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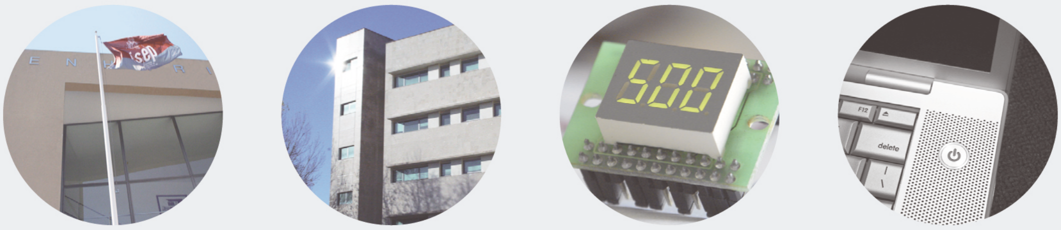

AVALIAÇÃO DO CICLO DE VIDA DA PEGADA DE CARBONO E ESTRATÉGIAS DE ECONOMIA CIRCULAR PARA A SUBESTAÇÃO DE PONTE DE LIMA

ANDRÉ SANTOS CARDOSO
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LIFECYCLE CARBON FOOTPRINT ASSESSMENT AND CIRCULAR ECONOMY STRATEGIES FOR THE PONTE DE LIMA SUBSTATION

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Do it or don’t, time will pass anyways – Earl Nightingale

Resumo

Este documento explora e contribui para a densificação da integração de critérios de economia circular e sustentabilidade na infraestrutura da REN - Redes Energéticas Nacionais, focando-se particularmente na subestação de Ponte de Lima. A existência de crescentes preocupações ambientais e metas ambiciosas da União Europeia em relação ao clima, faz com que o setor energético enfrente uma crescente pressão para evoluir do modelo tradicional de economia linear para um modelo mais sustentável de economia circular. Esta transição é de extrema importância visto que o setor energético é um *enabler* para a descarbonização da sociedade e, por outro lado, representa uma parte importante do consumo de matérias virgens e das emissões.

No contexto de economia circular, este documento aborda metodologias, *frameworks* e ferramentas de implementação assim como iniciativas para auxiliar na implementação de estratégias de aumento do ciclo de vida de ativos, integração de materiais reciclados em empreitadas e minimização de resíduos através do design de produtos e estratégias de operação e manutenção. O documento também explora o estado da economia circular na União Europeia e em Portugal, analisando as metas propostas por ambos, assim como o estado atual da utilização de matérias virgens, gestão de resíduos e a opinião pública quanto ao tema na União Europeia. Por fim, o documento dá enfâse aos desafios que operadores de transmissão de energia elétrica enfrentam e que necessitam de ser endereçados como a gestão do ciclo de vida dos seus ativos e a eficiência quanto à utilização de recursos, dando relevância à implementação de práticas circulares e quais os seus benefícios.

Seguidamente foi feito um benchmarking de várias operadoras de transporte de energia europeias que se assemelham à REN em termos de operações e objetivos, com o propósito de analisar as suas estratégias e esforços para uma possível incorporação de boas práticas. Esta análise permitiu constatar que já existem várias empresas a direcionar a sua atenção e recursos para evoluir para uma economia circular, com resultados quantitativos.

Por fim, fez-se uma breve descrição da infraestrutura nacional da REN e o papel que assume enquanto operadora. Analisou-se também as iniciativas e projetos realizados ou em curso pela REN para a integração da economia circular nas suas operações. A implementação de uma estratégia de uma economia circular na REN constituiu um grande desafio que é transversal às várias direções internas e que impacta na cadeia de fornecimento.

Palavras-chave: Autotransformador, Ciclo de Vida, Declaração Ambiental de Produto, Economia Circular, Economia Linear, Potencial de Aquecimento Global, Operadores de Sistemas de Transmissão, Sustentabilidade.

Abstract

This document explores and contributes to the strengthening of the integration of circular economy and sustainability criteria in the infrastructure of REN (Redes Energéticas Nacionais), focusing particularly in the Ponte de Lima substation. The growing environmental concerns and the European Union’s ambitious climate goals place increasing pressure on the energy sector to evolve from the traditional linear economy model to a more sustainable circular economy model. This transition is of utmost importance, as the energy sector is both an enabler of society’s decarbonization and, at the same time, a significant consumer of virgin materials and source of emissions.

In the context of the circular economy, this document addresses methodologies, frameworks, and implementation tools, as well as initiatives to support the adoption of strategies for extending the lifecycle of assets, integrating recycled materials into construction works, and minimizing waste through product design and operation and maintenance strategies. The document also explores the state of the circular economy in the European Union and in Portugal, analyzing the goals set by both, as well as the current state of virgin material use, waste management, and public opinion on the matter within the EU. Finally, the document emphasizes the challenges that transmission system operators face and need to address, such as asset lifecycle management and resource efficiency, highlighting the importance of implementing circular practices and their benefits.

Subsequently, a benchmark of several European transmission system operators comparable to REN in terms of operations and objectives was carried out, with the purpose of analyzing their strategies and efforts for the possible incorporation of best practices. This analysis revealed that several companies are already directing attention and resources toward transitioning to a circular economy, achieving quantitative results.

Lastly, a brief description of REN’s national infrastructure and the role it assumes as an operator was provided. The initiatives and projects implemented or underway at REN for the integration of the circular economy into its operations were also analyzed. The implementation of a circular economy strategy at REN represents a major challenge, one that cuts across several internal departments and impacts the entire supply chain.

Keywords: Autotransformer, Circular Economy, Linear Economy, Environmental Product Declaration, Global Warming Potential, Lifetime Cycle, Transmission System Operators, Waste Management.

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Acronyms and Abbreviations

List of Acronyms

CEAP	Circular Economy Action Plan
PAEC	National Action Plan for Circular Economy
REN	Redes Energéticas Nacionais

List of Abbreviations

C2C	Cradle to Cradle
CE	Circular Economy
EEA	European Environment Agency
EPDs	Environmental Product Declarations
ESG	Environmental, Social, and Governance
EU	European Union
MCI	Material Cycle Indicator
MFA	Material Flow Analysis
MVA	Megavolt-ampere
kV	Kilovolt
LCA	Life Cycle Analysis
RNC	Roadmap to Carbon Neutrality
TSOs	Transmission Systems Operators
SBT	Science-Based Targets

1 Introduction

This document has been developed within the framework of the Dissertation/Internship subject which is part of the second year of the Master's in Electrical Engineering – Power Energy Systems (MEE-SEE), from the Department of Electrical Engineering at the Porto Higher Institute of Engineering (ISEP), in collaboration with REN- Redes Energéticas Nacionais.

This document outlines the progress of this study, which centres on the application of circular economy (CE) and sustainability criteria in the management of grid infrastructure, with a particular focus on a 400/150 kV substation located in Ponte de Lima. The study will consist of developing a method/tool for REN that estimates the overall carbon footprint of a life cycle of a substation by calculating the carbon emissions phase by phase as well as by leveraging Environmental Product Declarations (EPDs) as proxies for similar components used in substations. Although there is already information from the EPDs, there is also data resulting from the survey of similar assets incorporated into REN's operations. The method aggregates life cycle carbon emissions data from these EPDs to approximate the total carbon footprint across the entire life cycle of the substation. This approach enables a practical estimation rather than an exact one given that detailed, component specific data is not available, thereby supporting informed sustainability assessments and course of action. In this context, the composition, life cycle and the sustainability of the components owned by REN, as well as practices of reutilization and recycling of materials will also be explored.

This section provides a contextualization of the project being developed, its primary objectives, planification and a description of the structure of the document.

1.1 Contextualization

In recent years, climate change has been one of the main issues that the world is facing, with profound impacts on our economy, environment and society [1]. Due to this, the international community has devoted great attention to the rise of carbon emissions making efforts to transition to a low-carbon economy [2]. As a response to this pending issue the energy sector is undergoing massive change, where renewable energies have been on the rise since there have been multiple agreements to make this happen. From the 2015 Paris Agreement which, aims for the increase in renewable energy to reduce greenhouse gas emissions [3], to even our very own Portuguese National Energy and Climate Plan, which aims for 80% electricity produced by renewables by 2030 according to the Portuguese Environment Agency [4]. The power sector, which is a subset of the energy sector that specifically deals with generation, transmission and distribution of electricity, garners special attention since it's one of the major contributors of carbon emissions. According to the International Environmental Agency the power generation and heating industry accounts for a staggering 41.2% of global carbon dioxide emissions [2].

With the increasing transition to renewable sources and pressure for a carbon free future, the power transmission sector needs a better sustainable approach and a better management plan for their inevitable expansion. The key challenges facing the power transmission sector today include the absence of standardized sustainability criteria, limited use of recycled materials in construction and maintenance, and a need for benchmarking against best practices in other TSOs.

Therefore, the adoption of new practices, like Circular Economy CE in this context, serves as a fundamental strategy to achieve sustainability and decrease carbon emissions, by reducing waste through a decrease in consumption of raw materials as well as increasing the efficiency of resource utilization, hence minimizing the environmental impacts associated with the production of the materials needed [5]. CE is a shift from the linear economy model that has a simple philosophy of acquiring raw materials, creating a product, and disposal of the product at the end of its lifetime, but with CE, the lifetime is extended with an emphasis in reducing, reusing, recycling and recovering fundamentals [6].

The power transmission infrastructure plays a crucial role in the transmission and transformation of electricity, and assets like transformers, transportation lines, and protection equipment have a very specific life cycle, since its life expectancy is correlated with the rate of use of the asset [7]. By implementing intelligent management systems of these assets with models like CE and sustainability practices, it can represent a huge reduction in carbon footprint in the energy sector.

REN is the entity responsible for the transmission of very high voltage electricity, ensuring the safety and stability of the national electrical system. According to REN, the management of electrical systems is becoming increasingly more complex with the increase of renewable energy, like solar and wind [8]. This is a challenge that REN is trying to address head on by trying to improve their sustainability management strategies and CE implementation.

1.2 Objective

The objective of this document is to provide insight into circularity practices, as well as to develop a replicable tool that can estimate the total carbon emissions of a substation lifecycle.

The objectives of this document will be as follows:

- Reviewing CE concepts, frameworks and tools.
- Reviewing the current state of CE in the European Union and Portugal and highlighting the importance of circular practices for TSOs.
- Conducting benchmarking with other TSOs to assess ongoing strategies in this area and identify recent adaptations in circularity strategies.
- Overviewing REN's role and infrastructure as well as their initiatives and projects towards CE and its importance to REN and main challenges.
- Organizing the substation lifecycle into phases.
- Calculating the carbon emissions of each phase and giving an insight into what EPDs are.
- Analyzing the results of the calculation
- Explaining the limitations of the methodology
- Providing a solution on how to improve the sustainability of a substation
- Reaching an overall conclusion of the study

1.3 Document Organization

This document is organized in eleven chapters. The first chapter gives an introduction that establishes motivation and context, giving a broad view of the relevance of the topic, linking climate change and the energy sector's evolving needs, and introducing key motivations behind the research. Chapter one also provides the main objectives of this document and gives a layout of the document.

In the second chapter, an overview of CE is given, providing a thorough description of the frameworks, tools and concepts in CE. This chapter also explores the current state of CE in the European Union and Portugal and the goals set by both, and it explores the relevancy of CE for TSOs.

The third chapter is meant to benchmark current practices put in place by main TSOs in Europe in the transition to a CE.

The fourth chapter gives a brief overview of REN's role and infrastructure. After that, the chapter explores circular initiatives and projects done by REN and it finalizes by highlighting the importance of adopting CE for REN and the main challenges being faced. Finally, a brief conclusion is given in the fifth and final chapter.

The fifth chapter organizes and links the substation lifecycle into different phases and it provides an explanation of each one. It describes what is relevant for each phase and what isn't.

The sixth chapter is where the methodology begins and where the carbon estimations are calculated for each phase. A thorough step by step explanation is given for these calculations.

The seventh chapter analyses the final and most important results from the sixth chapter.

The eighth chapter explains highlights the limitations found during the methodology

The ninth chapter provides ideas about potential improvements according to the overall results found.

Finally, the tenth chapter gives an all-encompassing conclusion of the study and the eleventh provides the annexes with content from the excel tool that was developed.

2 Circular Economy

2.1 Circular Economy Overview (CE)

A single, widely accepted definition for CE has yet to be established since the field continues to rapidly grow [6]; [9]. The Ellen Macarthur Foundation, which, is a non-profit organization that creates evidence-based original research on the benefits of a circular economy, defines CE as "a system where materials never become waste and nature is regenerated. In a CE, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting. CE tackles climate change and other global challenges, like biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources." [10].

This model is a shift from the current status quo of our socioeconomic system, which is still based on the linear economy model that has proven to have several shortcomings [11]. The linear economy model cannot be sustainable in the long run, with raw materials being used only once and early product end cycle, coupled with environmental damage, since more raw materials need to be continuously extracted leading to resource depletion [11]. In contrast CE aims to conserve natural resources by keeping resources in the economy for as long as possible, therefore extending product lifetime cycle. The European Environmental Agency (EEA) adds that the European Union is consuming far more than it should and not reusing and recycling as much as needed. The EEA emphasizes the need to embrace circular economic systems and moving away from linear production and consumption models [12]. Figure 1 shows the effects of maintaining product and material value from the 2023 EEA report extracted from EEA 2020 [13].

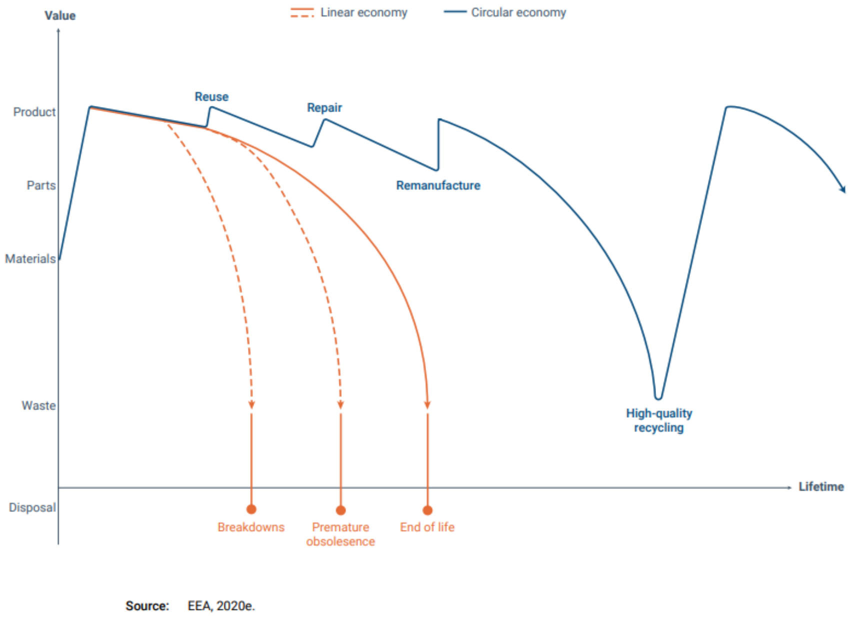


Figure 1 - CE effectiveness in maintaining material and product value [13].

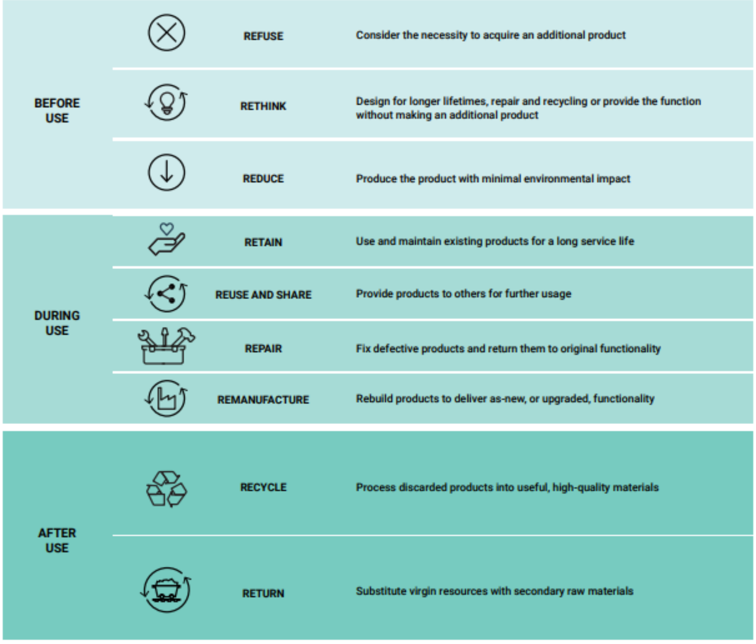
As we can see the circular model is able to extend the lifecycle of products and materials by repurposing them into new items after their initial use. Several initiatives have been implemented to make the EU more resource-efficient, according to the EEA [12], these initiatives include:

- Using recycled materials from waste.
- Prolonging existing products' lifespans through improved design, repair, refurbishment, repurposing, redistribution, and remanufacturing.
- Better waste collection to capture and reuse as much as we can.

Various CE objectives have been also set by the EU with the EU's circular economic action plan which aims to double the circular material use rate and cut the EU's residual waste in half [14].

2.2 Circular Economy Frameworks

In the early stages of CE development, a simple framework which many of us know was associated with this economic model. The framework was known as the 3R's (Reduce, Reuse and Recycle) [6] which were commonly accepted imperatives in concept and application [15], however these imperatives have been expanded on. The EEA report from 2023 also presented a set of circular actions within a framework of "before use, during use and after use". Like Figure 2 shows, the R's framework has been expanded by the EEA report to 9R's imperatives. These imperatives were based on the framework presented by José Potting where he defined up to 10 imperatives [16], [13].



BEFORE USE	**REFUSE**	**Consider the necessity to acquire an additional product**
	RETHINK	**Design for longer lifetimes, repair and recycling or provide the function without making an additional product**
	REDUCE	**Produce the product with minimal environmental impact**
DURING USE	**RETAIN**	**Use and maintain existing products for a long service life**
	REUSE AND SHARE	**Provide products to others for further usage**
	REPAIR	**Fix defective products and return them to original functionality**
	REMANUFACTURE	**Rebuild products to deliver as-new, or upgraded, functionality**
AFTER USE	**RECYCLE**	**Process discarded products into useful, high-quality materials**
	RETURN	**Substitute virgin resources with secondary raw materials**

Source: Developed by EEA based on Potting et al., 2017.

Figure 2 - 9R's framework developed by EEA [13].

There have been multiple proposals for R's frameworks from 5R's to even 60 R's but ultimately these imperatives serve as guides that help visualize and comprehend the different steps needed to implement a CE model [17].

2.3 Tools for Circular Economy Implementation

When implementing CE principles, key tools are essential for implementing such principles effectively. One such tool is Life Cycle Assessment or Life Cycle Analysis (LCA), defined by the Ellen Macarthur foundation as "a process for evaluating the environmental impacts of a product or service over the course of its entire life. It is often used to determine the best performing product, service, or other solution, at a given point in time, in terms of specific environmental impacts, such as carbon emissions." [10]. According to the organization, this tool has its limitations, since it can't measure unquantifiable metrics like environmental impacts and the tool is also very dependent on the assumptions the user makes and data used. However, the LCA tool is most useful when there is accurate data and few unknows [10].

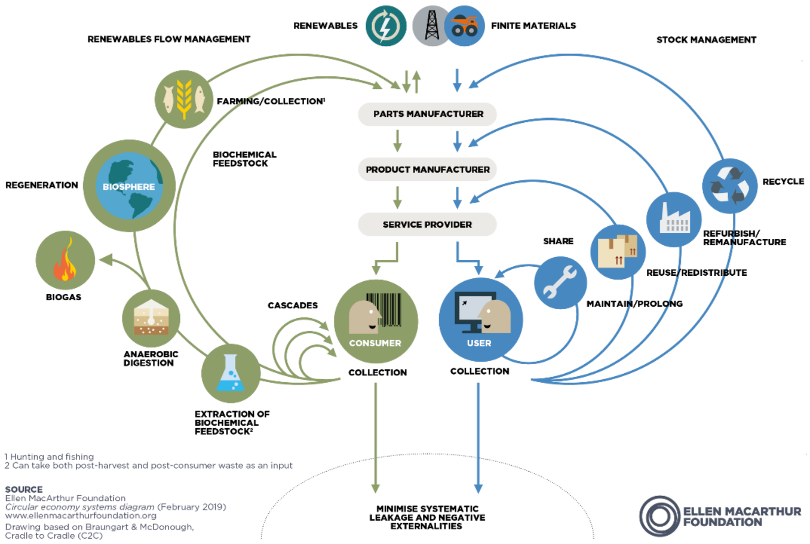
Material Circularity Indicator (MCI), also proposed by the Ellen Macarthur Foundation, is another key tool for the implementation of a circular model. MCI is a key metric to evaluate how circular a product's material flow is. It basically functions on three main aspects, where it evaluates the mass of raw virgin material used, the mass of non-recoverable waste of a product and a utility factor, that refers to the usage duration and intensity of the product. The indicator gives a score that ranges between 0 and 1, where a score of 0 means that the product is fully linear, meaning that 100% of the virgin materials that constitute the product end up in a landfill.

A score of 1 means that the product is fully circular made 100% with recycled materials with no losses. MCI is an important tool for companies to evaluate their progress by transitioning from a linear model to a circular one [18].

Another key tool for circularity of material systems is Material Flow Analysis (MFA), an established tool for waste management and environmental management. MFA is an important methodology for measuring material stocks and the flow of materials in a specific system. The core principle of this tool is mass conservation by calculating mass balances of inflows and outflows in a specific system, ensuring an accurate representation of material dynamics [19].

2.4 Circular Economy Concepts

Besides the R's framework that helps visualize a CE model in steps, there are other concepts that provide visual understanding of CE. One such concept is the butterfly diagram, also developed by the Ellen Macarthur Foundation, which shows the continuous flow of materials in a CE system into two cycles, represented in a diagram that resembles a butterfly like figure 3 demonstrates [20].



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough, Cradle to Cradle (C2C)

Figure 3 - The butterfly diagram represented by the Ellen Macarthur Foundation [20].

The right side of the wing is the technical cycle which bases upon some R's imperatives like refurbish, remanufacture, reuse, and recycle non-renewable materials to extend their lifetime, which ensures renewable resources can regenerate sustainably. The left side of the wing is the biological cycle, which refers to materials that are renewable and can regenerate sustainably for production and consumption [21].

Another commonly talked about concept is the cradle-cradle (C2C) concept, and like the butterfly diagram it promotes high level circularity on biological/technical cycles and the adoption of business models that focus on maximum material recovery. This concept highly emphasizes eco-effectiveness with principles like: 'waste equals food', 'use current solar income’, and ‘celebrate diversity. C2C is a structured concept for creating sustainable products and systems that benefit both humans and the environment [22].

2.5 Circular Economy in Europe

In March 2020, the European Commission decided to adopt a new CE Action Plan (CEAP) with the European Green Deal agenda in mind, it aims to transition Europe from a linear economy into a CE, where the dependency on natural resources is reduced and foster job growth in sustainable areas. Ultimately, it aims at achieving Europe’s distant goals of climate neutrality by 2050 [23].

This new action plan has a goal of making sustainable products the norm in Europe, putting importance on designs that consider durability, reusability and recyclability. Another goal is better transparency about the information of the products that the consumers buy, empowering consumers and public buyers. The main focus of the action plan is on high-impact sectors like electronics, batteries, vehicles, packaging, plastics, textiles, construction, food, water, and nutrients, where resource use is significant, and circular strategies hold great potential. Additionally, the plan pushes for efforts to reduce waste, enhancing recycling and reuse processes while fostering circularity within regions and cities to ensure inclusivity. Finally, the goal of this is to lead efforts on CE globally [23].

Despite the efforts, challenges remain. For instance, the EEA shows that in 2022 recycled material accounted for 11.5% of EU’s material usage, this is just a less than 1% increase since 2010. The EU plans to double the amount of circular material use within this decade, which will be quite challenging. Additionally, the EU's raw material footprint remains unsustainable, with per capita extraction being 14.8 tonnes in 2022, exceeding global averages[24].

Regarding waste management, the EU has a goal to reduce the amount of waste sent to the landfill. Even though waste generation continues to increase over the years, the EU-27 managed to decrease the amount of waste sent to landfills, from 23% in 2010 to 16% in 2020. Furthermore, the quantity of waste landfilled was reduced by 27% per citizen compared to the start of the decade [21]. The material footprint has remained relatively the same since 2010 as well as other key indicators. Figure 4 best shows the evolution of four key material flow indicators in the EU-27.

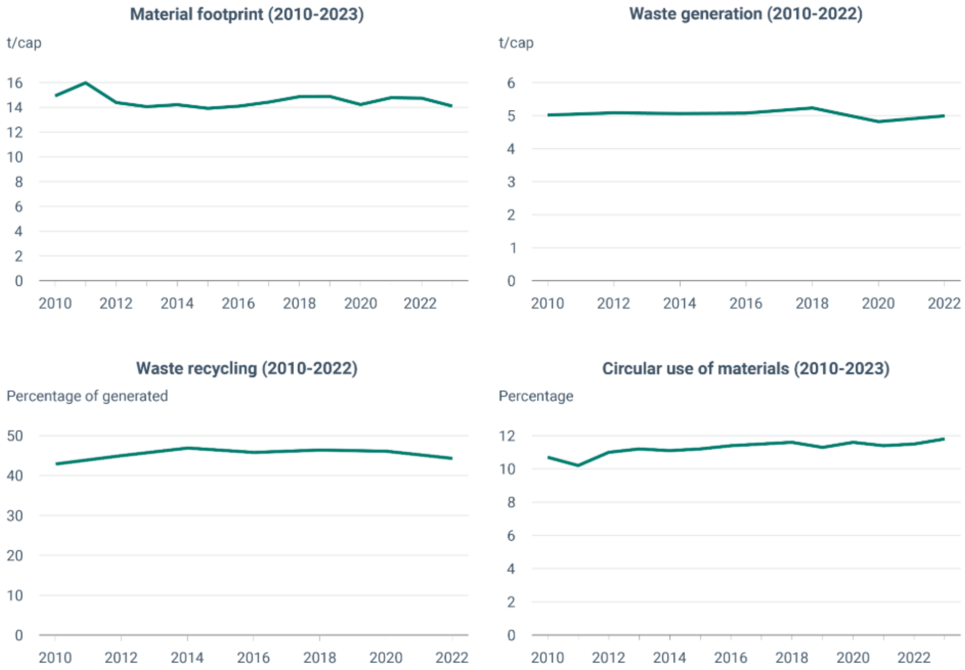


Figure 4 - Trend of four key material flow indicators in EU-27 [25].

As we can see, despite EU’s efforts to push for CE policies promoting resource efficiency, the consumption of materials remains high and largely unchanged in the past decade, showing a slow transition from a linear economy. Additionally, while waste generation hasn’t exactly drastically increased, the issue persists, showing that the efforts made by the EU to reduce waste generation haven’t succeeded all that much. Regarding waste recycling, it can be observed that it stagnated over the years. This shows that policies need to be improved for waste collection and innovation in recycling technologies is required. Finally, the circular use of materials chart indicate that the EU still has barriers regarding dependence of virgin materials, and perhaps insufficient incentives for businesses to embrace circular strategies. Doubling the circular material use rate by 2030 (as per the EU's CE Action Plan) will require enormous efforts.

The good news is that a good portion of EU citizens are aware of the issues we have today. About 65% of EU citizens recognize the impact of environmental issues on their daily lives and find the increase in waste generation concerning as we can see by the graph in figure 5 [26].

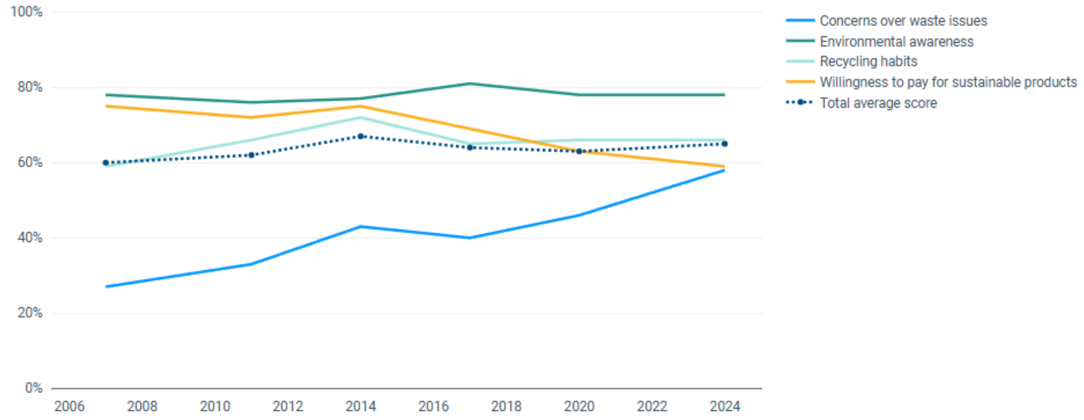


Figure 5 - Public views on CE [26].

Clearly environmental issues are of the utmost importance to EU citizens since 78% of Europeans claim that environmental problems impact their daily lives and health. Furthermore, the light blue line depicting recycling habits shows that about 66% of Europeans support waste recycling showing that a large portion of Europeans are on board with CE practices. However, even though most Europeans are willing to pay for sustainable products the percentage has gone down over the years potentially due to inflation rates but the strong public opinion about CE issues still remains largely unshaken over the years as depicted by the dotted line [26].

2.6 Circular Economy in Portugal

Regarding Portugal's own advance towards a CE, the country has aligned their strategies according to EU standards by incorporating CE into its national policies and action plans. The National Action Plan for CE (or PAEC in Portuguese acronym form), is one such action plan that Portugal first implemented in 2017. This action plan outlines priority sectors and initiatives for adopting circular practices, aligning with EU directives and the global agenda for sustainable development. The main strategic objective of PAEC is to increase resource efficiency by reducing the need for raw material imports and by implementing R frameworks. PAEC also outlined other strategic objectives for Portugal that focus on decreasing the volume of waste generated and minimizing landfill usage, thus encouraging businesses to adopt circular models and fostering collaboration between government, businesses, and citizens promoting awareness and action. By supporting businesses that take action and efforts to implement CE practices into their day-to-day operations, and by implementing legislation that supports CE like setting recycling targets and setting eco-design product requirements, the strategic objectives set by PAEC can be achieved. Another way that these strategic objectives can be achieved, is also by establishing metrics that track the progress of CE integration in Portugal. Metrics like circular material use rate and waste recycling rates are good metrics that help to observe the progress being made regarding CE transitioning [27].

In figure 6, it can be observed how the circular material use rate metric has been evolving. There is a clear underperformance by Portugal compared to the EU 27, only managing a 2.6% rate in 2022 which is below the EU 27 average.

Figure 6 - Material usage rate of Portugal compared to the EU27 [27].

It can be observed that after 2013 the circular material use rate in Portugal stagnated until 2017, which was when PAEC was implemented, after which, a steady increase of 0.1% per year can be observed. PAEC II aims to increase the circularity rate by enhancing production processes that generate minimum waste but there is no specific target for percentage of circular material use set for Portugal.

Portugal also shows a lack of eco-innovation investment and policies that help support eco-innovation, with businesses finding it hard to scale up these innovations to a global scale. Portugal sees a barrier when it comes to proper fiscal incentives that help businesses with circular models outcompete businesses with linear ones. Another barrier is transitioning from CE innovations to the adoption of CE strategies in larger scales. Other notable barriers facing Portugal when it comes to the implementation of CE, is the need of public participation for the transitioning process, companies collaborating for a shared purpose, increase common ground between different policies, avoid individual decisions and execute circular agreements implemented [27].

2.7 Relevancy of Circular Economy for Transmission System Operators (TSOs)

TSOs are the entities that are trusted with safely transporting energy on a national or regional level, and they are the ones responsible for managing the infrastructures in which this energy is transported, like transmission lines and substations. Therefore, TSOs should strive for the transition to circular models since they need to maintain large infrastructure which requires large amounts of resources. CE offers a framework to enhance their resource efficiency, which reduces their environmental impact and improves their economic performance within the energy sector by applying R frameworks like refurbishing, reusing, and recycling assets, minimizing waste and conserving resources. Applying CE strategies can lead to significant cost savings by refurbishing and extending the lifetime of certain existing assets. For instance, a power transformer is a crucial, yet expensive asset for TSOs with an expected lifespan of 30 to 40 years, many of which are close to the end of their lives in current infrastructures [28]. The European Commission's primary public repository and portal to disseminate information known as “The Community Research and Development Information Service” or CORDIS for short, notes that about 95% of a power transformers materials could potentially be recycled, with materials of high economic value, such as copper, being recyclable and possible even resold as secondary raw materials, aligning with the European Commission’s CE plan [28]. If the dependency on virgin materials is minimized by introducing circularity practices, it improves the supply’s chain resilience and it also secures a more sustainable approach to infrastructure development.

The discussion of circular economy principles and frameworks provides a strong theoretical base, but to understand their true impact, one must look at how they are being applied in practice. A closer examination of strategies adopted by European transmission system operators offers valuable insight into how these concepts are translated into real-world operations.

3 Benchmarking Transmission Systems Operators (TSOs)

3.1 Defining Benchmarking

Benchmarking is a tool that can be defined as "a continuous, systematic process for evaluating the products, services and work processes of organizations that are recognized as representing best practices for the purpose of organizational continuous improvement". It's a powerful tool that fosters innovation and the adoption of the best practices and strategies [29].

Benchmarking can be distinguished between two broader categories: Internal and external. Internal benchmarking is the process in which performance and practices are compared within an organization across departments or units, while external benchmarking refers to comparing against other industry peers to gain insight on the best practices [29], which is what this section aims at.

3.2 Selection of TSOs

This section aims to benchmark strategies that have been implemented by several TSOs, by examining their annual reports with the purpose of assessing all the efforts made by these TSOs, as well as examining the best practices implemented by them so that it can potentially be adapted. The TSOs selected for this benchmark are all major European operators that play an important role in managing the energy infrastructure in their specific regions. The TSOs were also selected based on operational similarities to REN such as, managing high-voltage transmission networks and their commitment to the implementation of CE practices in their operations. The selection of TSOs that are geographically and functionally similar to REN provide a great insight into the best practices regarding waste management and circular actions. The TSOs selected for this benchmark include:

- **Redeia** the operator responsible for managing and operating the electricity transmission system in Spain ensuring grid reliability and balancing electricity supply and demand.
- **Elia Group** operates in Belgium under the name Elia Transmission managing high-voltage grid and in Germany through its subsidiary called 50 Hertz responsible for managing the transmission grid in northeastern Germany.
- **National Grid** is a key operator in the United Kingdom responsible for managing the high-voltage electricity transmission system and natural gas infrastructure. In the US, it operates electricity and gas distribution networks.
- **TenneT** is an operator responsible for operating high-voltage grids in the Netherlands and parts of Germany.
- **Terna** is an operator responsible for operating Italy's electricity transmission grid;

3.3 Benchmarking TSOs

With the increasing need to meet sustainability goals set by multiple international agreements, it's no surprise these TSOs have been progressively implementing and pushing strategies of circularity into their operations. This section explores some of the strategies and actions developed.

3.3.1 Redeia

Redeia has shown that the integration of CE requirements in their process of acquisition of materials is one of their main strategic priorities. In 2022, Redeia worked with its suppliers to understand how to minimize the environmental impact of the materials and equipment they use. This collaboration with their procurement network consisted of developing a LCA methodology to assess the entire life cycle of products, from production to disposal. The collaboration also consisted of evaluating the use of recyclable materials, the origin of the materials, the durability and repairability of the equipment's, as well as the carbon and water footprint associated with the products. This collaboration enabled Redeia to measure the environmental impact of the materials and equipment they use, thus enabling them making more informed decisions that prioritize supply sustainability [30]. Redeia also set objectives for 2025 regarding the sustainability of their supply chain. They analysed 10 supplies with a sizable impact on their transmission grid, by employing LCA criteria. In 2030 their objectives are aimed at becoming the driver for change for their suppliers, increasing their supplies with circularity criteria that have a major impact to the transmission grid from 10 to 25 [31].

3.3.2 Elia Group

Elia group, which consists of Elia Transmission from Belgium and 50 Hertz from Germany, is also making their strides for a more sustainable future with comprehensive waste management systems. They employ a waste management hierarchy that prioritizes R frameworks like reusing, reducing and recycling waste from maintenance and infrastructure projects. Elia Transmission provides subcontractors with specific guidelines that ensure a proper dispose of waste. It also as a waste management policy in place for its administrative and technical sites and works with certified companies to collect, transport and recycle waste both hazardous and non-hazardous. Furthermore, Elia transmission is developing a digital tool that tracks waste flows, which will help visualizing waste quantities and handling across their operations as well as offering insight to the environmental impacts [32].

Similarly, 50 Hertz waste management plan includes the application of standardized waste management system for all its buildings and projects defining how materials should be disposed and focusing on reusing and separating materials, if possible, in alignment with EU regulations [32].

3.3.3 National Grid

National Grid is also embracing CE principles by focusing on designing assets that can be refurbished, reused or recycled and committed to eliminating single use plastics aiming to minimize as much as possible landfill waste from their main offices [33]. According to their 2023/2024 business report, National Grid does not yet have a specific target for the waste they generate. They report that 22% of hazardous waste is recycled, while 45% end up in landfill. For non-hazardous waste, 10% is sent to a landfill, 43% is reused, and about 39% is recycled. The remaining 8% of waste is disposed of via thermal processing and incineration [34].

National Grid has also updated the method they use to measure emissions from purchased goods and services, which is part of their Climate Transition Plan (CTP). With this update, they revised their list of key carbon-impact suppliers and committed to continually updating the list and reporting on progress made [34].

3.3.4 TenneT

TenneT believes that the shift from a linear economy to a CE is of utmost importance for a better green future. Their 2023 report voiced their concern with the high reliance they have with the large amount of virgin materials like copper and steel which can become scarce within the upcoming years due to geopolitical tensions and the increasing competition for these materials, hence shifting to a CE is a top priority.

To combat this, TenneT launched their first CE strategy in 2023 with the intent to minimize dependency on virgin materials and make a smooth transition to a circular model. To make this transition happen they deployed strategies that involved circular design, procurement and recovery of key materials like copper while also measuring the circularity of copper inflow and the material outflow. To do this, TenneT used tools like raw material passports and LCA to help track the source of the materials that they used, its recyclability as well as their environmental impact. In 2023 they reported that 36% of the 5100 tons of copper was circular and planned on recycling copper from old transformers to new ones.

TenneT encourages innovation by motivating suppliers to improve their product circularity with sustainability criteria like the environmental cost indicator, which is paving the way for power transformers using completely 100% recycled copper. Besides investigating how copper from non-functioning transformers could be used on new ones, TenneT is making efforts to digitalize waste reporting and improve processes thus enabling better circularity tracking. They report that in 2023 75% to 95% of their material outflow was recovered and as their material-intensive grid expands TenneT will prioritize optimizing material use and promote circularity [35].

3.3.5 Terna

In 2022, Terna developed a comprehensive CE strategy aimed at integrating circular practices in their business as well as their supply chain, with a roadmap of actions that for 2023 and beyond. Their strategy is based on four key pillars, shown in figure 7, which are circular procurement, asset circularity, operation of the electricity grid, and waste disposal.

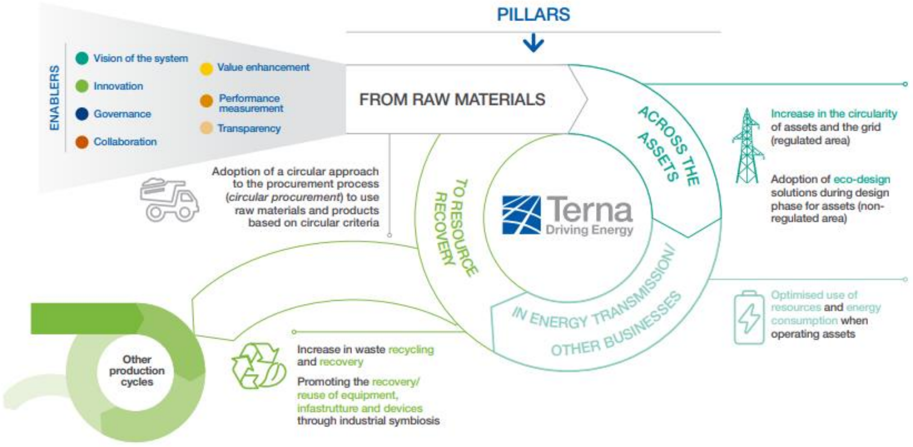


Figure 7 - Terna’s 4 key pillars [36].

The strategy also incorporates key factors like governance, innovation, collaboration, and performance assessment. Terna divided their project into three phases, where phase one is for the assessment of internal practices and external trends trying to identify areas of improvement to restructure the foundation of their CE strategy. Second phase is focused on expected strategic positioning, defining specific actions aligned with their goals and focusing on the key pillars mentioned above. Third phase systematizes the initiatives and actions to embed the CE model into Terna's business processes.

To support these goals Terna partnered with Synecom to regenerate the SF6 gas commonly used in insulation systems. This gas is a greenhouse gas and by regenerating it they avoid the production of new gas therefore reducing the emissions of SF6 into our atmosphere. Terna also implemented reuse initiatives donating their refurbished electronic devices like PCs, tablets, and smartphones to schools and non-profits, reducing electronic waste while providing social benefits.

In 2022 Terna conducted surveys to encourage their suppliers to use secondary raw materials in procurement processes. In the same year, they also managed to achieve a whopping 91% of waste recovery rate, which was achieved by giving priority to increasing recycled materials used in the components of their infrastructure like steel towers, cables and conductors.

Their future goals involve the regeneration of 42000 kg of SF6 gas by 2025 and the implementation of criteria that evaluates the circularity practices of their suppliers, such as the use of recycled steel and aluminium [36].

3.3.6 Bridging International Approaches with REN

The benchmarking exercise demonstrates that European transmission system operators are already reshaping their activities around circular principles. From supplier engagement and lifecycle assessment to innovative recycling and procurement strategies, each operator provides concrete examples of how sustainability can be embedded with varying degrees of ambition and success. Together, these cases show that circular economy is no longer a distant aspiration but an operational reality that can deliver measurable results.

However, the value of these comparisons lies not only in observing best practices abroad but in understanding how they can be applied within Portugal's energy landscape. REN faces a unique set of infrastructural, regulatory, and environmental conditions that require tailored approaches. The following analysis turns attention to REN itself, examining how circular economy principles are being integrated into its operations, where progress has been made, and where the main challenges still remain.

4 REN and Circular Economy

4.1 Contextualization of the Infrastructure and the Role of REN

REN is the key operator playing a critical role in Portugal's electricity and natural gas transmission systems. REN's infrastructure is vital for ensuring reliable and efficient transport of energy covering the entirety of Portugal's territory including interconnections with Spain's electrical grid.

REN is responsible for operating and managing very high-voltage transmission lines with voltage levels of 150 kV and 220 kV, which serves to support regional and cross-border transmission needs and 400 kV, which serves as a backbone for long-distance, high-capacity transmission. REN also operates and manages substations, switching and transition stations and interconnections forming the backbone of Portugal's grid, ensuring electricity is transmitted from generation sources to distribution grids or directly to major consumers. Currently, REN manages nationwide 9409 Km of circuit length, 70 substations, 17 switching and transition stations and 211 transformers. Figure 8 shows a representation of how the gird is laid out nationally, with the red lines representing the 400 kV lines, green representing the 200 kV lines and blue representing the 150 kV lines. The white dots represent an individual substation [37].

Figure 8 - Visual representation of RENs national infrastructure layout [37].

Substations are a critical component in the energy transmission infrastructure with the purpose of transforming and controlling voltage housing a variety of components like transformers, circuit breakers, switchgears, protection systems among other components.

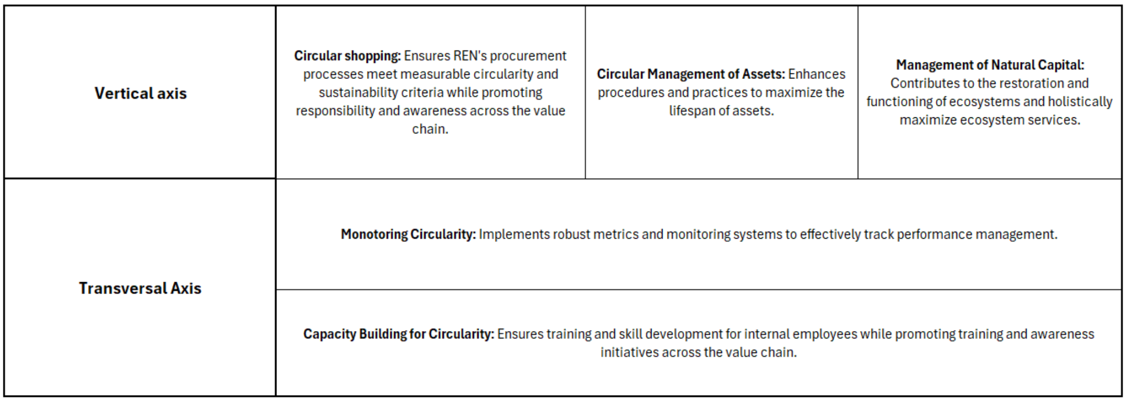
4.2 Circular Economy Initiatives and Projects

REN has ongoing initiatives for the decarbonization of their infrastructure, focusing on sustainability and CE practices. REN is committed to supporting its suppliers in navigating the Environmental, Social, and Governance (ESG) initiatives by providing guidance, training, and leadership. In 2023 REN collaborated with its suppliers to promote and build partnerships to align their practices with REN's sustainability goals. A total of 21 awareness sessions was raised with over 70 companies participating, representing more than 70% of REN's annual purchasing. The goal of these sessions was to analyse REN's proposed roadmap to achieve decarbonization and to inform suppliers of topics like Science-Based Targets (SBT), Environmental Product Declarations (EPDs), ESG ratings and CE strategies [38].

A roadmap and CE strategy was developed to establish a comprehensive vision for increasing circularity within its operations while contributing to REN's goal of carbon neutrality by 2040, and an intermediate goal of 60% carbon reduction in 2030 compared with the emissions of 2019 and 30% carbon reduction compared to 2021 [39]. This is to be achieved by setting and defining clear targets that lead to the implementation of key actions. The actions developed for this strategy involved benchmarking exercises using national and international references, to identify best practices. The categorization of patterns of resource use across REN's main assets and production of waste on different sectors was also a key action implemented. Additionally, to better identify the risks and opportunities associated with their resource management, it was developed an analysis of material flow within REN's operations, allowing them to prioritize circular criteria in the 2023 roadmap. This analysis focuses on material stock with objective of quantifying the amount of assets owned by REN and it focuses on potential value of decommissioned assets, either in product form, subproduct or waste. To better understand how effective REN is at retaining materials in the economy, it was utilized a Material Circularity Index (MCI). This tool is rather effective at measuring and enhancing the circularity of a product. Furthermore, to ensure that circular principles are not only embedded in REN's operations but also their supply chain, EPDs were designed and tested for gradual integration into procurement processes [40]. These actions collectively lay the groundwork for REN's comprehensive CE roadmap.

In the 2023 roadmap it was defined five priority areas of action, three vertical axes and two transversal axes which can be seen in Table 1, with specific goals and scheduled initiatives over time.

Table 1 – Five priority action areas [41] (Adapted by author).



Vertical axis	**Circular shopping:** Ensures REN's procurement processes meet measurable circularity and sustainability criteria while promoting responsibility and awareness across the value chain.	**Circular Management of Assets:** Enhances procedures and practices to maximize the lifespan of assets.	**Management of Natural Capital:** Contributes to the restoration and functioning of ecosystems and holistically maximize ecosystem services.
Transversal Axis	**Monotoring Circularity:** Implements robust metrics and monitoring systems to effectively track performance management.		
	Capacity Building for Circularity: Ensures training and skill development for internal employees while promoting training and awareness initiatives across the value chain.		

4.3 The Importance of Circular Economy for REN and Main Challenges.

Since REN operates large-scale energy infrastructures, which include substations and transmission lines, it becomes increasingly important to adopt CE strategies that can reduce dependence on virgin materials, improve the recyclability of components, and extend the lifecycle of these critical assets. By promoting these strategies decommissioned assets, such as transformers and transmission lines can have their lifetimes extended thus minimizing waste generation which aligns with the European Green Deal and REN's sustainability goals of achieving carbon neutrality by 2040. Another reason why CE is important is because REN is required to comply with European Union policies such as the CEAP and other directives, which put an emphasis on sustainable resource use, circular material flows, and the reduction of landfill waste. Adopting CE is also a great economic benefit for REN that can lead to significant cost savings and operational efficiencies, since by extending the lifetime of critical assets it leads to less regular spending buying new assets.

Even though transitioning to a CE is very important, REN still faces several challenges when it comes to this transition. These challenges can be divided into six key areas which are vital for the transitioning according to the 2023 roadmap developed. These areas can demonstrate the positioning of REN in this transition, showing where REN is leading and lacking. The six key areas consist of regeneration of natural capital, sustainable procurement, integration of CE into the climate strategy, efficient resource use, R&D and new business models and asset lifespan extension.

The newer initiatives deployed by REN are aligned with sector practices when it comes to sustainable procurement, but there needs to be concrete set targets and larger supplier engagement if REN wants to integrate circular principles into their operations successfully. REN also wants to further integrate CE goals into their climate strategies, with opportunities for improving this integration by setting clear targets for material use and waste management in their climate strategy plan. Similarly, REN shows good practices when it comes to resource efficiency with strict criteria but the same can't be said for strict target goals between material use and waste management. When it comes to R&D, REN is well positioned but there is still room for improving relations and collaborations with strategic partners both nationally and internationally to maximize innovation and effectiveness. Finally, the most critical challenge is extending the lifespan of assets, this area is one of the areas where more development and investment will be needed. Currently, there is no unified main strategy in place for all the assets in the company, and actions remain scattered and less effective. Figure 9 summarizes REN's positioning across the six key areas by evaluating from 0 to 5 its performance when it comes to CE transitioning and giving a visual representation of the areas REN succeeds and lacks [40].

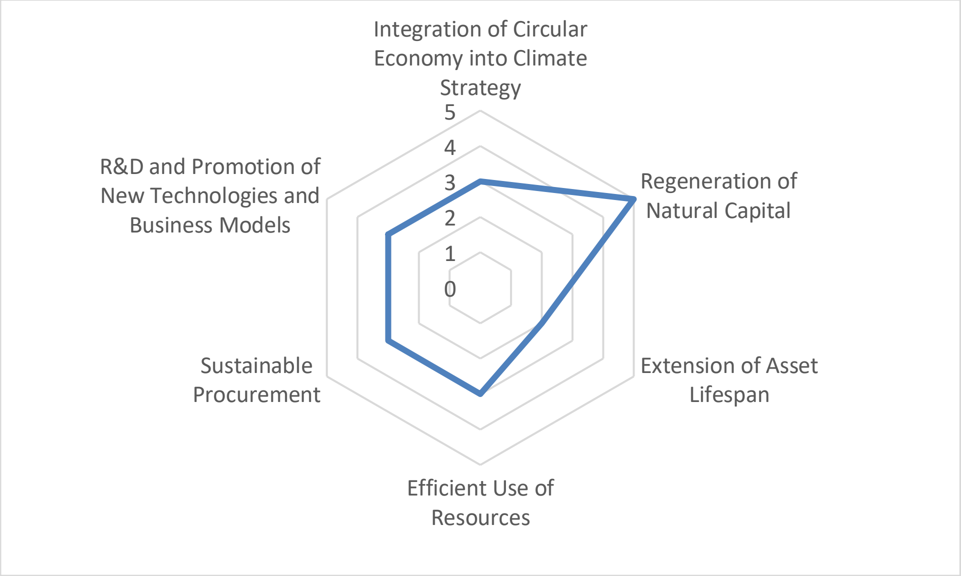


Figure 9 - RENs positioning in the six key areas for CE transitioning [40] (Adapted by author).

As we can see from the graph, currently extending the lifetime of the assets is the main challenge facing REN only having a grading of 2. With regards to regeneration of natural capital it can be observed that REN is clearly performing well with a high grade of 5 on their own standards. The remaining four key areas with grades of 3 have clear room for improvement.

The analysis of REN's initiatives makes clear that adopting circular economy principles is not only a strategic necessity but also a practical challenge. Efforts such as supplier engagement, material flow mapping, and roadmap development highlight promising directions, yet the real test lies in how these strategies play out across the company's extensive portfolio of assets. For circularity to be more than a policy statement, it must be measurable at the level of infrastructure itself.

This need leads directly to the lifecycle of the substation, one of REN's most critical assets. By decomposing a substation into its distinct phases it becomes possible to quantify environmental impacts with precision. This transition from organizational strategy to asset-level analysis provides the foundation for identifying where emissions are concentrated and where circular practices can deliver the greatest value.

5 Phases of a Substation Lifecycle

When REN began estimating GHG emissions in projects, it started by developing an LCA tool with respect to transmissions lines, where all the phases that went into those projects were identified and divided, each with important activities and components which was organized in a diagram structure for easier comprehension-like figure 10 shows. REN wanted to expand this idea to substations as well and develop a similar LCA tool based on the first transmission line projects which is now the purpose of this study. The breakdown of these projects into smaller phases with smaller components is essential for organizing information and to focus and calculate each phases step by step. To calculate the carbon footprint of a substation in its entirety it is important to first identify the phases of its lifecycle. Figure 10 shows that the substation is ultimately divided into 5 main phases: A (Site Area), B (Construction), C (Exploration and Maintenance), D (Forest Balance), and E (Decommissioning). Each of the main phases is further decomposed into smaller but important activities or components that were considered relevant for the calculation. The flow and hierarchy of the diagram allow for a clear visualization of how emissions are generated and linked across the lifecycle of the project.

The diagram is read vertically with each major phase coloured in dark blue identified by a letter of the alphabet. Phase A is the beginning of the substation lifecycle where the land is cleared so that the construction can commence. Phase B follows immediately with the inventory of the most materially relevant assets in the construction of the infrastructure, as shown in Figure 10, using the information contained in the EPDs. In addition, GHG emissions resulting from the use of energy to support the execution of the project were also accounted for, such as fuel consumption for contractors and service providers machinery, equipment, and vehicles. After that, phase C is comprised by the maintenances done during the whole lifetime of the substation that were considered more relevant. Phase C accounts also the energy for the operation of the equipment's/installation, the routine inspections that must be done, control, and minor interventions to keep the system functioning as well as the transportation to the site area and also the equipment's that have to be used. Phase D refers to the Forest Balance and aims to account for the substation's impact on the CO_2 flow and stock, whether through carbon sink capacity or carbon removal, both during the implementation and operational phases of the substation. As this stage is transversal to the entire lifecycle of the substation, it is positioned separately in the diagram from all other stages, which are organized linearly. The final phase is phase E, which marks the end of the infrastructure lifecycle, where assets are decommissioned and removed from the site. These phases were organized in a linear and vertical manner, so that each one constitutes the core technical lifecycle of the substation. Each phase depends on the completion of the previous one and feeds into the next, both in terms of time and the flow of materials, energy consumption, and emissions.

For the estimation of GHG emissions across the entire lifecycle, a time horizon of 42 years was considered.

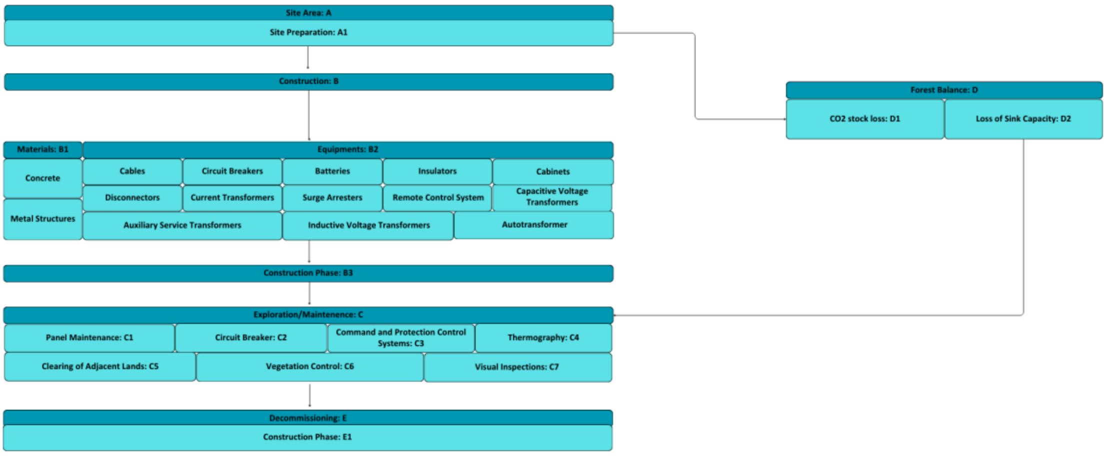


Figure 10 - Phase Diagram of the Substation Lifecycle (Elaborated by the author).

5.1 Site Area: A

The site area is designated as the area that is prepared or cleared up for the installation of the substation platform, this involves the removal of biomass. The area in question has eucalyptus and pine plantations, this implies that deforestation must be carried out. For other forest species, pruning is performed. Clearing is carried out, including cutting and/or uprooting trees and shrubs, transporting them any distance outside REN's land, and all other necessary operations. Topsoil is also stripped to an average depth of 0.40 meters. Additionally, access routes are opened, and biomass is removed from adjacent lands.

In this phase, the main GHG emission sources include:

i) Transport of equipment, materials and machinery.
ii) Electricity/fuel use by machinery (e.g., chainsaws, backhoes).
iii) Removal of vegetative ground cover for the installation area.

There are less significant contributors to GHG which include: use of the construction yard by workers (expected to have a low impact on overall GHG emissions); clearing of the area to support infrastructure installation (as the occupation is only temporary and conditions are mostly restored post-construction, with rare exceptions); and possible burning of deforestation residues. These activities were ruled out since it's considered insignificant.

5.2 Construction: B

In this phase activities begin with the setup of the construction yard and materials storage area, typically located at already-developed sites near the construction zone. After that, access to the substation implementation sites is identified, marked, and opened. Then, protection of the site is addressed by installing physical and marked fencing around the site area. Earthworks follow, including spreading and compaction, soil transport, soil retention, and subsequently paving. Drainage systems are also installed to ensure continuity of surface water flow. The construction concludes with the installation of substation equipment and materials which are highlighted in the diagram. B1 and B2 include the entire lifecycle of the materials and equipment present in the EPDs which will be addressed further on.

In this phase, the main GHG emission sources include:

i) Emissions related to the transportation of equipment.
ii) The use of machinery with energy/fuel consumption.
iii) The entire lifecycle of the materials and equipment's used.

The use of the construction yard by workers (expected to have a low contribution to total GHG emissions); potential burning of deforestation residues (a minor contribution compared to the total loss of carbon sink); production of construction materials (which are reusable and thus expected to have negligible impact for a single project); production of minor items such as signage and markers (mass contribution comparatively negligible); and water production for cement mixing and subsequent treatment of wastewater from concrete mixer cleaning (comparatively negligible contribution) were all considered irrelevant activities in this phase.

5.3 Exploration and Maintenance: C

This phase includes the additional maintenance and equipment replacement activities that must be done, with periodic site visits for inspections, which are part of the GHG accounting for this phase. This phase considers all maintenance cycles carried out throughout the lifecycle of the assets, in accordance with REN's technical specifications.

Thus, the relevant GHG contributors in this phase are:

i) Transport of workers or equipment for replacement and maintenance.
ii) Use of machinery for maintenance (e.g., platforms).
iii) Energy for the operation of the installation

Less relevant contributors include replacement of other components and changes due to third-party interference (both residual).

5.4 Forest Balance: D

The forest balance phase is a phase that encapsulates the full extent of carbon dynamics affected by the site preparation, exploration and maintenance and decommissioning of a substation. Within this phase there is two components which are: CO_2 stock loss and loss of sink capacity.

The first and most immediate impact is CO_2 stock loss. During site preparation activities, native vegetation is removed to clear space for construction. This vegetation includes mature trees, shrubs, and topsoil biomass which constitutes a significant stock of stored carbon. By removing the vegetation, the CO_2 stored is released into the atmosphere which contributes to greenhouse emissions.

Following this impact another long-term impact sets in called loss of sink capacity. By removing natural ecosystems that continuously remove CO_2 from the atmosphere the land's inherent ability to function as a carbon sink is permanently degraded.

5.5 Decommissioning: E

The final phase of the substation project involves the dismantling of the various pieces of equipment installed in the substation. The decommissioning/deactivation of the assets mirrors the construction phase in terms of significant GHG emission sources: related to the transportation of equipment and materials to the site, the use of machinery with energy/fuel consumption, the treatment of substation decommissioning waste.

Due to the implementation of the RCN 2050 (Roadmap for Carbon Neutrality 2050), no GHG emissions are expected during the decommissioning of these assets, in this stage and therefore no additional information is required, allowing the methodological framework of the study to be explored in the following chapter.

6 Methodology

This chapter details the methodological framework employed to estimate the total emissions associated with the full lifecycle of the Ponte de Lima substation. The methodology began with the selection of the most relevant assets and activities for the study so that EPDs could be searched for and the calculation could be structured. The EPDs were organized in an excel into different categories to see which ones would best align with the materials and assets acquired by REN for the Ponte de Lima Substation. The map of quantities, materials and assets as well as activities were provided by REN. For the search of EPDs it was used the EPD Italy and EPD Norge archives where the best EPDs were extensively searched for. These archives were found to be the only ones that had EPDs of substation components after extensive searching online. In the case of a lack of EPD documentation for a specific asset, REN suppliers were contacted to provide EPDs that they may have but haven't made it public yet. Additionally, information about the emissions caused by certain activities were obtained from sub-contractors of REN and reunions with REN members that have previous knowledge in the subject. After the EPDs were collected, careful analysis was done of key information like the lifetime of the equipment considered, which was useful to calculate how many replacement cycles would the equipment need in the entirety of the lifetime of the substation. Another key information were the assumptions made, and the phases or modules considered in the EPD, which was useful to determine which activities and criteria was important for the calculation. The place where the equipment was manufactured was also an important information to estimate the emissions of the transportation of the equipment from the factory to the site area based on assumed distances and mode of transportation. The specifications of the equipment being analysed in the EPD was one of the most important aspects of the EDP, since it determined the accuracy and validity of the equipment being analysed in the EPD versus the equipment's being installed. Additionally, the resultant GWP of each EPD was the data used to obtain an estimation of all the equipment's and materials. All this key information was used for the calculation of emissions in an excel tool which is available in the annexes. This excel was adapted from another tool that REN developed to calculate carbon emissions for transmission line projects**.**

The excel calculation tool is organized into modules or sheets, each serving a role in the accounting process. The initial sheets provide a general view as well as user guidance, including an initial description of why the tool was developed and an introduction diagram that organizes the project into phases already described in chapter 5. Following this, a dedicated input sheet allows for the insertion of data such as equipment and material quantities, as well as the forest balance emission factor of the activities. Additionally, a sheet for organizing all the EPDs collected, and their respective emission factors were made.

At the core of the tool lies the calculation tool sheet, which links the input data from all the other sheets used to calculate each phase. All this information is then consolidated in a final results sheet that gives the sum of all the constituents of each phase as well as the sum of all phases into one final result, along with graphs that help visualize the impacts of each phase and components.

The adapted excel serves as the tool that REN will use to input data of future substation projects to automatically return a total estimated carbon emission of the project. The tool is intended for any entity that wishes to estimate the direct and indirect GHG emissions both generated and avoided for construction projects under the responsibility of REN, throughout their lifecycle. Additionally, a user manual was developed to help any entity or person that wants to use the tool, providing a guide through the excel of where to put the data and how the data is processed.

This chapter will explain what EPDs are and what are they are for, as well as provide a comprehensive, step-by-step breakdown of how the total emissions was estimated and the assumptions that had to be made in some cases, data sources, emission factors, and equations used throughout the study. This ensures that every result is traceable, justified, and replicable.

6.1 Site Area Phase

To calculate the total emissions for the site area preparation phase, all the interventions done in that area had to be described, these interventions were only done once in the entirety of the project. The emission factor per intervention type was provided by REN from previous projects and the amount in percentage of the intervention done by type of occupation space was also provided by REN. Table 2 shows all the information provided to use for the calculation of total emissions.

Table 2 – Emissions of each forest type considering different intervention types

Intervention Type	Emissions per Intervention Type in Eucalyptus Forest (kgCO2e/ha)	Amount of intervention done in Eucalyptus Forest area	Amount of intervention done in Maritime Pine Forest areas	Emissions per Intervention Type in Maritime Pine Forest (kgCO2e/ha)
Tree felling, sectioning, and gathering (clear-cutting)	108.7	100%	100%	108.7
Tree felling, sectioning, and gathering (thinning)	0	0%	0%	0
Felling of isolated trees + Dismantling of trees + Topping or pruning of trees	0	0%	0%	0
Brush clearing	133.4	100%	100%	133.4
Stump removal	487.8	100%	0%	0

Soil mobilization (Pre-planting)	0	0%	0%	0

To calculate the total emissions, Equation 1 was used. Transportation related emissions, provided by the contractors, was considered to be 80 kg of CO_2e per hectare. The eucalypt forest area was measured to be 5.10 hectares and the area of maritime pine forest 9.70 hectares. The following equation 1 is of the author's own elaboration, developed specifically for the assessment of forest-related emissions in the substation project. It combines the emissions per intervention type, the percentage of intervention, and the emissions from transportation, adjusted by the forested area in hectares.

The rationale follows the same principle as the linear infrastructure LCA methodology from REN, the total emissions are obtained as the product of activity data (area of intervention and type of forest) and emission factors (per intervention and transportation). The structure was adapted to capture the particularities of the two forest types affected in the case study eucalyptus and maritime pine.

By summing the contributions of each forest type, the equation provides the total emissions associated with the land use change and site preparation activities.

$$TE_{ft} = \left(\left(\sum (E_{ti} \times A_{i(\%)}) \right) + E_t \right) \times ha \tag{1}$$

Where:

- TE_{ft} is the total emissions of each forest type (Eucalypt and Maritime Pine)
- E_{ti} is the emissions per type of intervention.
- $A_{i(\%)}$ is the amount of intervention in percentage.
- E_t is the emissions of transportation.
- ha is the hectares of type of forestation.

By adding the emissions of both forest areas, the total emissions for the site preparation phase amount to 7.3 tons.

6.2 Construction Phase

Before delving into how the construction phase was calculated it is important to first explain what EPDs are and what general information they usually have. This phase was the most complex phase and the EPDs played a crucial part in gathering information for the calculation of emissions in this phase.

6.2.1 Environmental Product Declarations (EPDs)

According to The International EPD System an EPDs purpose is to "transparently report objective, comparable and third-party verified data about products and services' environmental performances from a lifecycle perspective."[42]. This information helps manufacturers to optimize their products for recyclability, durability, and resource efficiency which are key principles of circular economy. It is also a commitment by the manufacturer to be hyper-transparent about the potential impacts of their products and services [42]. EPDs can also help companies and governments to make informed decisions when acquiring a product by comparing EPDs with lower environmental impacts and better end-of-life potential.

The creation of an EPD is usually from an LCA perspective and it is typically verified by an independent third-party verifier before being registered and published. An EPD is considered a type III environmental declaration compliant with the ISO 14025 standard [42]. These declarations can be a tool to enable carbon footprint reductions since they include carbon footprint data from all stages of the value chain, figure 11 gives an example of what stages are usually considered in a typical EPD document.

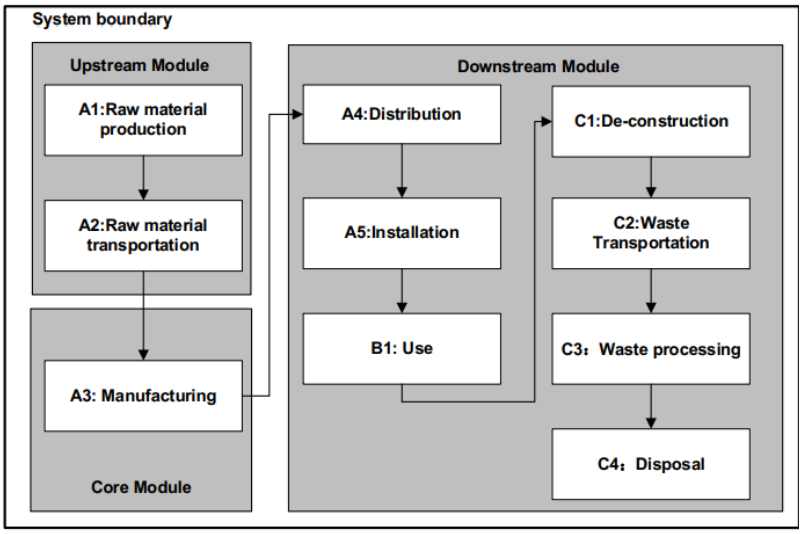
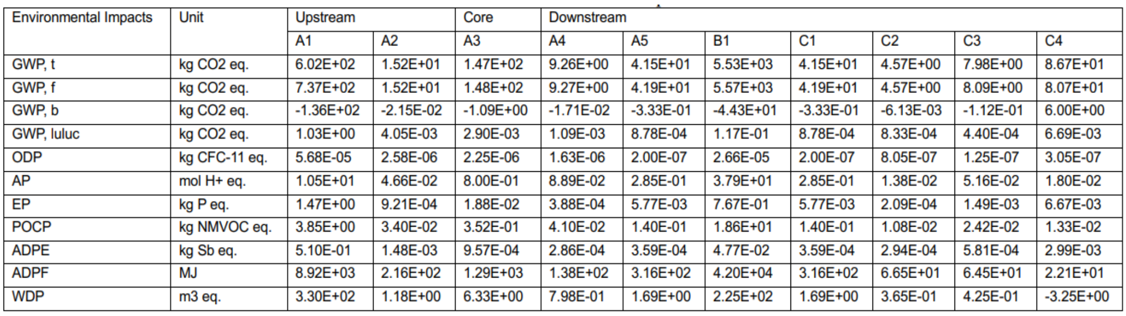


Figure 11 - Full value chain diagram [43].

Some EPDs divide their value chain into modules (Upstream module, Downstream Module and Core module) according to a particular Product Category Rule (PCR) that they must follow. A PCR is a set of specific guidelines that define how LCAs should be conducted for a particular product category. It ensures that all EPDs within the same category are developed using consistent methods, making them comparable and credible. The PCR provides the methodology to calculate the environmental impacts for a specific type of product. The EPD must follow an approved PCR to ensure they meet international standards, such as ISO 14025. The PCR dictates which life cycle stages to consider, what types of environmental impacts to report, and how to format the results [42]. For instance, the EPD where the diagram of figure 11 is from follows primarily the PCR EPDItaly007 – Electronic and electrical products and systems [43].

In these EPDs a table in accordance with the PCR being followed is provided, that shows all the potential environmental impacts of the declared product like figure 12 exemplifies.



Environmental Impacts	Unit	Upstream		Core	Downstream						
		A1	A2	A3	A4	A5	B1	C1	C2	C3	C4
GWP, t	kg CO2 eq.	6.02E+02	1.52E+01	1.47E+02	9.26E+00	4.15E+01	5.53E+03	4.15E+01	4.57E+00	7.98E+00	8.67E+01
GWP, f	kg CO2 eq.	7.37E+02	1.52E+01	1.48E+02	9.27E+00	4.19E+01	5.57E+03	4.19E+01	4.57E+00	8.09E+00	8.07E+01
GWP, b	kg CO2 eq.	-1.36E+02	-2.15E-02	-1.09E+00	-1.71E-02	-3.33E-01	-4.43E+01	-3.33E-01	-6.13E-03	-1.12E-01	6.00E+00
GWP, luluc	kg CO2 eq.	1.03E+00	4.05E-03	2.90E-03	1.09E-03	8.78E-04	1.17E-01	8.78E-04	8.33E-04	4.40E-04	6.69E-03
ODP	kg CFC-11 eq.	5.68E-05	2.58E-06	2.25E-06	1.63E-06	2.00E-07	2.66E-05	2.00E-07	8.05E-07	1.25E-07	3.05E-07
AP	mol H+ eq.	1.05E+01	4.66E-02	8.00E-01	8.89E-02	2.85E-01	3.79E+01	2.85E-01	1.38E-02	5.16E-02	1.80E-02
EP	kg P eq.	1.47E+00	9.21E-04	1.88E-02	3.88E-04	5.77E-03	7.67E-01	5.77E-03	2.09E-04	1.49E-03	6.67E-03
POCP	kg NMVOC eq.	3.85E+00	3.40E-02	3.52E-01	4.10E-02	1.40E-01	1.86E+01	1.40E-01	1.08E-02	2.42E-02	1.33E-02
ADPE	kg Sb eq.	5.10E-01	1.48E-03	9.57E-04	2.86E-04	3.59E-04	4.77E-02	3.59E-04	2.94E-04	5.81E-04	2.99E-03
ADPF	MJ	8.92E+03	2.16E+02	1.29E+03	1.38E+02	3.16E+02	4.20E+04	3.16E+02	6.65E+01	6.45E+01	2.21E+01
WDP	m3 eq.	3.30E+02	1.18E+00	6.33E+00	7.98E-01	1.69E+00	2.25E+02	1.69E+00	3.65E-01	4.25E-01	-3.25E+00

Figure 12 - Example of an environmental impact table for each stage of the value chain [43].

The abbreviations present in the figure are:

- GWP, t: Global Warming Potential total
- GWP, f: Global Warming Potential total fossil fuel
- GWP, b: Climate change - biogenic
- GWP, luluc: Climate change - land use and change in land use
- ODP: Ozone Depletion
- AP: Acidification
- EP: Eutrophication of water
- POCP: Photochemical ozone formation
- ADPE: Consumption of abiotic resources - minerals and materials
- ADPF: Consumption of abiotic resources - fossil resources
- WDP: Water consumption

These impacts may vary depending on the type of product being declared but it’s important to note that the GWP, t impact is what matters in this study since it measures the total climate impact, including fossil, biogenic, and land use changes in kg $CO_{2\ eq}$ by each stage.

6.2.2 Specifications of the Components and EPD Analysis and Collection

First and foremost, before researching any EPD for each particular component it was important to define what components were being considered for this phase and then try to find a respective EPD. Table 3 provides all the components being considered for the calculation of total carbon emissions as well as their respective specifications and quantities, these components were considered the most relevant to include in this calculation.

Table 3 – Asset quantities and specifications

Components	Quantities	Unit	Specifications
Autotransformer ONAN/ONAF$^{(*)}$	1	Un	450 MVA 400kV/150kV

Auxiliar distribution transformer	3	Un	400/0,4 KV – 100 kVa
Inductive voltage transformer	3	Un	400kV 50kA 2,5Lf (2x100/√3 + 100/3) (0,2 - 2x3P)
Capacitive voltage transformer	12	Un	400kV 50kA 2,5Lf (2x100/√3) (0,2 - 1x3PT2)
Current transformer	15	Un	400kV 50kA 2,5Lf (750-1500-3000/1A) (0,2S - 0,5 - 4x5P20)
Current transformer	3	Un	400kV 50kA 2,5Lf (750-1500-3000/1A) (0,2S - 0,5 - 3x5P20)
Pantograph disconnector SP 4002	7	Un	400kV 3150A 50kA 2,5Lf
Vertical Rotary Disconnector SV 4001	3	Un	400kV 3150A 50kA 2,5Lf
Vertical Rotary Disconnector SV 4003	3	Un	400kV 3150A 50kA 2,5Lf
Earth Disconnector	2	Un	400kV 50kA 2,5Lf
Insulators	960	Un	
Circuit Breakers	5	Un	400kV 3150A 50kA 2,5Lf
Batteries	54	Un	300Ah
Surge Arresters	9		400kV 50kA Ind 20kA Clas.(4) 2,5cm/kV
Telecontrol (Command and control systems)	1	Un	
Cabinets	46	Un	
Concrete	5280	Tons	
Metal Structures	139	Tons	
Ground Cable	15000	m	150mm^2
Low Voltage Cable	750	m	2 x 2,5mm^2
	460	m	2 x 4mm^2
	90	m	2 x 6mm^2
	950	m	2 x 10mm^2
	1350	m	4 x 2,5mm^2
	450	m	4 x 4mm^2
	10000	m	4 x 6mm^2
	1900	m	4 x 10mm^2
	25	m	4 x 16mm^2
	1000	m	7 x 2,5mm^2
	575	m	14 x 2,5mm^2
	2100	m	19 x 2,5mm^2
	1400	m	24 x 2,5mm^2
	600	m	37 x 2,5mm^2

	1700	m	1 x 95mm^2
	130	m	1 x 95 mm^2 RV -K
	200	m	1 x 120 mm^2
	450	m	3 x 50 + 25mm^2
XV Cable	20	m	3G 1mm^2
	800	m	3G 2mm^2
	50	m	5G 2,5mm^2

*ONAN – Oil Natural, Air Natural (51.1%)

*ONAF – Oil Natural, Air Force (100%)

With the components defined, the research for EPDs of these components began. The research was mainly conducted on EPD Italy and some in EPD Norge. To search for EPDs, it was first ensured that the EPD existed by confirming its availability within the available databases. Once confirmed, the EPD with the most similar specifications to the component in question was selected. It is very important to note that for each specific component an exact corresponding EPD of that component might not yet exist in the EPD archives, therefore, a few assumptions had to be made which were:

- The disconnector types were generalized into a single disconnector EPD
- When selecting EPDs for cables, the cables were grouped based on the availability of EPDs. For example, an EPD was found only for a 16 x 2,5mm^2 cable, so it was grouped with 19 x 2,5mm^2 ; 24 x 2,5mm^2 ; 37 x 2,5mm^2 cables, since specific EPDs for those sizes didn't exist. If an EPD with close specifications was found, then it would also be used for cables that could fit in that range. This approach was used to ensure that the available EPDs could still be applied to cables with similar characteristics, allowing for a broader comparison.
- All the different metal components used in the substation were generalized in one EPD that used the same type of metal composition.

With that said, all the relevant information from the EPDs collected was organized in an Excel spreadsheet. Given that the total GWP is the data that matters in this study, table 4 is provided with just the total GWP of each equipment and additionally a graph is provided in figure 13 to help visualize the proportion of total carbon emissions contributed by each component.

Table 4 – GWP of each component found in the EPDs

Components	GWP of one unit (ton CO$_2$e)
Autotransformer – [Confidential by author request]	39875.1
Auxiliar Distribution Transformer – [44]	29.9
Disconnector – [45]	33.73
Current Transformer – [46]	10.9
Capacitive Transformer – [47]	3.7
Inductive Transformer – [48]	21.4
Live Tank Circuit Breaker – [49]	198.2
Insulator –[50]	0.05

Command and Protection Systems – Telecontrol – [51]	0.8
Cabinets – [52]	4.6
Battery – [53]	3.9
Metal Structures – [54]	3.6
Low Voltage Cables – [55], [56], [57], [58], [59], [60]	65.7
Concrete – [54]	0.9
Surge Arrester - [Confidential by author request]	0.4

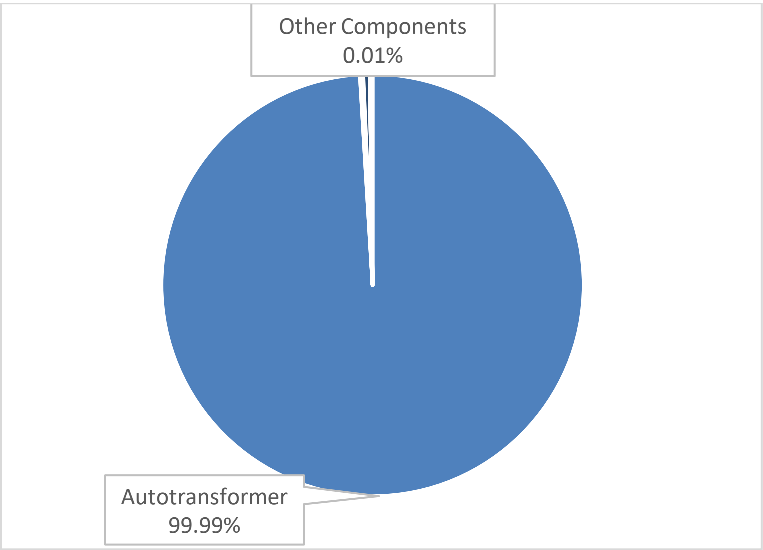


Figure 13 - Carbon footprint proportion by unitary component (Elaborated by the author).

It is important to note that this GWP data represents 1 unit during the entirety of the component's lifetime. Additionally, it's also important to note that the lifetime of the whole substation in question is 42 years. Figure 13 provides a visual representation of the lifetime of each component considered compared to the lifetime of the Ponte de Lima Substation. This information can be found in the EPDs collected.

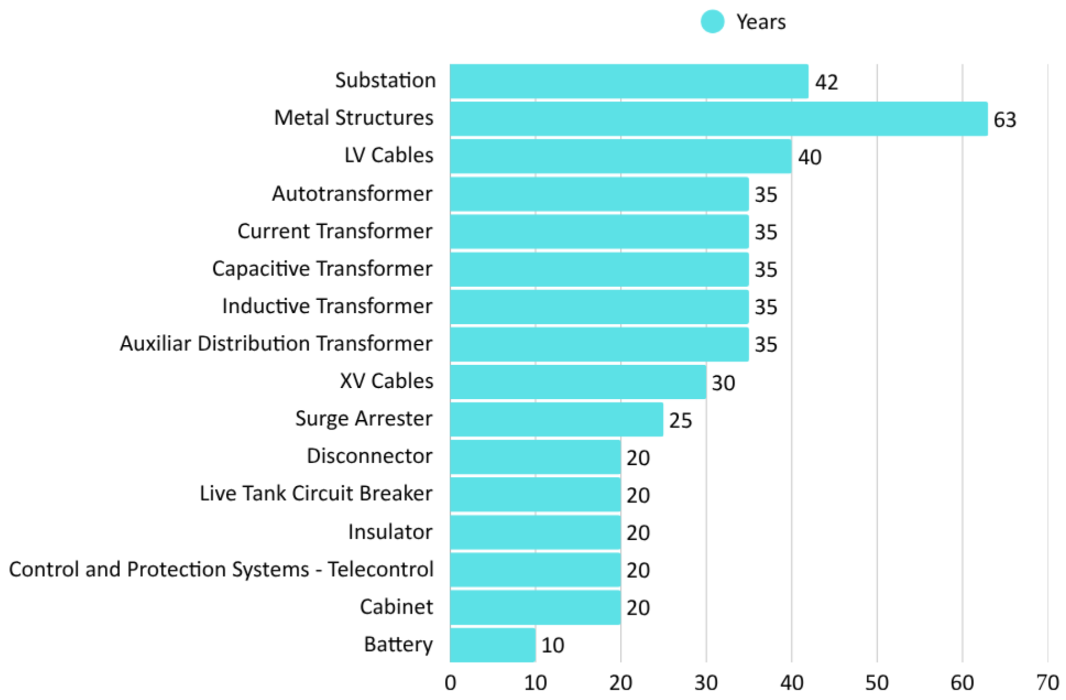


Figure 14 - Service lifetime of all the components (Elaborated by the author).

As we can observe from figure 13, the autotransformer represents nearly 100% of the total carbon footprint in a substation during its lifetime according to all the data compared, clearly being the most impactful component present. The resultant carbon footprint of the autotransformer, derived from the EPD, aligns closely with findings from existing studies of LCA of power transformers, even though the design of an autotransformer differs slightly from that of a traditional power transformer.

These differences in design makes autotransformers smaller, lighter, cheaper and often more efficient than a transformer of the same rating, using less material due to fewer windings. These differences make an impact on their losses, with an autotransformer generally having lower copper losses [61]. This leads to better operational efficiency, meaning less energy is lost as heat, and consequently, fewer CO_2e emissions are generated during the transformer's operational life. This explains why the total CO_2e emissions of the autotransformer EPD was impactful but lower than for example a case study from 2022 that measured GHG emissions from two different power transformers based on LCA. This case study revealed that during the operational stage a power transformer can reach up to hundreds of kilotons of CO_2e in 40 years of service lifetime. One of the transformers with a 220 kV voltage had an operation stage emission of 180000 tons of CO_2e by the end of its 40-year lifetime, showcasing just how impactful is the operation stage in comparison with all the other stages of a transformer life cycle like raw material acquisition and manufacturing, accounting for 96% of the total emissions in the transformer lifecycle [62].

This stark difference in carbon emissions in the operational stage is due to power losses where no-load losses and load losses make up the entirety of transformer power loss. Load losses occur when the transformer is under load, meaning it's supplying power to the system or connected devices. These losses primarily arise from the resistance in the windings of the transformer, which causes heat and results in energy loss when current flows through them. On the other hand, no-load losses occur when the transformer is energized but not supplying any power. These losses are mainly due to the magnetic core of the transformer and are independent of the load current [63]. Even though power losses account for 1% of the total electricity in a power transformer, during the entirety of a transformers lifetime it adds up. Load losses can contribute up to 82% of the total value of GWP 100 (Global Warming Potential over a 100-year period), while no-load losses can contribute at least 16% of the total climate change for a 500 MVA transformer [64]. This means that if the GHG emission of the transformer is to be reduced and subsequently the GHG emissions of the substation, the most important stage is to reduce its operating power loss [62].

6.2.3 Total Emissions Calculated Considering Quantities and Replacement Cycles.

By gathering the GWP information from the EPDs of each equipment we can multiply it by the quantity of the components being used in the substation, additionally the number of replacements for each component needed within a 42-year time frame also needs to be taken into account considering the information previously given on figure 14. The number of replacements was multiplied by the GWP previously calculated by multiplying the quantity of components. It was considered that the components with a service lifetime above 30 years could be prolonged to 42 years hence not needing replacements. Table 5 shows the result of the GWP for each component considering their number of replacements in 42 years and quantities.

Table 5 – Total Emissions of the Components Considering Replacement Cycles

EPDs	**Number of Replacements in 42 years**	**Total Emissions (ton CO_2e)**
Autotransformer	0	39875
Auxiliar Distribution Transformer	0	90
Disconnector	1	1011.9
Current Transformer	0	196.3
Capacitive Transformer	0	11.2
Inductive Transformer	0	64.1
Live Tank Circuit Breaker	1	1982.1
Insulator	1	34

Control and Protection Systems - Telecontrol	1	1.6
Cabinet	1	92
Battery	3	639
Metal Structures	0	196
Low Voltage Cables	0	81.3
Concrete	0	4528
Surge Arrester	1	7.21
Total GWP		48809.6

6.2.4 Emissions of the Transportation of Components.

To complete the emission calculations of the construction phase, the transportation process of the components to the site location needs to be considered. The location where the components were manufactured can be found in the EPDs, knowing this, an average distance between the manufacturing location and the construction site can be assumed. The type of transportation used was also assumed according to the type of component. Table 6 shows the types of transportation considered with their respective emission factors per kilometer provided by REN.

Table 6 – Emission factors for each respective mode of transportation

Transportation Mode	**CO_2**	**CH_4**	**NO_2**	**Total Emission factor (kg CO2e/t.km)**
Road - Heavy Goods Vehicle (all diesel) - All rigids and with 100% laden	0.1	0.00002	0.001	0.1
Sea - Cargo ship - General cargo - Average	0.01	0	0.0002	0.01

Table 7 provides the manufacturing locations as well as the distances assumed, mode of transportation assumed and the total CO_2e emissions in tons. It was assumed that the smaller components that were manufactured in the same location were transported in the same transport. Additionally, since the low voltage cables are manufactured all over Europe it was assumed an average distance for all. The command and protection systems – telecontrol and surge arresters were included as manufactured in Europe too.

Table 7 – Manufacturing locations of the components

Manufacturing Location	Components	Average Distance Assumed (Km)	Transport Mode	CO_2 (Tons)
China	Disconnector; Circuit Breaker Live Tank; Inductive Transformer; Capacitive Transformer; Current Transformer; Batteries; Insulators; Cabinets	21000	Cargo Ship	0.3
Portugal	Concrete; Metal Structures	100	Heavy Goods Vehicle	0.01
Brazil	Auxiliar Distribution Transformer	7000	Cargo Ship	0.09
Germany	Autotransformer	3500	Cargo Ship + Heavy Goods Vehicle	0.06
Europe	Command and Protection Systems – Telecontrol; Surge Arresters; Cables	2500	Heavy Goods Vehicle	0.3

Regarding the autotransformer due to its considerable size, it was assumed that the final 100 Km of those 3500 Km assumed was made by a heavy vehicle. The emissions were calculated by multiplying the distances by the emission factors, overall, the total emissions caused by the transportation of these components to the construction site was just 0.8 tons of CO_2e.

6.2.5 Final Emissions of the Construction Process.

To finalize the construction phase calculations, the construction itself must be accounted for. Furthermore, the safety and construction coordination were considered within this process.

The emissions caused by both of these actions were provided by the contractors and it amounts to 54.8 tons.

6.2.6 Construction Phase Result

Considering the information found in the respective EPDs, the replacement cycles as well as the quantity of components used, considering also how these components got to the site area and the construction process itself the total emissions of all of these activities amount to 47828.3 tons.

6.3 Exploration and Maintenance Phase

In this phase, all additional maintenance activities to be carried out during the project's lifecycle are considered. The accounting includes the number of trips to the site for maintenance, the duration of each maintenance activity, the travel distance, the vehicle's emission factor, and finally, emissions from any equipment used.

During the exploration and maintenance phase, the following emissions from these types of maintenance activities were considered:

- **Panel Maintenance (C1)** - Inspection, cleaning, testing, and tightening of electrical components inside control and protection panels to ensure safe and reliable operation.
- **Circuit breaker (C2)** - Inspection, cleaning, lubrication, and testing of circuit breaker components to ensure proper operation and fault interruption.
- **Command, control, and protection systems (C3)** - Checking, testing, and verifying the operation of systems that monitor, control, and protect electrical equipment in the substation.
- **Thermography (C4**) - Infrared scanning of electrical equipment to detect abnormal heat patterns that indicate potential faults or failures.
- **Clearing of adjacent lands (C5)** - Removal of vegetation and obstacles around the substation to prevent fire hazards, ensure accessibility, and maintain safety clearances.
- **Weed cleaning (C6)** - Removal of weeds within the substation area to prevent obstruction, reduce fire risk, and maintain clear access to equipment.
- **Visual Inspections (C7)** - Routine checks of equipment and installations to identify visible signs of damage, wear, or abnormalities.

For the calculation it was considered the number of times each maintenance is done over the substation lifetime and the number of days needed for each maintenance. Additionally, the amount of equipment was considered, and the emissions of said equipment were considered for each maintenance activity. The distance traveled to the site area and the number of vehicles used during the whole project lifecycle was also considered. Table 8 provides the data about each type of maintenance. It is important to note that C5 was calculated differently from the other maintenance types, therefore it is not considered in the table below.

Table 8 – Maintenance types

Maintenance Type	N_m	$N_{d/m}$	N_{eq}	N_v
C1	5	5	1	2
C2	6	2	1	2
C3	20	1	0	1
C4	41	1	1	1
C6	168	1	0	1

C7	168	1	0	1

Where:

- N_m is the number of maintenances done in 42 years, which is the established lifetime of the substation.
- $N_{d/m}$ is the number of days that each type of maintenance usually takes.
- N_{eq} is the number of equipment's utilized for each maintenance type, in this case diesel articulated platforms were considered as relevant.
- N_v is the number of vehicles needed to transport everything.

To accurately calculate the total emissions (T_e) of the maintenance a few auxiliar calculations had to be made.

6.3.1 Calculation of the Emissions of the Equipment's Used.

For this calculation the only relevant equipment used is the articulated diesel platform. The articulated platform works for 4 hours and has a consumption of 3 liters per hour therefore using 12 liters of diesel.

The emissions of the equipment used during the entirety of the substation lifetime was calculated with the following equation 2 which is also of the author's own elaboration, developed by combining the fuel consumption with the respective emission factor, multiplied by the parameters of the maintenance activities.

$$EQ_e = (F_c \times EF_{Diesel}) \times N_m \times N_{d/m} \times N_{eq} \tag{2}$$

Where:

- EQ_e is the equipment's emissions
- F_c is the fuel consumption which is 12 liters.
- EF_{Diesel} is the emission factor of diesel which is 2.7 Kg CO_2 [65].

6.3.2 Calculation of the Emissions of Vehicles Used.

For this calculation it was considered that a Mitsubishi L200 was used as transportation which emits 0.19 Kg CO_2e/Km. This was calculated by adding the emission factor of all the gases with GWP provided by REN and the manufacturer of the vehicle, that are emitted (CO_2, CH_4, and N_2O) during combustion. This equation is also original, designed based by the author on the standard methodology for transport emissions (activity × emission factor × distance).

The total emissions of using vehicles can be calculated by the following equation 3:

$$TV_e = EF \times T_d \times N_V \times N_m \tag{3}$$

Where:

- TV_e means total vehicle emissions.
- T_d is the total distance travelled which was assumed to be 300 Kilometres total

6.3.3 Calculation of C1, C2 and C4 Maintenance Types

Since these maintenances share the fact that diesel articulated platforms are needed and also transportation to the site area, they can be lumped together and calculated by the following equation 4. This equation was elaborated by the author, based on the identified activity data and emission factors.

$$C_{1/2/4} = EQ_e + TV_e \tag{4}$$

6.3.4 Calculation of C3, C6 and C7 Maintenance Types

These maintenance types do not need to be carried out with diesel articulated platforms, so their emissions derive only from traveling to the site area. Therefore, C3, C6 and C7 are equal to TV_e.

6.3.5 Calculation of C5 Maintenance Type

This type of maintenance is for the removal of regrowth vegetation such as eucalypts and maritime pines around the substation area, and it is done by the same contractors who intervened in the site area phase. For this reason, the transportation related emissions used for the calculation of this maintenance type are the same emissions provided by the contractor which is 80 kg of CO_2e. For the calculation of this maintenance type the same logic as the site area phase calculation applies but with different amounts of intervention done and also types of intervention. Table 9 shows what interventions were done and amount of it for this maintenance activity.

Table 9 – Intervention typer per forest area

Intervention Type	Emissions per Intervention Type in Eucalyptus Forest (kgCO2e/ha)	Amount of intervention done in Eucalyptus Forest area	Amount of intervention done in Maritime Pine Forest areas	Emissions per Intervention Type in Maritime Pine Forest (kgCO2e/ha)
Tree felling, sectioning, and	0	0%	0%	0

gathering (clear-cutting)				
Tree felling, sectioning, and gathering (thinning)	0	0%	0%	0
Felling of isolated trees + Dismantling of trees + Topping or pruning of trees	61	20%	20%	61
Brush clearing	133.4	80%	80%	133.4
Stump removal	0	0%	0%	0
Soil mobilization (Pre-planting)	0	0%	0%	0

The calculation of this maintenance type can be expressed by the same equation used for the site area phase but with the only difference that this is an intervention done every year so it's necessary to multiply it by the years of the substation lifetime which was established as 42 years. Equation 5 goes as follows:

$$TE_{ft} = \left[\left(\left(\sum(E_{ti} \times A_{i(\%)})\right) + E_t\right) \times ha\right] \times 42 \tag{5}$$

The total maintenance emissions (T_e) is the sum of equipment emissions and vehicle emissions which equals 3468.5 tons.

6.4 Forest Balance

For simplicity's sake, this phase was divided into two separate categories of forest balance. The first category is the forest balance in adjacent terrains, and the second category is the forest balance in the platform, slopes, and accesses. In each category the CO_2e stock loss and the loss of sink capacity is calculated and then it's added together to get the forest balance.

6.4.1 Forest Balance of Adjacent Terrains

It is considered that adjacent terrains are any natural terrains that surround the infrastructure of the substation. The following table 10 shows the values to calculate the CO_2e stock loss of adjacent terrains in eucalyptus and maritime pine shrubland.

Table 10 – CO_2e stock loss of adjacent terrains for each type of soil occupation

Soil Occupation	**S0 LB/T**	**S0 LB/U**	**S0 DB**	**IA**	**CO_2e Loss$_{AT}$**

Eucalyptus forest shrubland	63.6	6.6	1.21	8	571.6
Maritime pine forest shrubland	82.5	5.7	2.2	13.1	1183.1

Where:

- S0 LB/T is the live biomass and trees stock ton CO2e/ha on year 0
- S0 LB/U is the live biomass and understory stock in tons CO2e/ha on year 0
- S0 DB is the dead biomass stock in tons CO2e/ha on year 0
- IA is the intervention area in hectares
- CO_2e $Loss_{AT}$ is the stock loss of CO_2e of adjacent terrains in tons

The stock loss of CO_2e in adjacent terrains is calculated by the following equation 6:

$$CO_2eLoss_{AT} = (S0_{LB/T} + S0_{LB/U} + S0_{DB}) \times IA \qquad (6)$$

Table 11 shows the values for the loss of sink capacity for adjacent terrains for each type of soil occupation.

Table 11 – CO_2e loss of sink capacity for each type of soil occupation

Soil Occupation	**Seq_i**	**IA**	**CO_2eLSC_{AT}**
Eucalyptus forest shrubland	39.1	8	13135.9
Maritime pine forest shrubland	8.6	13.1	4713.4

Where:

- Seq_i (initial sequestration) is the amount of carbon initially sequestered in the soil in tons of CO_2e /ha/year
- CO_2e LSC_{AT} is the CO_2e loss of sink capacity of adjacent terrains in tons

The CO_2e loss of sink capacity in adjacent terrains is calculated by the following equation 7:

$$\mathrm{CO}_2eLSC_{AT} = Seq_i \times IA \times 42 \qquad (7)$$

The total forest balance of the adjacent terrains is the sum of CO_2e stock loss and CO_2e loss of sink capacity which equates to 13707.6 tons of CO_2e.

6.4.2 Forest Balance of the Platform, Slopes, and Accesses

The platform is considered the levelled area where the whole substation infrastructure will be installed, whereas the slopes are the transition areas where the platform has been cut into a hill or built up with fill. The accesses are roads or paths that provide an entry to the substation.

The following table 12 shows the values to calculate the CO_2e stock loss of the platform, slopes and accesses in eucalyptus and maritime pine shrubland.

Table 12 – CO_2e stock loss of the platform, slopes and accesses for each type of soil occupation

Soil Occupation	S0 LB/T	S0 LB/U	S0 DB	IA	$CO_2eLoss_{P/S/A}$
Eucalyptus forest shrubland	63.6	6.6	1.2	2.9	207.2
Maritime pine forest shrubland	82.5	5.7	2.2	3.4	307.1

Where $CO_2eLoss_{P/S/A}$ is the CO_2e stock loss of the platform, slopes and accesses in tons which can be calculated by the same equation 7.

Table 13 shows the values for the loss of sink capacity for the platform, slopes and access for each type of soil occupation.

Table 13 – CO_2e loss of sink capacity of the platform, slopes and accesses for each type of soil occupation

Soil Occupation	Seq_i	IA	$CO_2eLSC_{P/S/A}$
Eucalyptus forest shrubland	39.1	2.9	4761.8
Maritime pine forest shrubland	8.6	3.4	1223.3

Since these areas are considered permanently transformed from the start, only the initial sequestration is counted. Basically, in these areas it is considered that it is a permanent loss of forest cover since day 1 that continues for the lifetime of the project. This loss can be calculated exactly like equation 7.

Overall, by calculating the forest balance of the adjacent terrains and the platform, slopes and accesses and adding the results together, the total forest balance phase resulted in 26103.3 tons of CO_2e.

6.5 Decommissioning

In accordance with the RCN 2050 (Roadmap for Carbon Neutrality 2050), the decommissioning of assets is expected to produce no GHG emissions. Therefore, this phase is excluded from the quantitative emission calculations. No emission factors or formulas are applied, and no further data collection is required for this stage. The methodological focus is maintained on phases where emissions are expected. While this phase contributes zero emissions, the tool remains adaptable to accommodate any future updates.

7 Final Results

This chapter presents the final results and final findings of the lifecycle assessment for the Ponte de Lima substation. The aim was to have an estimation as close as possible to reality of total GHG emitted during the totality of the substation lifetime, from land clearing and equipment installation to the decades of operation and the eventual decommissioning. The final results were gathered up in the emission calculation tool, organized by all the phases and its constituents. As previously mentioned, the results were expressed in tons of equivalent CO_2 over a projected 42 year lifespan and the data was collected with EPDs, estimations and third-party information.

Beginning with phase A, the results for this phase amounted to 7.3 t CO_2e, originating entirely from the clearing of vegetation which included only two distinct forest types. Although it shows a significantly small impact, this phase marked the first disturbance to the ecosystem which set in motion the longer-term impacts accounted for in Phase D (Forest Balance).

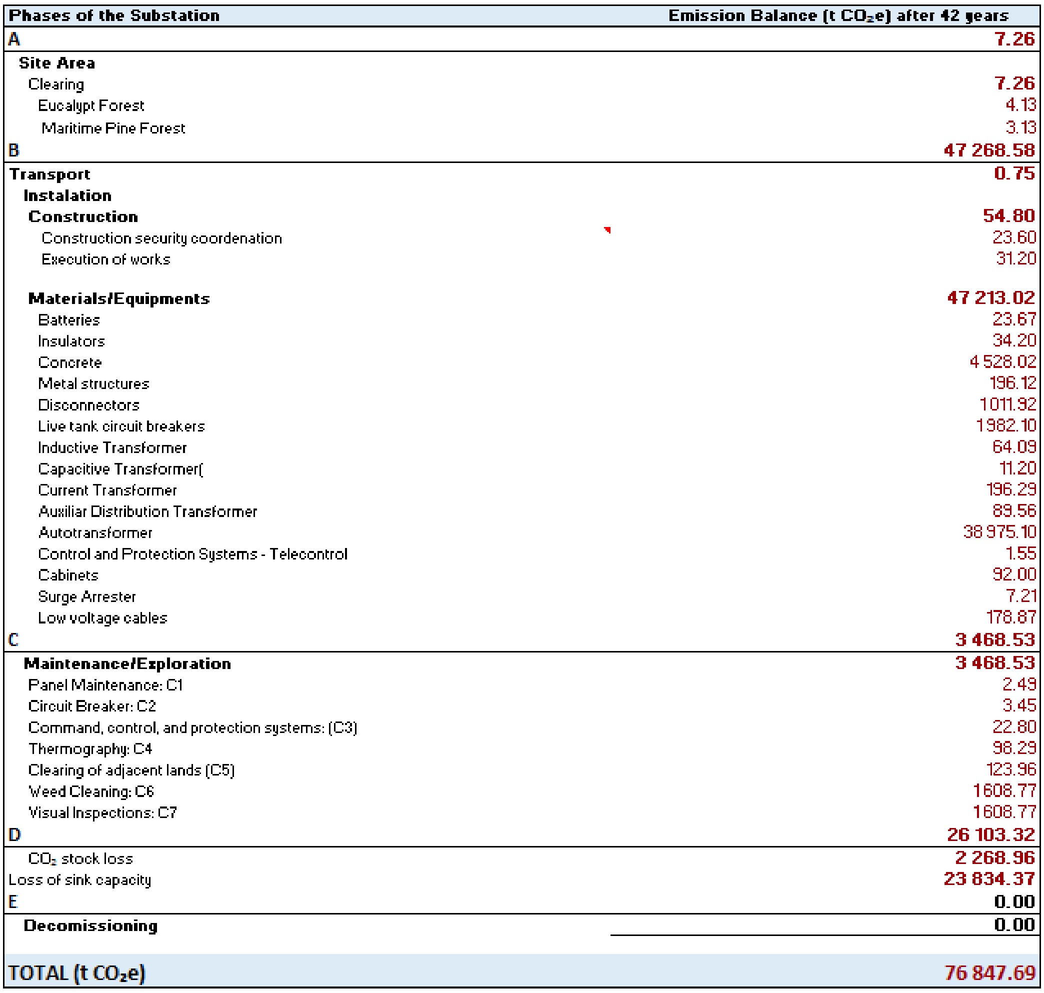
Regarding phase B it was shown to be by far the most carbon intensive phase amounting to a total of 47 268.6 t CO_2e. The transportation of the equipment and materials to the site area for installation and construction although coming from all corners of the world it only amounted to an estimated 0.8 tons. The construction of the substation itself also had a relatively small carbon impact only amounting to 54.8 tons. The most relevant part comes from the emissions caused by the equipment's and materials used which amounted to a total of 47 213 tons. This is to be expected since it was estimated using EPDs which are based on LCA. Unlike emissions from transport and construction, which are limited to specific activities, EPDs account for the entire lifecycle of each component from raw material extraction to manufacturing and even operational losses in some cases. This broader scope naturally leads to significantly higher emission values.

Phase C accounted for 3 469.5 tons where the maintenance types C5 and C6 has the most emissions. They had the same number of emissions since they required exactly the same number of maintenance cycles during the 42 years (a total of 168) hence being the most impactful maintenance type out of all.

Phase D was shown to be the second largest emission contributor, totalling 26 103.3 t CO_2e, with the Loss of sink capacity being the biggest contributor, since it represents the long term inability of the land to sequester carbon due to permanent removal of vegetation These results show just how impactful the simple removal of vegetation for area usage is in the grand scheme of things.

Finally, phase D accounted for 0 tons. It was previously mentioned that REN assumes that after the year 2050 when the substation enters de decommissioning phase the implementation of the RCN 2050 (Roadmap for Carbon Neutrality 2050) will take effect therefore no GHG emissions were expected in this stage.

Overall, the final emission balance estimation for the Ponte de Lima substation after 42 years of lifetime amounted to 76 847.7 t CO_2e. Figure 15 shows the totality summary of the estimations made for each phase and constituents. This table is present in the results sheet in the tool.



Phases of the Substation	**Emission Balance (t CO_2e) after 42 years**
A	**7.26**
Site Area	
Clearing	**7.26**
Eucalypt Forest	4.13
Maritime Pine Forest	3.13
B	**47 268.58**
Transport	**0.75**
Instalation	
Construction	**54.80**
Construction security coordenation	23.60
Execution of works	31.20
Materials/Equipments	**47 213.02**
Batteries	23.67
Insulators	34.20
Concrete	4 528.02
Metal structures	196.12
Disconnectors	1011.92
Live tank circuit breakers	1982.10
Inductive Transformer	64.09
Capacitive Transformer(	11.20
Current Transformer	196.29
Auxiliar Distribution Transformer	89.56
Autotransformer	38 975.10
Control and Protection Systems - Telecontrol	1.55
Cabinets	92.00
Surge Arrester	7.21
Low voltage cables	178.87
C	**3 468.53**
Maintenance/Exploration	**3 468.53**
Panel Maintenance: C1	2.49
Circuit Breaker: C2	3.45
Command, control, and protection systems: (C3)	22.80
Thermography: C4	98.29
Clearing of adjacent lands (C5)	123.96
Weed Cleaning: C6	1608.77
Visual Inspections: C7	1608.77
D	**26 103.32**
CO_2 stock loss	**2 268.96**
Loss of sink capacity	**23 834.37**
E	**0.00**
Decomissioning	**0.00**
TOTAL (t CO_2e)	**76 847.69**

Figure 15 - Final results table for all phases and constituents from the excel tool (Adapted from excel tool).

After analysing the final results table, it can be noted that phase B accounted for 61% of the total emissions, followed by phase D accounting for nearly 34% of the total emissions. Within phase B the autotransformer was shown to be by far the biggest carbon intensive equipment accounting for 82% of phase B. It was previously analysed in figure 13, the carbon footprint proportion of unitary components, which shown that the autotransformer was the unitary component with the largest carbon footprint totalling almost 100% of all the carbon footprint of the components. Figure 16 shows the carbon footprint proportion when accounting the quantities of each component and the number of component replacements.

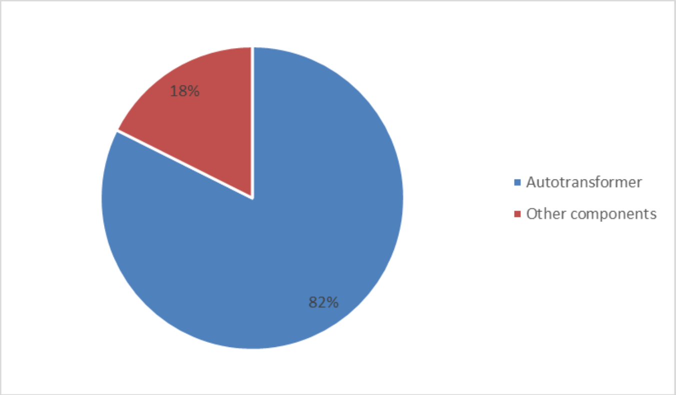


Figure 16 - Carbon footprint proportion with quantities (Elaborated by the author).

As we can see, despite the substation only having one autotransformer and never needing replacements during the substations lifetime it still is the most impactful component with 82% of carbon footprint. Figure 16 shows that in the entire substations' lifecycle the loss from a single autotransformer has a larger carbon footprint during its lifetime than all the components and materials combined including their replacements. Furthermore, this single autotransformer accounted for 51% of all the emissions considering the whole lifecycle.

The reliability of these findings depends on openly recognizing the boundaries of the analysis. Every methodological choice carries assumptions, and every dataset comes with uncertainties that must be acknowledged if the results are to be trusted.

Reflecting on these limitations does not weaken the study, rather, it strengthens it by showing where caution is needed and where further refinement is possible. Transparency in this regard is fundamental to ensuring credibility and building confidence in the pathways proposed.

8 Limitations

While this study provides a comprehensive assessment of circularity ideas and carbon estimation of the Ponte de Lima Substation, several limitations with this study must be acknowledged.

One of the limitations found was the lack of academic research on this topic. The circularity and sustainability aspect particularly in the power transmission sector remains underexplored in academia. In particular there is no comparable research about carbon estimation of a whole substation lifecycle which limits the ability to benchmark results, validate methodologies, or draw comparisons with established studies. The only valid study to benchmark methodologies and results was conducted by REN about high voltage transmission which was used as a basis for this study but differs in terms of materials and components used as well as work activities.

Another limitation is the fact that there is a lack of EPDs specifically on key components and materials of a substation. There is a lack of variety with regards to specifications of electrical components particularly in the area of high voltage power transmission with only EPD Italy and EPD Norge having archives of certain electrical components. This scarcity of component specific EPDs made it so that the methodology had to rely on approximations and estimations which introduces uncertainty on the final result for the total carbon emissions.

Furthermore, the inherent complexity of obtaining a detailed and in-depth carbon estimation of the whole substation lifecycle is a limitation in and of itself. Building a whole substation from scratch involves numerous components and activities which in turn involves the use and wear of various kinds of machinery each with their own manufacturing, operational and end of life emissions. As the analysis goes deeper it uncovers more layers that will add up to the total estimation of carbon emissions. Each machinery used, like the articulated platform and even simple tools, have their own supply chain, transportation and their eventual disposal emissions with often limited documentation and information.

While this study covers what is considered to be the most impactful activities and components of a substation lifecycle, the many layers that can still be uncovered makes it challenging to truly produce an exact estimation of the carbon footprint of the Ponte de Lima Substation.

9 Future Strategies for Total Carbon Footprint Reduction

To decrease the total carbon footprint substations their best attempt is to find a way to decrease the carbon footprint of the autotransformer from phase B and also to decrease their disturbance in the ecosystem from phase D, since these two phases were the most impactful to the overall GWP of the entire project.

With regards to phase D the most effective way for REN to mitigate the carbon impact of the ecosystem disturbance is through reforestation strategies. By restoring equivalent or larger areas of cleared land with native, high-sequestration vegetation, REN can generate long term carbon uptake converting a onetime carbon loss into a regenerative carbon sink, which accumulates over decades.

With regards to phase B one of the ways REN can tackle this issue is by improving their procurement process to increase progressively sustainability requirements when evaluating and selecting a power transformer for a new substation project. This can be done by prioritizing suppliers that offer the lowest GWP per unit, in this case suppliers of power transformers often use a functional unit of kg of CO_2e per MVA. This could be proposed as a new operational indicator for REN to adopt, since it’s grounded in LCA thinking and it’s easy to verify with available EPDs. Additionally, a study where a comprehensive LCA study compared two transformer models, TRF-1 and TRF-2 reported emissions normalized per unit of capacity in t CO_2e per MVA verifying that it is an actual, academically validated indicator [66]. This indicator can also help compare which transformer option provides the required MVA with the lowest emissions per unit of service. If more TSOs start to use this metric in their procurement processes this can become a new benchmarking metric between suppliers encouraging them to innovate towards a low emission but high efficiency components and promoting circularity and lifecycle efficiency.

It is important to note with regards to the power transformers operational losses that it is influenced by the energy mix of where it happens to operate in. In this case due the Portuguese Energy and Climate Plan which foresee more than 80% RES in the electricity mix by 2030 the operational losses of a power transformer, such as an autotransformer, instead of the importance of the efficiency in terms of losses (represent wasted energy within the substation), these losses create a demand that must be compensated continuously over the transformer’s lifetime by the national grid. These losses must be replaced by additional electricity generation upstream, and this replacement power carries its own carbon intensity based on the country’s energy mix, this is a factor that EPDs of power transformers consider when creating an LCA. A country where the electricity is predominantly generated from fossil fuels, the operational losses of a transformer translate into higher indirect emissions, making efficiency and low-loss design critical. In contrast, in regions with a cleaner or renewable-heavy grid, the same losses would result in lower associated emissions, and efforts might be better focused on material circularity or recyclability. Therefore, the optimal strategy for minimizing emissions from substation equipment must consider the local energy mix, as it directly affects the emissions attributed to operational energy use over the asset’s lifespan. In the case of REN, there has been heavy investment in renewables in recent years therefore there may be a lower indirect emission factor compared to other regions, so there is already improvement in that aspect.

To conclude, if more and more TSOs like REN start to demand suppliers to provide EPDs for each of their products it can create a market pressure that encourages EPD certification and circular economy practices. When suppliers create an EPD they conduct a full LCA of their products accounting for raw material extraction, manufacturing processes, service emissions and end of lifetime emissions. By doing so they can uncover inefficiencies in their LCA pushing companies to redesign their products with lower impact materials, improve recyclability or their overall design which is all core circular economy principles. By demanding EPDs and adopting new indicators it can raise the baseline across the power sector normalizing circular economy.

10 Conclusion

This study began by providing a comprehensive analysis about CE principles, strategies and concepts and to examine the integration of this model within the operations of REN. This study also highlighted how CE offers a possibility to separate economic growth from the consumption of finite resources, addressing pressing global issues like climate change.

The EU shows that it is committed to change by implementing actions plans such as CEAP, which is a plan that shines light on the growing need to shift to a circular model and sets ambitious objectives such as doubling circular material use and achieving climate neutrality by the year 2050. Even though public awareness and agreement is rising and the reductions in landfill waste in the EU is remarkable, there are still challenges that the EU is facing such as stagnated recycling rates, high material consumption, and over-reliance on virgin resources. These challenges demonstrate that there is still room for improvement with regards to further integrate CE in Europe. With regards to Europe's challenges, it can be concluded that improvement can be accomplished by implementing improved policies, investing in innovative recycling technologies, and incentivise businesses as well as important sectors like the energy sector to adopt circular strategies.

Portugal also has their own challenges implementing CE strategies with its circular material use rate being only 2.6%, lagging the EU average and lack of investment in eco-innovations and of fiscal incentives for businesses with circular models. However, in the ETC CE Report 2022/5 Portugal has ways of tackling these barriers.

For TSOs, integrating circular strategies into their operations is particularly relevant, since they are responsible for managing vast infrastructures. By benchmarking several key TSOs from Europe it was found that while REN aligns with sector leaders in areas such as sustainable procurement, ecosystem regeneration, and the incorporation of CE into corporate strategies there are also gaps in areas such as comprehensive asset lifecycle management and the integration of specific CE targets into climate strategies, presenting clear opportunities for REN to strengthen its practices. REN could adopt strategies from Redeia since both have similar goals and strategies.

With regards to the methodology of this study, the lifecycle of the substation was broken down into phases where the carbon emissions could be estimated by each phase. Through this methodology it was found that between phase A, B, C, D and E, phase B had by far the biggest carbon emissions totalling 47213.2 tons of CO_2e which represents 61% of the 77 Kilotons total emissions of CO_2e calculated for the entire substation. In this phase B, through the leveraging of EPD documents it can be concluded that the autotransformer is by far the most impactful component of the substation due to its service lifetime losses which is consistent with findings in academic literature. That autotransformer alone accounted for 51% of the total emissions of the entire substation and 82% of the carbon footprint caused by all the components and materials in 42 years of service lifetime and replacement cycles.

Phase D was the second most impactful accounting for 34% of the total emissions. This phase is a phase that is not directly tied to equipment, construction or material emissions but rather to the disturbance and alteration of the carbon dynamics of the ecosystem. For phase D, reforestation emerges as a key mitigation strategy which REN has already taken steps in this direction with reforestation along transmission line corridors, turning carbon stock losses into long term carbon sinks. The reforestation sequestration process attempts to mitigate some of the damage done during the vegetation clearing process by restoring the loss of ecosystem with activities such as tree planting or ecological rehabilitation.

For phase B, the conclusion that can be had from the final results is that acquisition of power transformers requires a shift towards a more strategic and sustainable procurement practice. The traditional procurement practices for power transformers across most TSOs focus almost exclusively on cost efficiency as well as the rated capacity (MVA) needed. While these indicators are essential for procurement an additional environmental impact indicator could be consider. REN could be the pioneer in this aspect by also prioritizing transformer models that demonstrate lower carbon footprint, by leveraging and demanding EPDs and by using a functional indicator such as GWP per MVA. This indicator which expresses the total global warming potential (in kg or t CO_2e) per MVA of installed capacity allows for a direct comparison between equipment options in terms of carbon efficiency, not just technical performance. This indicator not only is academically sound but also used in EPDs of power transformers which enables a fair and accurate benchmarking practice across suppliers. Moreover, in addition to adding this environmental performance layer to an already multi-criteria decision-making process, REN can also mitigate the carbon footprint that results from the operational losses during the transformers lifetime by leveraging the energy mix of Portugal. The operational losses of a transformer are essentially an unavoidable consequence of power transmission. It was previously mentioned in this study that according to academia the operational stage of a transformer accounts for 96% of the total carbon footprint of the entire transformer lifecycle, this means that this carbon impact depends directly on the source of electricity used to compensate for those losses. Knowing this, REN can play a strategic role by supporting policies and grid management practices that favour the integration of renewables lowering the operational carbon footprint of their power transformers as a side effect.

Additionally, it was concluded that this study had some inherent limitations. One limitation found is the fact that the academic studies in this field, with particular focus on substation LCA, are non-existent or very scarce which means that the final estimation of this study can't be benchmarked against other similar studies. Another limitation was found during the making of the methodology with regards to the EPDs available. There is still a lack of EPD archives online in the power transmissions sector since it is not yet a requirement for manufacturers to do so, this made it hard to find component specific EPDs for an accurate estimation, hence why assumptions had to be made. Furthermore, it was also concluded that the methodology itself had a limitation, which is the complexity of the calculation and estimation of a full substation lifecycle. Each activity, however insignificant, and each tool used has its own impact which adds up in the final result. For this reason, it was determined from the get-go that only the highest impact activities and components would be accounted for.

Finally, it can be stated that if more TSOs begin requiring EPDs across their supply chains, it can create industry wide pressure for greater transparency and circular design, it can push innovation towards lower emission products accelerating the shift towards a more circular future. Overall, the analysis and results demonstrate that all objectives outlined for this study have been successfully addressed. TSOs and in particular REN can play a critical role in accelerating the transition of the power sector towards a circular economy, not just by their own sustainability efforts with regards to their infrastructures but by reshaping the behavior of their supply chains.

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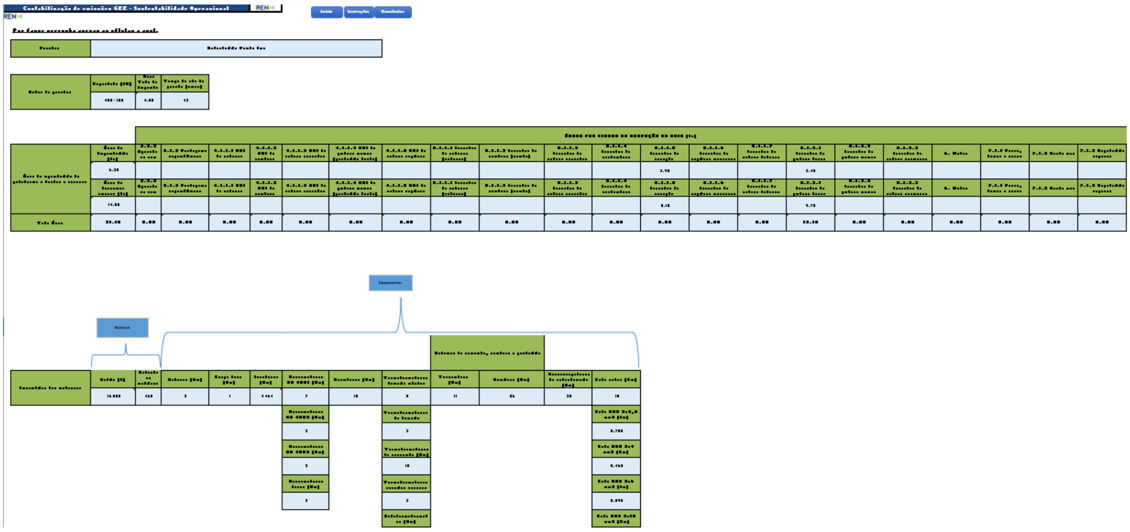
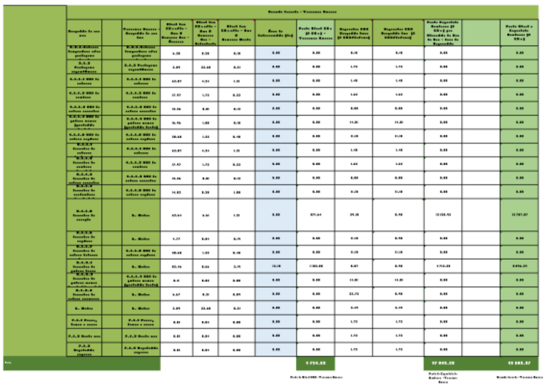
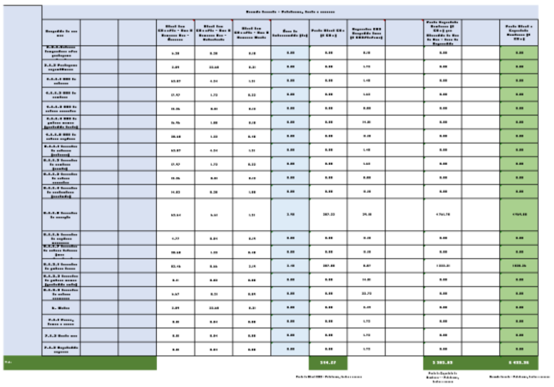
11 Annexes

11.1 Data Insertion Sheet for Quantities and Forest Balance







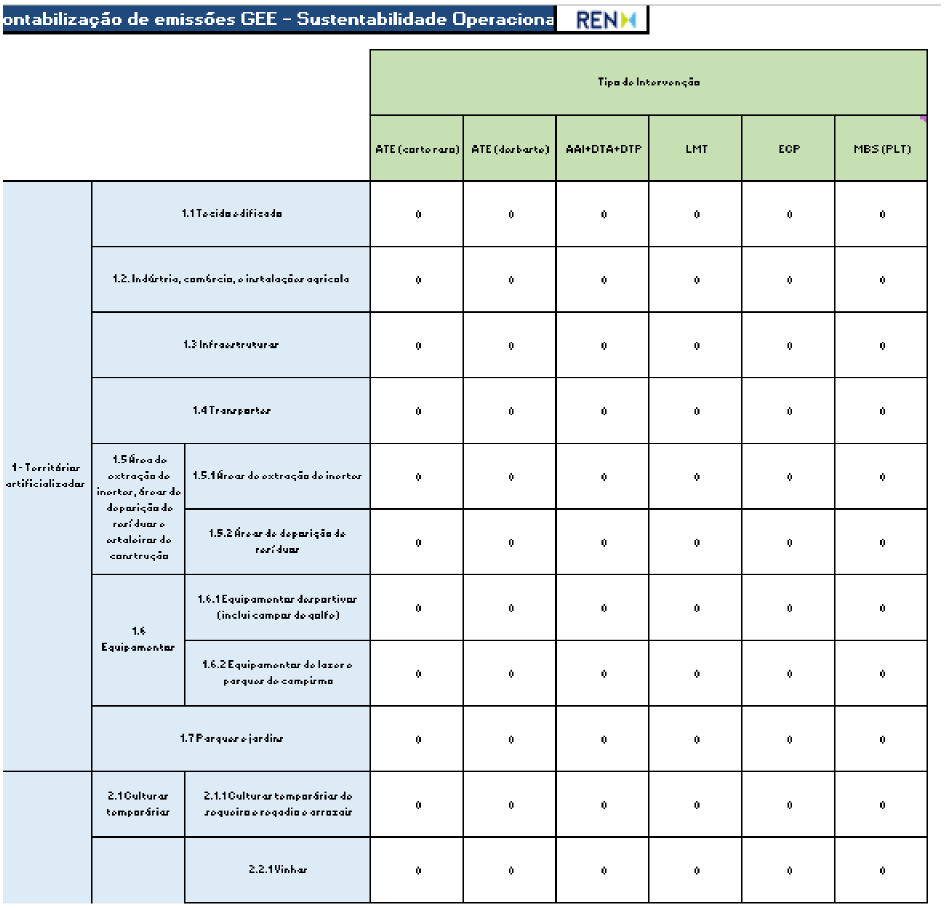
11.2 Calculation Tool Sheet

Contabilização de emissões GEE – Sustentabilidade Operacional

Ferramenta de cálculo de emissões

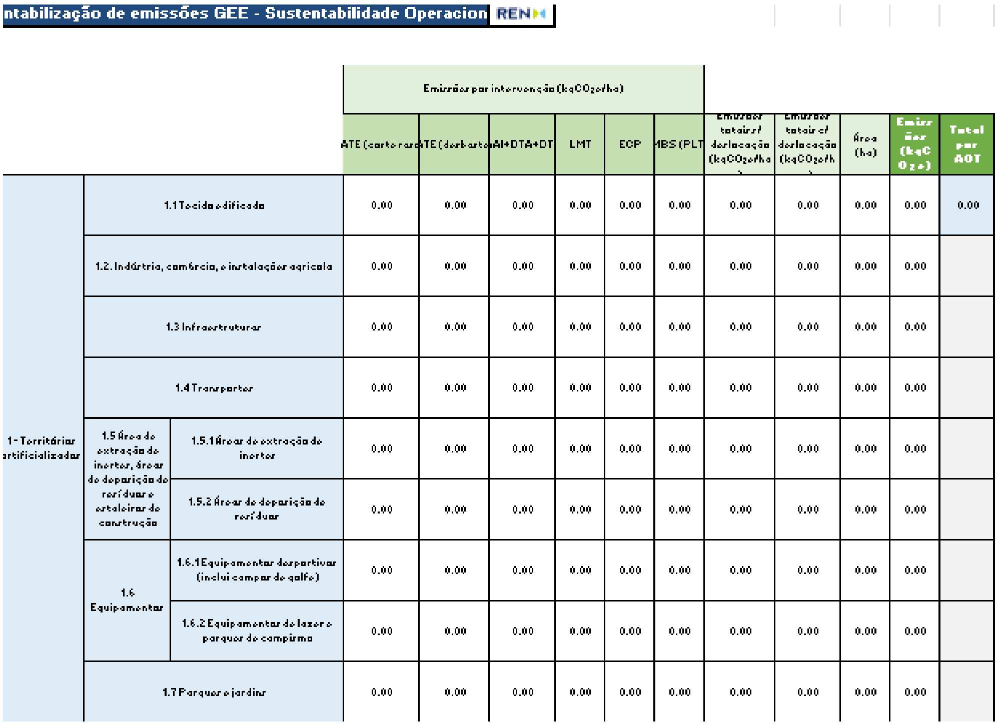
Fases	Fases 2	Atividade/Materiais	Observações	Fator de emissão por unidade (FE)	Unidade	Emissões TOTAIS (t CO_2e)	Ciclos de substituição em 42 anos	Emissões totais em 42 anos (t CO_2e)	Fonte:
A	Terrenos Anexos	Abertura	Floresta eucalipto		t CO_2e/ha	4.13	N/A	0.00	Redes e servidões
A	Terrenos Anexos	Abertura	Floresta pinheiro bravo		t CO_2e/ha	3.13	N/A	0.00	Redes e servidões
B	Transporte	Transporte de materiais e equipamentos	Locais de fabrico de materiais e equipamentos retirados das DAPs			0.75	N/A	0.75	Calculado com pressupostos
B	Instalação	Equipamentos	Baterias (Un)	3.94	t CO_2e/bateria	7.89	3	23.67	EPDItaly
B	Instalação	Equipamentos	Isoladores (Un)	0.018	t CO_2e/ isolador	17	2	34	EPDItaly
B	Instalação	Materiais	Betão (t)	0.86	t CO_2e/t betão	4 528	1	4 528	Relatório Anual 2023 Secil
B	Instalação	Materiais	Estrutura metálicas (t)	3.63	t CO_2e/t metal	196	1	196	Metalogalva
B	Instalação	Equipamentos	Seccionadores SV 4001 (Un)	33.7	t CO_2e/ Seccionador	236.11	2	472.23	EPDItaly
B	Instalação	Equipamentos	Seccionadores SV 4002 (Un)	33.7	t CO_2e/ Seccionador	101.19	2	202.38	EPDItaly
B	Instalação	Equipamentos	Seccionadores SV 4003 (Un)	33.7	t CO_2e/ Seccionador	101.19	2	202.38	EPDItaly
B	Instalação	Equipamentos	Seccionadores terra (Un)	33.7	t CO_2e/ Seccionador	67.46	2	134.92	EPDItaly
B	Instalação	Equipamentos	Disjuntores (Un)	198	t CO_2e/ Disjuntor	991.1	2	1 982.1	EPDItaly
B	Instalação	Equipamentos	Transformadores tensão indutivo (Un)	21.4	t CO_2e/ Transf. Tensão indutivo	64.09	1	64.09	EPDItaly
B	Instalação	Equipamentos	Transformadores de tensão capacitivo (Un)	3.73	t CO_2e/ Transf. Tensão Capacitivo	11.20	1	11.20	EPDItaly
B	Instalação	Equipamentos	Transformadores de corrente (Un)	10.90	t CO_2e/ Transf. Tensão Corrrente	196.29	1	196.29	EPDItaly
B	Instalação	Equipamentos	Transformadores serviços auxiliares (Un)	30	t CO_2e/ Transf. Auxiliar	90	1	90	EPDItaly

11.3 Emissions Factor Sheets of Intervention Activities



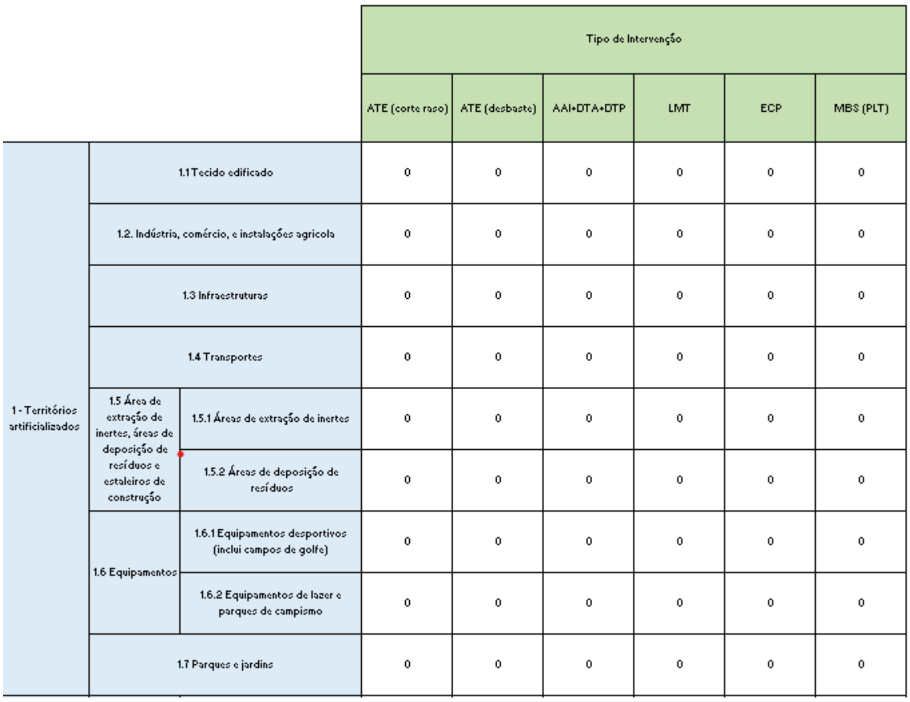
ontabilização de emissões GEE – Sustentabilidade Operaciona

			Tipo de Intervenção					
			ATE (corte raso)	ATE (desbaste)	AAI+DTA+DTP	LMT	ECP	MBS (PLT)
1 - Territórios artificializados	1.1 Tecido edificado		0	0	0	0	0	0
	1.2. Indústria, comércio, e instalações agrícolas		0	0	0	0	0	0
	1.3 Infraestruturas		0	0	0	0	0	0
	1.4 Transportes		0	0	0	0	0	0
	1.5 Área de extração de inertes, áreas de deposição de resíduos e estaleiros de construção	1.5.1 Áreas de extração de inertes	0	0	0	0	0	0
		1.5.2 Áreas de deposição de resíduos	0	0	0	0	0	0
	1.6 Equipamentos	1.6.1 Equipamentos desportivos (inclui campos de golfe)	0	0	0	0	0	0
		1.6.2 Equipamentos de lazer e parques de campismo	0	0	0	0	0	0
	1.7 Parques e jardins		0	0	0	0	0	0
	2.1 Culturas temporárias	2.1.1 Culturas temporárias de sequeiro e regadio e arrozais	0	0	0	0	0	0
		2.2.1 Vinhas	0	0	0	0	0	0

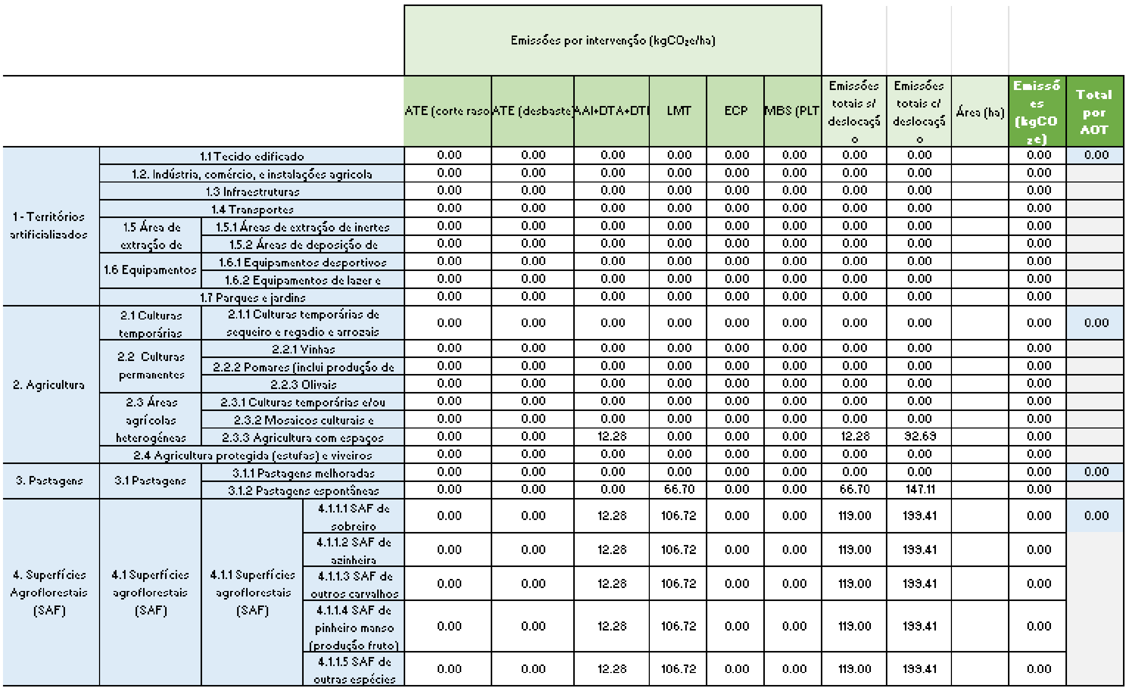


ntabilização de emissões GEE - Sustentabilidade Operacion

			Emissões por intervenção (kgCO2e/ha)										
			ATE (corte raso	ATE (desbaste	AI+DTA+DT	LMT	ECP	MBS (PLT	Emissões totais s/ deslocação (kgCO2e/ha)	Emissões totais c/ deslocação (kgCO2e/h	Área (ha)	Emissões (kgCO2e)	Total por AOT
1 - Territórios artificializados	1.1 Tecido edificado		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1.2. Indústria, comércio, e instalações agricola		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	1.3 Infraestruturas		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	1.4 Transportes		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	1.5 Área de extração de inertes, áreas de deposição de resíduos e estaleiros de construção	1.5.1 Áreas de extração de inertes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
		1.5.2 Áreas de deposição de resíduos	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	1.6 Equipamentos	1.6.1 Equipamentos desportivos (inclui campos de golfe)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
		1.6.2 Equipamentos de lazer e parques de campismo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	1.7 Parques e jardins		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

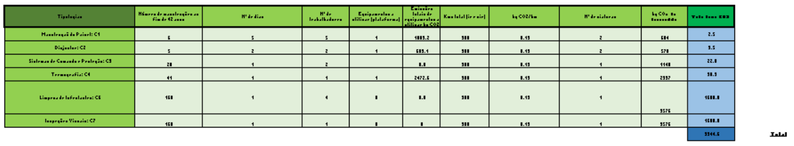


			Tipo de Intervenção					
			ATE (corte raso)	ATE (desbaste)	AAI+DTA+DTP	LMT	ECP	MBS (PLT)
1 - Territórios artificializados	1.1 Tecido edificado		0	0	0	0	0	0
	1.2. Indústria, comércio, e instalações agricola		0	0	0	0	0	0
	1.3 Infraestruturas		0	0	0	0	0	0
	1.4 Transportes		0	0	0	0	0	0
	1.5 Área de extração de inertes, áreas de deposição de resíduos e estaleiros de construção	1.5.1 Áreas de extração de inertes	0	0	0	0	0	0
		1.5.2 Áreas de deposição de resíduos	0	0	0	0	0	0
	1.6 Equipamentos	1.6.1 Equipamentos desportivos (inclui campos de golfe)	0	0	0	0	0	0
		1.6.2 Equipamentos de lazer e parques de campismo	0	0	0	0	0	0
	1.7 Parques e jardins		0	0	0	0	0	0

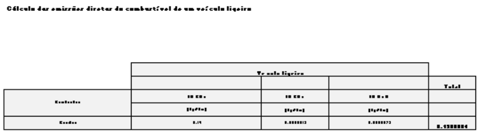


				Emissões por intervenção (kgCO₂e/ha)										
				ATE (corte raso	ATE (desbaste	AAI+DTA+DTI	LMT	ECP	MBS (PLT	Emissões totais s/ deslocação	Emissões totais c/ deslocação	Área (ha)	Emissões (kgCO2e)	Total por AOT
1 - Territórios artificializados	1.1 Tecido edificado			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00
	1.2. Indústria, comércio, e instalações agricola			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
	1.3 Infraestruturas			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
	1.4 Transportes			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
	1.5 Área de extração de	1.5.1 Áreas de extração de inertes		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
		1.5.2 Áreas de deposição de		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
	1.6 Equipamentos	1.6.1 Equipamentos desportivos		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
		1.6.2 Equipamentos de lazer e		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
	1.7 Parques e jardins			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
2. Agricultura	2.1 Culturas temporárias	2.1.1 Culturas temporárias de sequeiro e regadio e arrozais		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00
	2.2 Culturas permanentes	2.2.1 Vinhas		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
		2.2.2 Pomares (inclui produção de		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
		2.2.3 Olivais		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
	2.3 Áreas agrícolas heterogéneas	2.3.1 Culturas temporárias e/ou		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
		2.3.2 Mosaicos culturais e		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
		2.3.3 Agricultura com espaços		0.00	0.00	12.28	0.00	0.00	0.00	12.28	32.69		0.00	
	2.4 Agricultura protegida (estufas) e viveiros			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	
3. Pastagens	3.1 Pastagens	3.1.1 Pastagens melhoradas		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00
		3.1.2 Pastagens espontâneas		0.00	0.00	0.00	66.70	0.00	0.00	66.70	147.11		0.00	
4. Superfícies Agroflorestais (SAF)	4.1 Superfícies agroflorestais (SAF)	4.1.1 Superfícies agroflorestais (SAF)	4.1.1.1 SAF de sobreiro	0.00	0.00	12.28	106.72	0.00	0.00	119.00	139.41		0.00	0.00
			4.1.1.2 SAF de azinheira	0.00	0.00	12.28	106.72	0.00	0.00	119.00	139.41		0.00	
			4.1.1.3 SAF de outros carvalhos	0.00	0.00	12.28	106.72	0.00	0.00	119.00	139.41		0.00	
			4.1.1.4 SAF de pinheiro manso (produção fruto)	0.00	0.00	12.28	106.72	0.00	0.00	119.00	139.41		0.00	
			4.1.1.5 SAF de outras espécies	0.00	0.00	12.28	106.72	0.00	0.00	119.00	139.41		0.00	

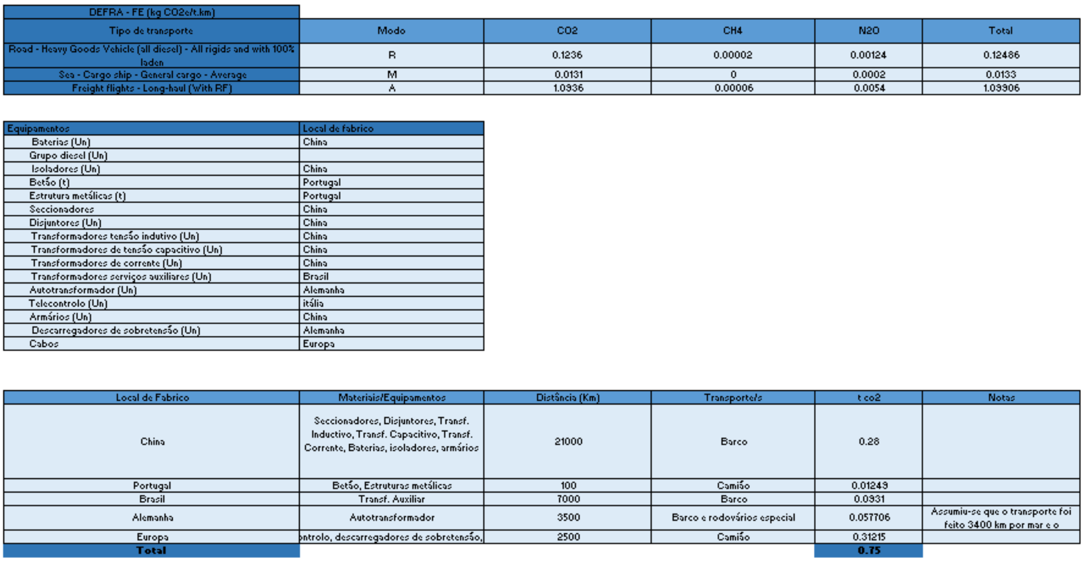
11.4 Emission Factors Sheet from Maintenance



Cálculos Auxiliares para veículos ligeiros



11.5 Emission Factor Sheet from Transportation



DEFRA - FE (kg CO2e/t.km)					
Tipo de transporte	Modo	CO2	CH4	N2O	Total
Road - Heavy Goods Vehicle (all diesel) - All rigids and with 100% laden	R	0.1236	0.00002	0.00124	0.12486
Sea - Cargo ship - General cargo - Average	M	0.0131	0	0.0002	0.0133
Freight flights - Long-haul (With RF)	A	1.0936	0.00006	0.0054	1.09906

Equipamentos	Local de fabrico
Baterias (Un)	China
Grupo diesel (Un)	
Isoladores (Un)	China
Betão (t)	Portugal
Estrutura metálicas (t)	Portugal
Seccionadores	China
Disjuntores (Un)	China
Transformadores tensão indutivo (Un)	China
Transformadores de tensão capacitivo (Un)	China
Transformadores de corrente (Un)	China
Transformadores serviços auxiliares (Un)	Brasil
Autotransformador (Un)	Alemanha
Telecontrolo (Un)	itália
Armários (Un)	China
Descarregadores de sobretensão (Un)	Alemanha
Cabos	Europa

Local de Fabrico	Materiais/Equipamentos	Distância (Km)	Transporte/s	t co2	Notas
China	Seccionadores, Disjuntores, Transf. Inductivo, Transf. Capacitivo, Transf. Corrente, Baterias, isoladores, armários	21000	Barco	0.28	
Portugal	Betão, Estruturas metálicas	100	Camião	0.01249	
Brasil	Transf. Auxiliar	7000	Barco	0.0931	
Alemanha	Autotransformador	3500	Barco e rodoviários especial	0.057706	Assumiu-se que o transporte foi feito 3400 km por mar e o
Europa	ntrolo, descarregadores de sobretensão,	2500	Camião	0.31215	
Total				**0.75**	

ISEP INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO

P.PORTO

DECLARAÇÃO DE INTEGRIDADE

DECLARAÇÃO DE INTEGRIDADE

Declaro ter conduzido este trabalho académico com integridade. Não plagiei ou apliquei qualquer forma de uso indevido de informações ou falsificação de resultados ao longo do processo que levou à sua elaboração.

Declaro que o trabalho apresentado neste documento é original e de minha autoria, não tendo sido utilizado anteriormente para nenhum outro fim.

Declaro ainda que tenho pleno conhecimento do Código de Conduta Ética do P.PORTO.

ISEP, Porto, 6 de Setembro de 2025

Assinado por: André Santos
Cardoso
Identificação: BI13666103
Data: 2025-09-03 às 19:19:06