transformer's capacity to handle the electrical load. The EDS tool allows for the optimization of winding design to improve efficiency and reduce losses. The tool provides a concrete idea of the actual weights and dimensions of the materials used; a winding can be several kilometers long.
- **Active Part**: This includes the core and the windings of the transformer. The design of the active part is crucial to ensure the stability and efficiency of the transformer.
- **Main Insulation**: The main insulation is designed to ensure the safety and longevity of the transformer, preventing short circuits and other electrical issues.

Verification:

Once the design of the active part is complete, the EDS tool uses various verification software to ensure that the transformer meets the requirements. Among the verification tests included in the EDS tool are:

- **Cooling System**: Verification of the effectiveness of the transformer cooling system.
- **Impulse Withstand Tests**: Tests to ensure that the transformer can withstand the expected electrical impulses.

- **Short-Circuit Current Withstand Tests**: Tests to ensure that the transformer can handle short-circuit currents.
- **Sound Level Measurement Tests**: Verification of the sound level emitted by the transformer during operation.

The EDS tool uses an iterative process to converge on possible transformer designs that meet factory construction constraints and customer specifications. After input data such as transport constraints, oil temperature, dimensions, test withstand, and PEI, the EDS tool generates optimal designs that balance construction costs and materials used.

It also allows for ECO-friendly design in compliance with European Directive 548/2014. This ensures that transformers fall within the limits of the PEI (Performance Efficiency Index), helping to reduce environmental impact.

Finally, the designer's task is to verify that the transformer design is within the established limits and to use their experience to adopt solutions that can further improve the design.

5.2 CO2 Calculation

The calculation and documentation related to the environmental impact of PT are increasingly becoming a part of costumers' project specifications.

Although there is no unified interest in these practices nor a bureaucratic requirement obliging buyers to request them, the largest European companies in the electrical sector are following this trend by requesting official documentation that identifies every aspect of environmental impact of the goods bought.

Motivations can vary, but two stand out for their significance.

- **Net Zero Emissions**: Many companies have set a target to eliminate their emissions within the next few decades. One of the first steps is to conduct a more in-depth study of emissions.
- **Visibility and Publicity**: Companies aim to improve their visibility and transparency from multiple perspectives, including emissions.

To address these needs, EcoSmart was created. This tool allows, through input data, the creation of detailed preliminary documentation on the impact of PT throughout its lifecycle, not just CO2 emissions.

Moreover, clients seek more comprehensive documentation and greater decision-making power in the early design phases. This means that during the quotation phase, after the initial electrical design phase and before the customer's confirmation, the customer is presented not only with a price range, but also with a preliminary CO_2 emission value for the entire life of the transformer, based on the values and results from the initial electrical design.

The result is that the choice of transformer would not be based only on cost, given equal technical specifications, but a new parameter, the projected CO_2 emissions of the PT over its entire lifecycle, would play a crucial role.

In particular, companies interested in this sustainability strategy, based on their position and target, assign a monetary value to the total CO_2 emissions of the PT throughout its lifecycle. Therefore, they tend to prefer transformer designs that, although more expensive, have different designs or use different materials but result in lower net CO_2 emissions.

However, EcoSmart is not versatile in this situation, as it is a comprehensive tool that requires extensive manual input and detailed information that designers often lack during the design phase, such as the weights of individual components or detailed transportation documentation. Additionally, this tool is created in Power BI with many more functionalities, which would make its integration within EDS much more complex and time-consuming. This is especially challenging given that several customer requests already require a more immediate evaluation of the transformer's emissions.

Therefore, a more intuitive and immediate approach was adopted: I have developed a calculation methodology that considers only the CO_2 emissions of the PT throughout its entire lifecycle. This method will be integrated into the EDS tool, allowing designers during electrical design to obtain the necessary data more quickly and easily, as most of the required input data are directly sourced from EDS without manual retrieval.

This direct CO_2 calculation will be the first step to be integrated into EDS. Subsequently, all parameters obtained with EcoSmart could be added in the future to have a clear idea of the transformer's impact in all its forms. So far EcoSmart, created by Hitachi's Sustainability team, is still under development and is currently used for specific and custom LCA calculations.

5.2.1 CO2 Methodology Identification and Implementation

Step 1

First, I started with an in-depth analysis of EcoSmart, fully understanding the calculations performed by the tool and the essential sources from which it derives the various multiplicative factors used to calculate CO2 emissions related to each individual process of PT realization. Subsequently, I conducted an internal company research to gather information regarding the Bill of Material, which represents the list of the composition of the PT modules.

I made all the calculations by using some input data taken from external sources automatically and some provided by the designer themselves.

Then, all the phases were interconnected through hyperlinks, with each one assigned a specific task:

- **Ecoinvent**: This sheet was structured to retrieve each multiplicative factor through tables; each factor is taken from the official Ecoinvent database exposed in EcoSmart, for which Hitachi Energy holds the license.

  The created tables are divided into:

  - **GHG emission factors by TRANSPORTATION**: These factors include the means of transport that carry a certain weight for a certain distance, such as rail, trucks of various sizes, ships, air freight. Unit of measure:

    $$\left(\frac{\text{kgCO2eq.}}{\text{km} \cdot \text{kg}}\right)$$

  - **GHG emission factors of the ELECTRICITY GRID MIX**: These factors are related to countries with their own energy mix, different from others; additionally, some entries are linked and customized to power plants such as coal, nuclear, and photovoltaic plants (the energy mix of a coal plant will be much larger compared to that of a photovoltaic plant or wind farm). Unit of measure:

    $$\left(\frac{\text{kgCO2eq.}}{\text{kWh}}\right)$$

– **GHG emission factors of MANUFACTURING SITE**: These factors are customized for each Hitachi Energy transformer production site worldwide. This is to analyze based on the consumption of the individual factory. Unit of measure:

$$\left(\frac{\text{t CO2eq.}}{\text{MVA}}\right)$$

where MVA is the power of the transformer produced at that specific site.

– **GHG emission factors of the MATERIALS**: These factors represent the impact of individual materials from their extraction to the factory entrance (cradle to gate). Unit of measure:

$$\left(\frac{\text{kgCO2eq.}}{\text{kg}}\right)$$

– **GHG emission factors of the MATERIALS END OF LIFE**: Factors related to materials and particularly their impact during dismantling and recycling. Unit of measure:

$$\left(\frac{\text{kgCO2eq.}}{\text{kg}}\right)$$

– **Overview of energy RECYCLING %**: These values are also related to materials, particularly their recycling percentage. Unit of measure:

$$\%$$

Each entry, and therefore each parameter (e.g., Truck), is composed by 4 multiplicative factors present when a deep LCA analysis is made:

– "Fossil CO_2 Emission Factor".

– "Biogenic CO_2 Emission Factor".

– "Land use and land use change CO_2 Emission Factor".

– "Total CO_2 Emission Factor". That is, the sum of the previous ones.

GHG emission factor by TRANSPORTATION				
Mean of transport	Total CO2 Emission Factor (kgCO2eq.)/(km*kg)	Fossil CO2 Emission Factor (kgCO2eq.)/(km*kg)	Biogenic CO2 Emission Factor (kgCO2eq.)/(km*kg)	Land use and land use change CO2 Emission Factor (kgCO2eq.)/(km*kg)
Air freight - long haul	-	-	-	-
Air freight - short haul	-	-	-	-
Big ship	-	-	-	-
Rail	-	-	-	-
Small ship	-	-	-	-
Truck	-	-	-	-
Truck all sizes Europe	-	-	-	-
Truck load >32 metric tons	-	-	-	-
Truck load 16-32 metric tons	-	-	-	-
Truck load 3.5-7.5 metric tons	-	-	-	-
Truck load 3.5-7.5 metric tons	-	-	-	-

Figure 5.2: TRANSPORTATION multiplication factors representation but without values because they are proprietary to the Hitachi Ecoinvent license.

- **PT_Specification**: In this section, all relevant data related to the PT such as power, total losses, and the weight of the materials used are collected.

  The idea for this initial CO2 calculation was that the data related to the weights of the modules (conservator, tank, windings, etc.) used will be automatically taken from an internal Hitachi file. This file, which can be created after the mechanical design*, contains all the weights of the transformer taken into account and is used to provide the customer with a guide for its decommissioning.

  Subsequently, these weights related to the modules reported in this sheet will be divided into materials with the creation of a second table.

  For electrical parameters such as power and total losses, these values will be automatically taken from the EDS electrical design tool via a hyperlink.

  All of the values present are essential for the emission calculations carried out in the following sections.

- **Raw materials**: In this sheet, the sum of emissions related to individual materials (cradle to gate) is calculated by associating their weight with the corresponding multiplicative factors.

*Mechanical design is the process of designing the transformer that takes place after customer acceptance during the quotation phase and after completing the electrical design. In these steps, the process starts with a primitive design and gradually integrates more components and accessories to fully meet the customer's technical specifications. Finally, the complete mechanical design undergoes a detailed automatic process, resulting in a fully comprehensive design used for the transformer construction.

- **Raw material transportation**: In this sheet, the sum of emissions related to the transportation of individual materials from suppliers to the Hitachi factory is calculated by associating their weight and the distance traveled with the transportation method used and its corresponding multiplicative factor.
- **Manufacturing**: In this sheet, the emission related to the production of the transformer in the factory is calculated by associating the power of the PT with the multiplicative factor related to that specific factory.
- **Distribution**: In this sheet, the emission related to the transportation of the PT from the factory to the customer is calculated by associating the total weight and the distance traveled with the transportation method used and its corresponding multiplicative factor.
- **Operational losses**: In this sheet, the emission related to losses during the entire life of the PT is calculated by associating values such as yearly operating hours, lifetime, average load during lifetime, total losses with the energy mix to which it is subjected and its corresponding multiplicative factor.
- **Decommissioning**: In this sheet, the sum of emissions related to the decommissioning of materials is calculated by associating values such as their weight with the recycling percentage and the corresponding multiplicative factor.
- **RESULTS**: The last sheet contains the aggregation of all emission values calculated in the previous sections, including the percentage representation of individual items and a graphical pie representation.

RESULTS					
	TOTAL	%	FOSSIL	BIOGENIC	LAND USE AND LAND USE CHANGE
OPERATIONAL LOSSES EMISSION (kgCO2e.)	-	-	-	-	-
DISTRIBUTION EMISSION (kgCO2e.)	-	-	-	-	-
MANUFACTURING EMISSION (kgCO2e.)	-	-	-	-	-
RAW MATERIALS EMISSION (kgCO2e.)	-	-	-	-	-
RAW MATERIALS TRANSPORTATION EMISSION (kgCO2e.)	-	-	-	-	-
DECOMMISSIONING EMISSION (kgCO2e.)	-	-	-	-	-
TOTAL CO2 EMISSION (kgCO2e.)	-	-	-	-	-

Figure 5.3: RESULTS table representation

To validate the accuracy of the calculations performed in the various sections, I carried out two calculation tests with existing transformers.

The first transformer was taken from the EcoSmart tool to compare individual emission values step by step. The PT is 36MVA with 176 kW of total losses, installed in France, with a lifetime of 40 years, yearly operating hours of 5275, and an average load during the lifetime of 40%.

The results obtained are identical to those found in EcoSmart; therefore, the precision is 100%.

The second test was conducted by considering one of the transformers for which the EPD mentioned in the previous chapter was made; "Mineral and vegetable oil immersed transformers (40MVA)" which can be found on the EPDItaly website. The PT is 40MVA with 216kW of total losses, installed in Italy, with a lifetime of 35 years, yearly operating hours of 8760, and an average load during lifetime of 70%.

In this case, the total emission value found is 110% compared to the value found in the EPD.

Given the very similar results provided by CO2 calculation method compared to the actual results given by the two examples, it can be stated that the methodology used is correct, making the file reliable for estimating CO2 emissions during the design phase.

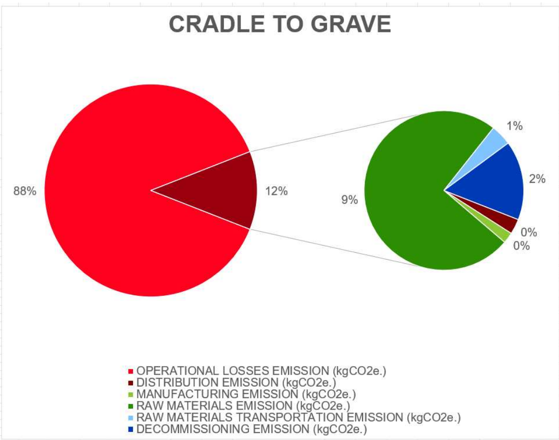


Figure 5.4: 36MVA EcoSmart PT CO2 subdivision.

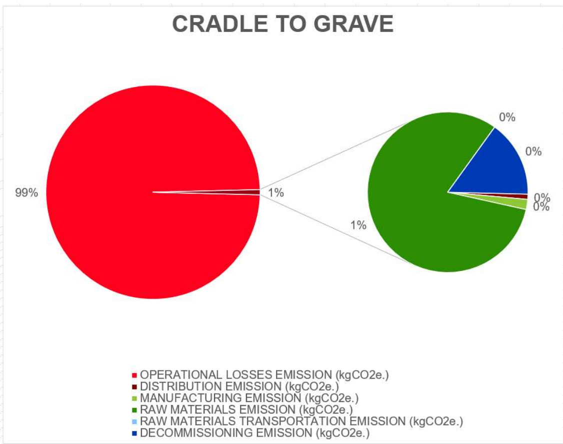


Figure 5.5: 40MVA EPD PT CO2 subdivision.

From the graphs above, we can observe three important concepts:

- When Most of the emissions are due to losses. This is because the energy circulating in the transformer is generated from various power plants, and these sources have an impact for every kWh generated.

  Additionally, the transformer is a machine designed to operate for many hours annually with a relatively long lifespan.

- The carbon emissions associated with transformer losses are also dependent on the energy mix, meaning that the higher the contribution of clean and renewable energy sources, the lower is the environmental impact. Therefore, the decarbonization of the energy system and the reduction of the transformers' carbon footprint go hand in hand as more "green" electrons pass by.

  So he location of the PT plays an essential role. If the circulating energy, and consequently the lost energy, is generated from renewable sources or from a country with a green energy mix, the associated CO_2 emissions will be much lower.

  If, for instance, is put "nuclear" as energy mix instead of Italy in the EPD CO_2 calculation example, the value would be much smaller.

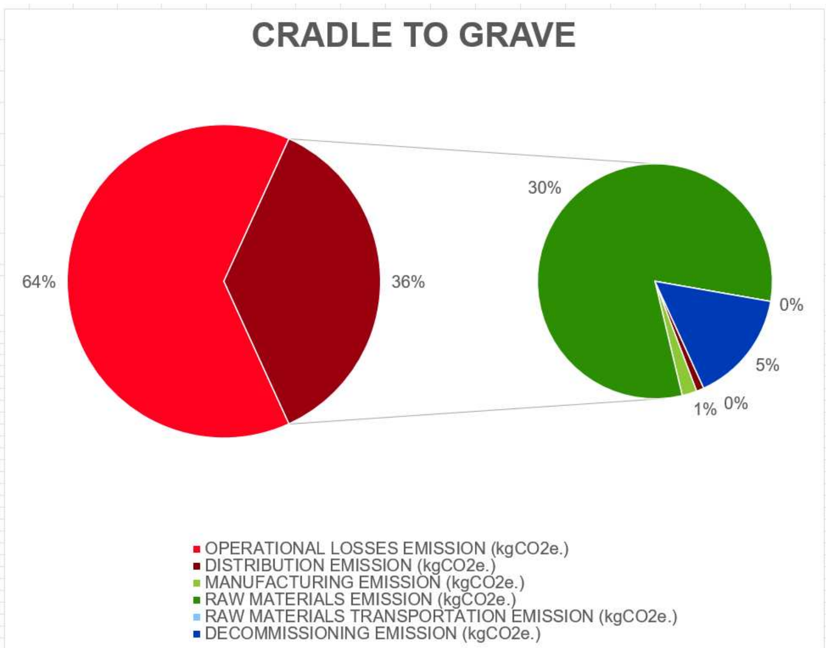


Figure 5.6: 40MVA EPD PT CO2 subdivision with nuclear energy input.

- Finally, losses, being the most important contributor, are not the only factor affecting transformers' carbon footprint. A transformer, in a nutshell, contains electrical steel, insulated copper or aluminum conductors, insulation, mineral oil or ester fluids, steel tanks, plus some auxiliary equipment (cooling equipment, steel parts, bolts, cabling, mechanical and digital accessories).

  The extraction, production, and transportation of all those materials release GHGs further up in the supply chain.

  The emission factors of the different materials vary greatly depending on the source, how they are processed, and on the share of reused / recycled materials.

  Considering that almost 99% of the transformer materials could be reused or recycled a normalization of the total materials to a unit weight of 1 metric ton can be done, using a typical material split:

  - **Electrical Steel 30% - 40%:** The core material is valuable, and in many cases, it is disposed to be reused in smaller size electrical machines.
  - **Copper conductor 10% - 15%:** Copper is one of the most recycled materials, and it can be recycled over and over with no loss of properties and for that is requiring up to 80% – 90% less energy than the primary production.
  - **Steel tank and steel accessories 15% - 20%:** Steel production is one of the highest carbon-dioxide-emitting industries with still no fossil-free steel production. On the other hand, all metal parts can be recycled to nearly 100%.
  - **Insulation paper 3% - 5%**
  - **Mineral oil/Ester fluid 10% - 20%**

  It can be observed that the remaining emissions are mostly related to materials (cradle to gate). As for the other components, they account for less than 2% in the EcoSmart example and are basically negligible in the EPD example.

Step 2

After approving the feasibility and reliability of the CO_2 calculation method, I made an improvement stage. Three main actions were achieved.

The first action involved simplifying the calculation by eliminating terms that do not add any significant value. As previously noted, the calculation contains multiple inputs for each multiplicative factor (”Fossil”, ”Biogenic”, ”Land use and land use change” and ”Total CO_2 Emission Factor”). Since the only factor considered is the Total Factor, the others were eliminated.

Next, as shown in Figures 5.4 and 5.5, the share of some emissions is very small and can therefore be eliminated. The criterion for eliminating emissions is based not only on the small share they represent, but also on the ease of input data compilation by the designer in the relevant calculation sheet.

Emissions from the transportation of materials and the decommissioning of the transformer require input values that are not immediate and must be requested, so they introduce a level of difficulty that must be avoided.

On the other hand, the remaining entries do not require high compilation difficulty, with input values directly provided by the customer or easily obtainable. The values retained with their respective calculation sheets are: ”Raw materials,” ”Manufacturing,” ”Distribution,” and ”Operational losses.”

The second action was to reassess the source from which the weights of the individual modules/materials of the PT were taken. Essentially, the file used, which contains all these values, as mentioned earlier, is an internal Hitachi file used to assist the customer in the disposal of the PT.

However, this file is created during the mechanical design phase and not in the electrical design phase. The mechanical design phase occurs only after confirmation from the customer, and therefore the values in this file, although more detailed because they are taken at a more advanced stage, are not suitable.

Another approach was taken: a .txt file named ”optimizer” is considered.

This file can be obtained during the electrical design stage and contains all the technical PT parameters.

The optimizer includes not only the weights of the transformer modules (with a more primitive level of detail but still adequate for our emission calculations), but also data such as power, total losses, and a preliminary cost analysis.

The goal was to create a new optimizer section that allows the aggregation of all relevant data for a more organized analysis and a more immediate hyperlink connection with the CO_2 calculation method.

In Fig. 5.7, the new section I proposed can be seen.

```
---------------------------------------------------------------------------
    CO2 CALCULATION PARAMETERS
---------------------------------------------------------------------------
---- General Data ----
Rated power............(MVA): ...
Load losses.............(kW): ...
No load losses..........(kW): ...
Total losses............(kW): ...

---- Mechanical Data ----                    ---- Materials ----
Conductor Aluminum......(kg): ...            Carbon Steel............(kg): ...
Conductor Copper........(kg): ...            Electrical Steel........(kg): ...
Cleats & Leads..........(kg): ...            Aluminum................(kg): ...
Connection plates.......(kg): ...            Copper..................(kg): ...
Core lamination.........(kg): ...            Pressboard..............(kg): ...
Tank shunts total mass..(kg): ...            Oil.....................(kg): ...
Core clamps.............(kg): ...            Wood....................(kg): ...
Tank....................(kg): ...
Cover...................(kg): ...
Conservator.............(kg): ...
Tie rods................(kg): ...
Constr. scrap...........(kg): ...
Insul. windings.........(kg): ...
Insul. ducts............(kg): ...
Insul. wind-yokes.......(kg): ...
Core insulation.........(kg): ...
Press ring Pressboard...(kg): ...
Press ring Wood.........(kg): ...
Oil free................(kg): ...
TOTAL WEIGHT............(kg): ...
```

Figure 5.7: Optimizer CO2 calculation section.

The final action was to integrate an additional calculation allowing the designer to customize the losses. This results in obtaining not only the total CO_2 value from the optimizer's losses but also a new total CO_2 value accounting for the designer's set losses. Since the losses from EDS and the optimizer are calculated and not guaranteed to the customer, giving the designer additional freedom provides more detail and intelligent integration into the CO_2 calculation.

5.2.2 Program Specification

The main goal of the project was not to create a final CO_2 calculation directly used by the designer, but to develop a methodology that will later be integrated as a new feature into the EDS tool. This will allow designers easier access to CO_2 calculations, especially by having automatic input data filling.

The implementation in EDS cannot be carried out directly by the project team; a dedicated team of programmers is responsible for these tasks. This team specializes in implementing various tools upon request from different company departments. The request for implementation must be formalized through a document called ”program specification”.

The program specification is a file that aims to provide detailed instructions to programmers regarding the implementation or update to be carried out. For this project, it is necessary to create a specification that considers the following points:

- **Update the optimizer:** The optimizer must be updated with the new section mentioned in Figure 5.7. This update is essential to ensure that the CO_2 calculation is accurate and integrated into the optimization process of electrical designs.

- **Create hyperlinks:** It is necessary to create hyperlinks between the optimizer and the CO_2 calculation feature. These links will allow easy and intuitive navigation between the different tools, improving the usability of the EDS tool.

- **Develop an interface**: An interface must be created to include all calculations necessary to accurately determine the CO_2 emission value. This interface should be user-friendly for designers, primarily involving the selection of input data entry and the numerical and graphical representation and explanation of the results obtained.

- **Provide training specifications**: Designers should receive clear instructions on how to use the CO_2 calculation feature effectively. This includes initial guidance for first-time users and contextual comments during the input data entry process.

It is essential that the documentation be complete and detailed to provide all the necessary information to programmers for correct implementation. The documentation must include a detailed description of the functionalities, specifying their purpose and how they should be integrated into the EDS tool.

Precise technical instructions must be provided on how to carry out the integration, including system requirements and necessary configurations. Additionally, the documentation must include testing and validation procedures to ensure that the integration has been carried out correctly and that the tool functions as expected.

6
Conclusions

This new feature in EDS to calculate CO_2 emissions, along with increasing but still insufficient awareness among companies about sustainability, will embrace the growing commitment of Hitachi Energy and its competitors.

In fact, this project was taken over by Hitachi and brought to realization due to significant interest. Currently, this concern is based on internal analysis by the largest and most important customers, but is increasingly being translated into a real necessity. This increased focus on sustainability is expected to drive significant improvements in the adoption of high-efficiency transformers.

The adoption of high-efficiency transformers represents a strategic choice not only for long-term economic savings but also for reducing greenhouse gas emissions. The total cost of ownership (TCO) takes into account the purchase price, the operational costs, and energy losses.

Investing in high-efficiency transformers not only reduces energy consumption, which translates into significant economic savings, but also decreases greenhouse gas emissions, as energy is used more effectively and sustainably.

Awareness of a reliable value associated with CO_2 emissions during the electrical design phase can not only make customers aware of the environmental impact, but, by meeting their project specifications, find innovative methods to reduce losses.

This approach allows for a more detailed analysis of the lifecycle of the individual materials used, focusing on adopting solutions such as redesign, recycling, and reusing not only the materials but also entire modules at the end of the transformer's life, such as the tank, the core, and various accessories.

A potential future implementation, considering all the points discussed before, could be a feasibility study on the integration of CO_2 emission values within the Electrical Design System not just as an output but as a variable.

In this way, the CO_2 emission value would not just be an output but a real design constraint that, along with losses and construction constraints, would contribute to the design of transformers that also directly meet the customer's environmental specifications.

Furthermore, this direct CO_2 calculation could be the first step to be integrated into EDS. Subsequently, all parameters obtained with EcoSmart can be added in the future to provide a full understanding of the transformer's environmental impact.

However, all of this must match careful and continuous supervision and updating of the various Ecoinvent databases within different environmental impact calculation tools, such as EcoSmart and the CO_2 calculation file I developed.

Data from these sources are constantly being updated; new materials, updates to multiplication factors, and the integration of new data are just some of the essential considerations that Hitachi Energy must prioritize to maintain leadership in this new trend.

The challenges associated with this project extend beyond the implementation of the new CO_2 calculation feature, encompassing a variety of interconnected factors.

Firstly, it involves a thorough examination of all documentation required for environmental impact assessment, such as Life Cycle Assessment and Environmental Product Declarations, along with internal research within the company to review what has already been accomplished.

This foundational work is crucial for understanding the current state and identifying areas for improvement.

In addition, familiarization with various calculation tools, such as EcoSmart, was essential. This process included understanding their limitations and areas of application.

The integration of these tools into the Electrical Design System required feasibility studies to explore different strategies for CO_2 calculation.

Moreover, continuous updates of various Ecoinvent factors needed to be studied and implemented. This ongoing process ensures that the data remains updated, reflecting the latest update in materials and more.

Regular updates of these databases are important to maintain the accuracy and reliability of environmental impact assessments.

In conclusion, the project required an ongoing evaluation and study of updates from sustainability team stakeholders.

This collaboration was crucial in aligning the project goals with the main sustainability objectives of the company, ensuring that the project not only meets the technical specifications but also contributes to the company's environmental responsibility. During project execution, specific tasks were defined and general supervision was provided to ensure alignment with these objectives.

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