

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Development of a Calculation Model for REN's Circularity Index

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Resumo

A transição para um sistema energético de baixo carbono é intensiva em materiais, exigindo que os operadores das redes de transporte considerem cada vez mais a circularidade e o desempenho carbónico ao longo do ciclo de vida das infraestruturas que desenvolvem. Esta dissertação apresenta um modelo de avaliação da circularidade, ao nível do projeto, para a REN, o operador português da rede de transporte de eletricidade. O modelo adapta o *Material Circularity Indicator* da Ellen MacArthur Foundation a ativos infraestruturais de longa duração e constituídos por múltiplos componentes, através de uma formulação baseada na massa efetiva e de um fator de extensão da vida útil limitado por critérios físicos. É igualmente introduzido um indicador de circularidade ponderado pela exergia, que pondera os fluxos de materiais de acordo com a sua *Cumulative Exergy Demand*, refletindo diferenças na qualidade dos recursos e no esforço associado à sua produção, em vez de considerar apenas a massa. Um módulo paralelo de contabilização de carbono quantifica as emissões de gases com efeito de estufa ao longo dos módulos A a D da norma EN 15978 e associa-as às categorias relevantes do inventário corporativo de emissões, sendo a maioria enquadrada no Âmbito 3. Uma componente de *benchmarking* estima o potencial de melhoria da circularidade e do desempenho carbónico face às melhores práticas, enquanto uma análise de sensibilidade de Sobol e uma matriz de ecoeficiência apoiam a interpretação dos resultados.

O modelo foi aplicado a dois projetos de infraestrutura da REN: uma linha de muito alta tensão (LMAT) de 150 kV e uma subestação de 400/150 kV. A LMAT apresentou um indicador de circularidade ponderado pela massa de 0.42 e um indicador ponderado pela exergia de 0.60, com uma pegada de carbono de ciclo de vida de 28 341 tCO₂e, predominantemente associada aos condutores de alumínio. A subestação apresentou valores correspondentes de 0.16 e 0.54, com uma pegada de 35 114 tCO₂e, sendo o seu desempenho no indicador ponderado pela massa fortemente penalizado pelo elevado contributo das fundações de betão. Foram analisados três cenários de aquisição de ambição crescente: continuidade das práticas atuais (*business as usual*, BAU), conformidade regulatória e ambição circular. No cenário de ambição circular, o indicador ponderado pela massa aumenta de 0.42 para 0.79 na LMAT e de 0.16 para 0.71 na subestação. Relativamente ao indicador ponderado pela exergia, ambos os projetos atingem 0.70 no cenário de conformidade regulatória e 0.79 no cenário de ambição circular. Os resultados mostram que a maior parte desta melhoria depende da ação regulatória e da aquisição ativa de materiais com conteúdo reciclado, e não apenas da continuação das tendências atuais. Demonstram ainda que as ponderações pela massa e pela exergia identificam prioridades materiais distintas e confirmam que a circularidade e o desempenho carbónico ao longo do ciclo de vida devem ser avaliados conjuntamente, de modo a apoiar as decisões de aquisição, gestão de ativos e reporte de sustentabilidade.

Palavras-chave: Transição Energética • Economia Circular • Indicador de Circularidade de Materiais • Exergia • Pegada de Carbono • Infraestrutura de Transporte de Eletricidade

Abstract

The transition to a low-carbon energy system is material-intensive, requiring transmission system operators to increasingly consider both the circularity and the life-cycle carbon performance of the infrastructure they develop. This dissertation presents a project-level circularity assessment model for REN, the Portuguese electricity transmission system operator. The model adapts the Ellen MacArthur Foundation's *Material Circularity Indicator* to long-lived, multi-component infrastructure assets through an effective-mass formulation and a physically bounded service-life extension factor. It also introduces an exergy-weighted circularity indicator that weights material flows according to their *Cumulative Exergy Demand*, reflecting differences in resource quality and production effort rather than material mass alone. A parallel carbon accounting module quantifies greenhouse gas emissions across Modules A to D of EN 15978 and maps them to the relevant corporate emissions inventory categories, with most emissions falling under Scope 3. A benchmarking component estimates the potential improvement in circularity and carbon performance against best-practice conditions, while a variance-based Sobol sensitivity analysis and an eco-efficiency matrix support the interpretation of the results.

The model was applied to two REN infrastructure projects: a 150 kV extra-high-voltage overhead transmission line (LMAT) and a 400/150 kV substation. The LMAT achieved a mass-weighted circularity indicator of 0.42 and an exergy-weighted indicator of 0.60, with a life-cycle carbon footprint of 28 341 tCO₂e, predominantly associated with the aluminium conductors. The substation achieved corresponding values of 0.16 and 0.54, with a footprint of 35 114 tCO₂e, its mass-weighted performance being strongly penalised by the large contribution of the concrete foundations. Three procurement scenarios of increasing ambition were assessed: business as usual (BAU), regulatory compliance, and circular ambition. Under the circular ambition scenario, the mass-weighted indicator increases from 0.42 to 0.79 for the LMAT and from 0.16 to 0.71 for the substation. Regarding the exergy-weighted indicator, both projects reach 0.70 under the regulatory compliance scenario and 0.79 under the circular ambition scenario. The results show that most of this improvement depends on regulatory action and the active procurement of materials with recycled content, rather than on the continuation of prevailing trends. They further demonstrate that mass-based and exergy-based weighting approaches identify different material priorities and confirm that circularity and life-cycle carbon performance should be assessed jointly to support procurement, asset-management, and sustainability-reporting decisions.

Keywords: Energy Transition • Circular Economy • Material Circularity Indicator • Exergy • Carbon Footprint • Power Transmission Infrastructure

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Rodrigo Rodrigues

“If I have seen farther, it is by standing on the shoulders of giants.”

Isaac Newton

Contents

1	Introduction	1
1.1	Project Framework and Motivation	1
1.2	Project Objectives	2
1.3	Methodology	3
1.4	Dissertation Structure	4
2	Circular Economy: Concepts, Measurement and Assessment Frameworks	5
2.1	Circular Economy: Concept and Evolution	5
2.2	Measuring Circularity: Indicators and Methodologies	6
2.2.1	The Circular Material Use Rate	7
2.2.2	The Material Circularity Indicator	7
2.3	Life Cycle Assessment and Material Flow Analysis	8
2.3.1	Life Cycle Assessment	8
2.3.2	Material Flow Analysis and In-Use Stocks	9
2.3.3	Integration of LCA and Circular Economy	9
2.4	Carbon Footprint and Circularity	10
2.4.1	Carbon Footprint Methodology and Accounting Standards	10
2.4.2	Embodied Carbon in Transmission Infrastructure	10
2.4.3	The Link Between Circularity and Carbon Footprint	11
2.5	Thermodynamic Resource Accounting and Exergy	12
2.6	Circular Economy in Electricity Infrastructure	13
3	Circularity Challenges in Energy Networks	15
3.1	Characterization of REN's Operations and Infrastructure	15
3.1.1	Regulatory Context and Business Structure	15
3.1.2	The National Electricity Transmission Network (RNT)	16
3.1.3	The National Natural Gas Infrastructure (RNTIAT)	17
3.1.4	Strategic Role in the National Energy Transition	17
3.2	Characterization of REN's Current Situation	18
3.2.1	The Transmission Grid as an Anthropogenic Material Sink	18
3.2.2	Material Composition and the Pareto Concentration Principle	19
3.2.3	Project Typologies and Lifecycle Phases	20
3.2.4	Current Resource Management Performance	22
3.2.5	Sustainability Strategy and ESG Commitments	23
3.3	Analysis of the Current Assessment Model	24
3.3.1	The Existing Internal Framework	24
3.3.2	Operational Boundaries of the Current Model	24
3.3.3	Sectoral Benchmarking: European TSO Landscape	25

3.4	Strategic Targets and Asset Replacement Outlook	25
3.4.1	Strategic Sustainability and Supply Chain Targets	26
3.4.2	Asset Replacement Dynamics and Future Material Flows	26
3.5	Circularity Assessment Optimization Strategy	27
4	Proposed Solution and Model Development	29
4.1	Framework Architecture and Design Principles	29
4.2	Baseline Circularity Assessment: The Adapted MCI	31
4.2.1	Standard MCI Formulation	31
4.2.2	Temporal Adaptations: Effective Mass and Service Life Extension	34
4.2.3	Mass-Weighted Project Aggregation	37
4.3	Thermodynamic Extension: The Exergy-Weighted Circularity Indicator	38
4.3.1	Cumulative Exergy Demand as a Thermodynamic Proxy	38
4.3.2	Two-Level Exergy-Weighted Formulation	39
4.3.3	Diagnostic Interpretation: Mass versus Exergy Convergence	40
4.4	Carbon Accounting and Lifecycle Emissions	41
4.4.1	Emission Inventory Structure	42
4.4.2	GWP Calculation with Replacement Cycles	42
4.4.3	Scope 3 Reporting Linkage	43
4.5	Benchmarking: Circularity and Carbon Improvement Potential	43
4.5.1	Circularity Benchmarking: Baseline and Best-Practice Targets	44
4.5.2	Carbon Improvement Potential and Material Sensitivity	45
4.5.3	Scenario Construction	46
4.6	Verification and Sensitivity Analysis	47
4.6.1	Automated Compliance and Data Quality Checks	47
4.6.2	Mass Balance and Boundary Verification	48
4.6.3	Sensitivity and Uncertainty Analysis	48
5	Results and Discussion	50
5.1	Computational Implementation	50
5.2	Case Study 1: LMAT Overhead Transmission Line	50
5.2.1	Material Inventory	50
5.2.2	Physical Service Life Limits	51
5.2.3	Material Circularity Indicator	52
5.2.4	Lifecycle Carbon	54
5.2.5	Service Life Extension	55
5.2.6	Eco-efficiency Matrix	56
5.2.7	Project-Level Emissions Context	58
5.3	Case Study 2: Ponte de Lima Substation	58
5.3.1	Material Inventory	59
5.3.2	Physical Service Life Limits	59
5.3.3	Material Circularity Indicator	60
5.3.4	Lifecycle Carbon	62
5.3.5	Service Life Extension	63
5.3.6	Eco-efficiency Matrix	65
5.3.7	Project-Level Emissions Context	66
5.4	Comparative Analysis	66
5.4.1	Circularity Comparison	67
5.4.2	Carbon Profile Comparison	67

5.5	Circularity Improvement Potential	69
5.5.1	Improvement Scenarios	69
5.5.2	Improvement by Asset and Component	69
5.6	Sensitivity Analysis	72
6	Conclusions and Future Work	75
6.1	Conclusions	75
6.2	Limitations of the Current Model	77
6.3	Future Improvements	78
	References	79
A	REN's Operations	89
B	Material Emission Factors	91
C	Web Application Interface	92
D	Material Inventories	101
E	Material Flow Diagrams	102
F	Sensitivity Analysis: Supporting Results	107

List of Figures

2.1	Circular economy butterfly diagram. Adapted from [5].	6
2.2	Life cycle modules according to EN 15978. Adapted from [31].	8
2.3	GHG Protocol scopes across the value chain. Adapted from [47].	11
3.1	Material composition of high-voltage transmission infrastructure. (a) Mass share by category. (b) Environmental value intensity per tonne, normalised to steel. Percentages in (a) are rounded to the nearest whole number and may therefore not sum exactly to 100%. Adapted from [48, 71, 77].	20
3.2	Example of REN overhead transmission line. Adapted from [68].	21
3.3	Example of a REN high-voltage substation, located in Valdigem. Adapted from [62].	22
3.4	REN 2030 climate commitments and 2040 neutrality target. Adapted from [7].	23
3.5	REN's position across six circular economy areas. Adapted from [81].	27
4.1	Information flow and outputs of the proposed assessment framework.	30
4.2	Material flow structure underlying the Material Circularity Indicator, adapted from [5].	32
4.3	MCI as a function of the Utility Factor X. Adapted from [5].	34
4.4	Effective mass approach example.	35
5.1	Stream-level MCI, current and best practice, Viana do Castelo - Vila Fria Overhead line.	53
5.2	Lifecycle carbon by material stream, Viana do Castelo - Vila Fria LMAT line.	54
5.3	Project MCI against the utility factor, Viana do Castelo - Vila Fria LMAT line.	56
5.4	Eco-efficiency matrix at baseline, Viana do Castelo - Vila Fria Overhead line.	57
5.5	Mass-weighted circularity of the Ponte de Lima substation under current and best-practice conditions.	61
5.6	Ponte de Lima substation lifecycle carbon by stream and phase.	63
5.7	Substation circularity against the utility factor.	64
5.8	Eco-efficiency of the substation streams.	65
5.9	Lifecycle carbon by phase, both case studies.	68
5.10	Component circularity by scenario, LMAT line.	70
5.11	Component circularity by scenario, Ponte de Lima substation.	71
A.1	REN electricity value chain.	89
A.2	REN gas value chain.	89
A.3	Geographical map of the RNT. Adapted from [68].	90
E.1	Viana do Castelo - Vila Fria LMAT input flows, current procurement.	102

E.2	Viana do Castelo - Vila Fria LMAT input flows, best practice.	103
E.3	Viana do Castelo - Vila Fria LMAT output flows, current procurement.	103
E.4	Viana do Castelo - Vila Fria LMAT output flows, best practice.	104
E.5	Substation input flows, current procurement.	104
E.6	Ponte de Lima Substation input flows, best practice.	105
E.7	Ponte de Lima Substation output flows, current procurement.	105
E.8	Ponte de Lima Substation output flows, best practice.	106
F.1	Sobol indices, Viana do Castelo - Vila Fria LMAT line.	107
F.2	Sobol indices, Ponte de Lima substation.	108
F.3	ISAN ranking and Spearman correlation, Viana do Castelo - Vila Fria LMAT line.	108
F.4	ISAN ranking and Spearman correlation, Ponte de Lima substation.	109
F.5	Concrete F_R and E_c interaction, Viana do Castelo - Vila Fria LMAT line.	109
F.6	Concrete F_R and E_c interaction, Ponte de Lima substation.	110
F.7	Monte Carlo uncertainty band, Viana do Castelo - Vila Fria LMAT line.	110
F.8	Monte Carlo uncertainty band, Ponte de Lima substation.	111

List of Tables

4.1	MCI variables in the TSO infrastructure context.	35
4.2	Cumulative Exergy Demand by material stream.	41
4.3	Current and best-practice circularity parameters by material stream.	44
5.1	Physical service life limits by stream, Viana do Castelo - Vila Fria LMAT line. . .	52
5.2	Stream-level MCI at baseline and benchmark, Viana do Castelo - Vila Fria LMAT line.	53
5.3	Lifecycle carbon by material stream, Viana do Castelo - Vila Fria LMAT line. . .	54
5.4	Stream-level MCI at baseline and physical ceiling, LMAT line.	55
5.5	Project-level emissions by phase, Viana do Castelo - Vila Fria LMAT line.	58
5.6	Reference and physical service lives, Ponte de Lima substation.	60
5.7	Stream-level MCI at baseline and benchmark, Ponte de Lima substation.	61
5.8	Ponte de Lima substation lifecycle carbon by phase.	62
5.9	Lifecycle carbon by asset category, Ponte de Lima substation.	63
5.10	Stream-level MCI at baseline and physical ceiling, Ponte de Lima substation. . .	64
5.11	Project-level emissions by phase, Ponte de Lima substation.	66
5.12	Circularity indicators, both case studies.	67
5.13	Lifecycle carbon by phase, both case studies.	68
5.14	Global circularity indicators by scenario.	69
5.15	Dominant sensitivity indices, Viana do Castelo - Vila Fria LMAT line.	72
5.16	Dominant sensitivity indices, Ponte de Lima substation.	72
B.1	Cradle-to-gate carbon intensity by production route (Modules A1-A3).	91
D.1	Material inventory, Viana do Castelo - Vila Fria LMAT line.	101
D.2	Ponte de Lima substation material inventory by category.	101

List of Acronyms

ACSR	Aluminium Conductor Steel Reinforced
BAU	Business as Usual
CE	Circular Economy
CEAP	Circular Economy Action Plan
CExD	Cumulative Exergy Demand
CMUR	Circular Material Use Rate
CO ₂	Carbon Dioxide
CSRD	Corporate Sustainability Reporting Directive
EAF	Electric Arc Furnace
EC	European Commission
ECR	Electrical grade, Corrosion Resistant (glass fibre)
EMF	Ellen MacArthur Foundation
EN	European Norm
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSO-G	European Network of Transmission System Operators for Gas
EPD	Environmental Product Declaration
ERSE	<i>Entidade Reguladora dos Serviços Energéticos</i>
ESG	Environmental, Social, and Governance
ESPR	Ecodesign for Sustainable Products Regulation
ESRS	European Sustainability Reporting Standards
EU	European Union
FEUP	<i>Faculdade de Engenharia da Universidade do Porto</i> (Faculty of Engineering of the University of Porto)
GHG	Greenhouse Gas

GRI	Global Reporting Initiative
GWP	Global Warming Potential
HV	High Voltage
IEC	International Electrotechnical Commission
ISAN	Index of Sensitivity, Amplitude-Normalised
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LFI	Linear Flow Index
LMAT	<i>Linha de Muito Alta Tensão</i> (Very High Voltage line)
LNG	Liquefied Natural Gas
MCI	Material Circularity Indicator
MFA	Material Flow Analysis
OPGW	Optical Ground Wire
PCB	Polychlorinated Biphenyls
PE	Polyethylene
PNEC	<i>Plano Nacional de Energia e Clima</i> (National Energy and Climate Plan)
RC	Recycled Content
REN	<i>Redes Energéticas Nacionais</i> (National Energy Networks)
RNC	<i>Roteiro para a Neutralidade Carbónica</i> (Roadmap for Carbon Neutrality)
RNT	<i>Rede Nacional de Transporte</i> (National Transmission Network)
RNTG	<i>Rede Nacional de Transporte de Gás</i> (National Gas Transmission Network)
RNTIAT	<i>Rede Nacional de Transporte, Infraestruturas de Armazenamento e Terminais de GNL</i> (National Transmission Network, Storage Infrastructures, and LNG Terminals)
RTE	<i>Réseau de Transport d'Électricité</i>
SBTi	Science Based Targets initiative
SEN	<i>Sistema Elétrico Nacional</i>
SF ₆	Sulphur Hexafluoride
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan

WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute
XLPE	Cross-linked Polyethylene

1 Introduction

This dissertation presents the work carried out during a five-month internship at REN, *Redes Energéticas Nacionais*. The work was developed within the scope of the Master's in Mechanical Engineering at the Faculty of Engineering of the University of Porto (FEUP), as part of the Dissertation curricular unit, during the second semester of the 2025/2026 academic year.

1.1 Project Framework and Motivation

The energy transition represents one of the most significant challenges in addressing climate change, with the energy sector playing a central role. In Portugal, this transition is supported by national strategies such as the PNEC 2030, the *Plano Nacional de Energia e Clima* (National Energy and Climate Plan) [1], which defines ambitious targets for decarbonization, energy efficiency, and the integration of renewable energy sources, aligned with the broader European climate framework [2].

REN plays a key role as Portugal's Transmission System Operator (TSO), managing critical infrastructure such as the National Electricity Transmission Grid (RNT) and the National Natural Gas Transmission Network (RNTG). In 2025, REN ensured high levels of service reliability, with electricity availability reaching 99.83% and gas transmission availability 99.99%. Renewable energy sources accounted for 68% of total electricity consumption, while total demand reached an all-time high of 53.1 TWh [3].

In parallel, REN has established ambitious sustainability commitments, including a reduction of 60% in Scope 1 and Scope 2 emissions by 2030 relative to 2019 levels, a 30% reduction in Scope 3 emissions by 2030 relative to 2021, and the objective of achieving carbon neutrality by 2040 [4]. These targets highlight the importance of addressing both direct and value chain emissions.

In addition to emissions reduction, increasing attention has been given to the efficient use of materials and resources. The continuous expansion and modernization of infrastructure, reflected in annual investments of approximately €474.9 million in 2025 [3], reinforce the need to adopt circular economy principles [5], particularly in asset-intensive sectors such as energy transmission.

Circularity focuses on improving resource efficiency through strategies such as material reduction, reuse, recycling, and lifetime extension of assets [6]. In energy infrastructure, this involves analysing material composition, recyclability, and reintegration potential. These principles are increasingly embedded in REN's strategy, influencing procurement processes, supplier engagement, and asset management practices [7].

The relevance of circularity is closely linked to Scope 3 emissions, largely driven by supply chain activities and infrastructure development [8]. Improving circular performance therefore represents a key lever for reducing indirect emissions and enhancing overall sustainability.

To complement this perspective, Life Cycle Assessment (LCA) methodologies are used to evaluate environmental impacts across different life cycle stages, enabling the identification of critical phases and supporting informed decision-making [9].

Standard material circularity metrics, however, are largely insensitive to the energy quality of the materials they track and to the multiple replacement cycles of long-lived assets, which limits their use for infrastructure procurement decisions [10]. Full lifecycle assessments of overhead lines have historically been dominated by operational losses [11]. As the electricity system decarbonises, that operational share diminishes, and cradle-to-gate assessments show material manufacturing dominating the embodied carbon footprint [12], so material sourcing becomes the principal lever for reducing embodied emissions. These two observations motivate an assessment framework that couples a quality-aware, multi-cycle circularity indicator with parallel lifecycle carbon accounting.

The present work was developed within REN's sustainability framework and focuses on the assessment of circularity in energy infrastructure assets, combining material-based analysis with life cycle impact evaluation to identify opportunities for improving circular performance and reducing environmental impacts.

1.2 Project Objectives

The primary objective of this dissertation is to develop a quantitative, decision-oriented assessment model capable of integrating material circularity and lifecycle carbon performance for long-lived transmission infrastructure.

To achieve this overarching goal, the research pursued the following specific objectives:

- **Advancement of Circularity Models for Long-Lived Assets:** Overcoming the limitations of traditional frameworks by fundamentally re-engineering the Ellen MacArthur Foundation's Material Circularity Indicator (MCI) for complex infrastructure, introducing an effective-mass formulation and a physically bounded service-life extension factor.
- **Thermodynamic Weighting of Material Flows:** Formulating an exergy-weighted circularity indicator based on the Cumulative Exergy Demand (CExD), shifting the assessment from a purely mass-based approach to one that reflects resource quality and thermodynamic production effort.
- **Lifecycle Carbon Integration:** Developing a parallel carbon accounting module aligned with the EN 15978 standard (Modules A to D) to quantify embodied and operational greenhouse gas emissions, mapping the results to Scope 3 corporate reporting categories.

- **Benchmarking and Eco-Efficiency Assessment:** Establishing a benchmarking layer to estimate the improvement potential of specific material streams against best-practice recycled content and end-of-life recovery rates.
- **Application to Representative Infrastructure Case Studies:** Validating the proposed framework through its application to two distinct infrastructure typologies within the Portuguese transmission network, a 150 kV overhead transmission line and a 400/150 kV substation.
- **Uncertainty and Sensitivity Analysis:** Conducting a variance-based Sobol sensitivity analysis to identify the critical parameters driving circularity and carbon performance, ensuring the robustness of the decision-support outputs.
- **Future Scenario Projection Framework:** Establishing the methodological foundation to project the circularity and carbon trajectory of the transmission network from asset replacement rates, procurement strategies, and industry decarbonisation scenarios.

Together, these objectives aim to provide Transmission System Operators (TSOs) with a scientifically robust instrument to prioritise circularity interventions, optimise procurement specifications, and support sustainability reporting.

1.3 Methodology

The methodology adopted in this dissertation follows a structured, quantitative modelling approach, transitioning from theoretical formulation to empirical validation through real-world infrastructure case studies. The core methodological stages are defined as follows:

1. **System Boundary and Inventory Definition:** Establishment of the operational boundaries for the infrastructure assets, followed by a high-resolution material characterisation of the components, drawing on Environmental Product Declarations (EPD) and technical specifications to extract mass, declared service life, and material composition.
2. **Mathematical Formulation of the Assessment Framework:** Development of the computational model, integrating the modified MCI equations for in-service replacements and life extension. This stage includes the definition of the exergy-weighting vectors using CExD factors extracted from lifecycle inventory databases such as ecoinvent [13].
3. **Lifecycle Carbon Accounting:** Structuring the carbon quantification across the product, construction process, use, and end-of-life stages, ensuring strict alignment with EN 15978 standard guidelines and compatibility with ESRS E5 Scope 3 reporting requirements.
4. **Computational Implementation:** Translation of the mathematical framework into a structured calculation engine in *Microsoft Excel*, supported by an interactive *Python* interface using *Streamlit* to facilitate scenario analysis and data visualization.

5. **Case Study Application and Benchmarking:** Execution of the model on the Viana do Castelo - Vila Fria 150 kV overhead line and the Ponte de Lima 400/150 kV substation. This stage computes the baseline mass-weighted and exergy-weighted indicators, the total carbon footprint, and evaluates the distance to best-practice circularity targets.
6. **Sensitivity and Eco-Efficiency Analysis:** Application of Monte Carlo simulations and variance-based Sobol sensitivity analysis to determine parameter interactions, complemented by an eco-efficiency matrix to correlate circularity gains with avoided carbon emissions.

This methodology bridges the gap between thermodynamic material accounting and corporate environmental strategy, delivering a comprehensive toolkit for sustainable asset management.

1.4 Dissertation Structure

This dissertation is structured into six chapters.

Chapter 1 introduces the project, presenting its motivation, objectives, methodology, and the organizational context within REN.

Chapter 2 provides the theoretical background on circular economy, covering key concepts, frameworks, and tools, as well as European and national policies. It also addresses the relevance of circularity in the energy sector, including its application to Transmission System Operators (TSOs), and reviews existing initiatives and challenges, with particular focus on REN.

Chapter 3 characterizes REN's operations and infrastructure, positioning the transmission grid as a massive anthropogenic material sink. It evaluates the existing internal circularity framework, establishes the operational boundaries, and outlines the strategic sustainability targets and asset replacement dynamics.

Chapter 4 details the development of the proposed assessment framework. It covers the adaptation of the Material Circularity Indicator (MCI) for long-lived assets, introduces the thermodynamic extension using exergy, formulates the lifecycle carbon accounting module, and defines the benchmarking and verification procedures.

Chapter 5 presents the application of the developed model to two representative case studies, a Very High Voltage overhead transmission line and a substation. It provides a comparative analysis of mass-weighted and exergy-weighted circularity scores, evaluates the lifecycle carbon footprint, and quantifies the improvement potential against best-practice benchmarks.

Finally, Chapter 6 summarizes the main findings and contributions of the dissertation. It critically discusses the limitations of the current model and proposes recommendations and extensions for future work.

2 Circular Economy: Concepts, Measurement and Assessment Frameworks

2.1 Circular Economy: Concept and Evolution

The concept of the Circular Economy (CE) is widely framed as a systemic alternative to the dominant linear economic model that has characterised industrial society since the twentieth century. This linear approach, commonly summarised as *take-make-dispose*, treats natural resources as unlimited inputs: raw materials are extracted, transformed into products, and ultimately discarded at the end of their useful life, with no structured mechanism for recovering the embedded material or energy value [5, 14]. The CE proposes, by contrast, a restorative and regenerative economic system designed to keep materials, components, and products in use for as long as possible, preserving their value at each stage of the life cycle.

Despite its widespread adoption by policymakers and industry leaders, the CE has no single, universally accepted definition. A systematic content analysis of 114 existing definitions found that the concept is most frequently framed around reduce, reuse, and recycle activities, often without an explicit link to broader sustainability goals or the systemic transformation that a meaningful circular transition requires [6]. The co-existence of a linear growth paradigm with a regenerative one has been explicitly mapped in the literature, distinguishing the CE from the broader concept of sustainable development while identifying the former as a condition to achieve the latter [15]. Furthermore, business models are increasingly recognised as the vehicle for this transition, shifting the focus from product ownership to performance-based services [16].

It was the Ellen MacArthur Foundation (EMF) that, from 2012 onwards, consolidated these ideas into an operational framework, defining the circular economy around three principles: (i) eliminating waste and pollution by design, (ii) keeping products and materials in use through both biological and technical cycles, and (iii) regenerating natural systems [5]. The so-called “butterfly diagram” represents these material flows, distinguishing biological materials (returning to the biosphere through composting or anaerobic digestion) from technical materials (circulated through maintenance, reuse, repair, remanufacturing, and, as a last resort, recycling).

The CE is inherently hierarchical in its treatment of material strategies, often described through the **R-framework** (ranging from Refuse and Rethink through to Recycle and Recover). Repairing or remanufacturing a component retains far more embedded value than shredding and recycling

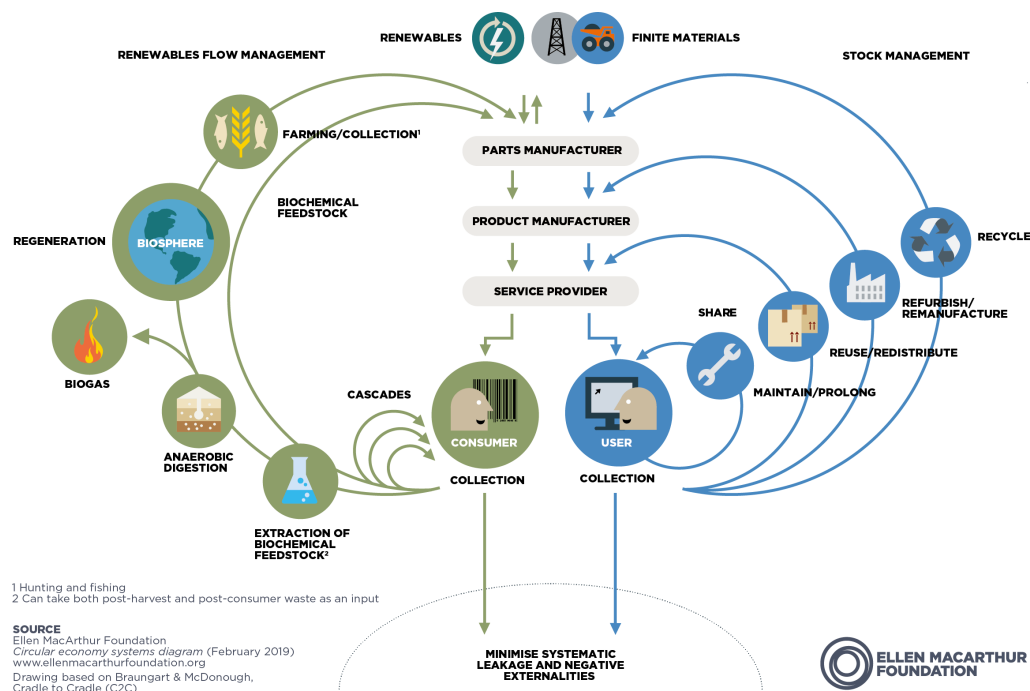


Figure 2.1: Circular economy butterfly diagram. Adapted from [5].

the materials it contains [6, 17]. Material efficiency strategies (broadly defined as providing material services with less material production) represent a class of interventions largely overlooked by conventional climate policy, yet capable of making a substantial contribution to deep decarbonisation targets precisely because they reduce the demand placed on energy-intensive primary production [18]. This principle is particularly significant in infrastructure contexts, where high-value materials are locked in long-lived, complex assemblies. On the policy front, the European Union has institutionalised the CE as a cornerstone of the European Green Deal, through the New Circular Economy Action Plan (CEAP 2020) and the emerging Ecodesign for Sustainable Products Regulation (ESPR), which is broadening mandatory requirements for durability, reparability, recyclability, and recycled content across virtually all physical goods placed on the EU market [19, 20].

2.2 Measuring Circularity: Indicators and Methodologies

Measuring circularity performance is a prerequisite for managing the transition to a circular economy effectively. The literature documents a large and growing number of circularity indicators, though a persistent challenge is the lack of standardisation, which limits comparability and complicates application across sectors [21, 22]. A systematic review of existing indicators, classifying them by circular strategy and measurement scope, concluded that most available metrics focus narrowly on recycling, ignoring higher-value strategies such as repair, reuse, and remanufacturing [23]. A taxonomy of 55 circularity indicators has since been proposed, providing a structured framework for matching management objectives to appropriate measurement tools [24].

These indicators can be organised across three analytical levels [21]:

- **Macro level:** indicators applied to cities, regions, or national economies to track the overall material metabolism of a socioeconomic system.
- **Meso level:** indicators applied to industrial networks, supply chains, or specific sectors to capture material exchanges between organisations.
- **Micro level:** indicators applied to individual products, components, or companies to enable granular assessment of circular strategies.

For capital-intensive systems such as electricity transmission infrastructure, micro-level indicators are the most operationally actionable, yet remain the least developed in sector-specific terms [21, 25].

2.2.1 The Circular Material Use Rate

At the macro level, the primary indicator adopted by the European Union is the **Circular Material Use Rate** (CMUR), which quantifies the share of material resources used in the economy that originates from recycled waste, thereby displacing primary extraction [26].

While useful for tracking policy progress, the CMUR has recognised limitations: it does not distinguish the quality of recycled materials, does not capture the thermodynamic efficiency of recycling processes, and fails to reward higher-value strategies such as reuse or life-extension [23]. These limitations motivate the use of product-level indicators for asset-intensive applications.

2.2.2 The Material Circularity Indicator

The **Material Circularity Indicator** (MCI), developed by the Ellen MacArthur Foundation in collaboration with Granta Design, is the most robust and widely referenced micro-level indicator for quantifying the circularity of a specific product [5, 27]. It is scaled between 0 and 1, where 0 represents a fully linear product made entirely from virgin materials and sent to landfill or incineration, and 1 represents a fully circular product made entirely from recovered materials and fully recoverable at end of life.

The MCI is built around a **Linear Flow Index** (LFI) that captures the fraction of material flowing linearly through the system: the share of virgin feedstock entering the product, the share of end-of-life material lost to landfill or incineration, and the collection efficiency for recovery. It also applies a **utility correction factor** $F(X)$ that adjusts the score for the product's actual lifetime relative to the sector average, consistent with the CE principle that life extension is itself a circular strategy [5]. The complete formulation of the MCI, including the adaptations required for long-lived infrastructure assets, is presented in Chapter 4.

Despite its strengths, the MCI has recognised limitations. A higher score does not necessarily imply improved environmental performance, since the indicator does not capture greenhouse gas emissions, toxicity, or water use [28]. Nor does it distinguish whether materials are recovered into

equivalent applications or downcycled [29]. For organisations managing large, material-intensive portfolios, the most actionable approach is integrating the end-of-life recycling rate, recycled content, and process efficiency alongside Life Cycle Assessment (LCA) methodologies [25, 30].

2.3 Life Cycle Assessment and Material Flow Analysis

2.3.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a standardised methodology (ISO 14040/14044) that quantifies the environmental impacts of a product across all stages of its life cycle [9]. For infrastructure, the life cycle is structured according to EN 15978, dividing the cycle into four modules:

- **Module A** (Product and construction stage): raw material extraction (**A1**), transport to manufacturer (**A2**), manufacturing (**A3**), transport to site (**A4**), and installation (**A5**).
- **Module B** (Use stage): maintenance (**B2**), repair (**B3**), replacement (**B4**), refurbishment (**B5**), and operational energy use (**B6**).
- **Module C** (End of life): deconstruction (**C1**), transport to waste processing (**C2**), waste processing for recovery (**C3**), and disposal (**C4**).
- **Module D** (Beyond system boundary): net benefits from reuse, recovery, and recycling, representing the avoided primary production credit attributable to recovered materials.

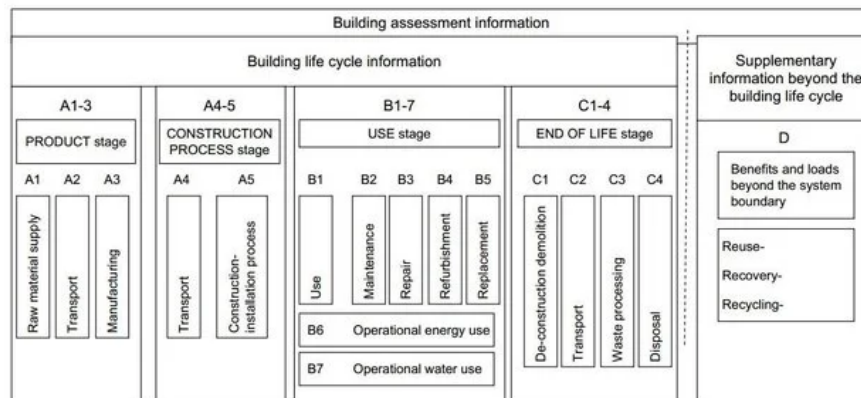


Figure 2.2: Life cycle modules according to EN 15978. Adapted from [31].

When applied to transmission infrastructure, **phases A1 to A3 consistently account for the dominant share of the carbon footprint**. The energy intensity of metal production (structural steel, aluminium, and copper) concentrates the majority of embodied carbon in the manufacturing stage [11, 12]. Earlier LCA studies reported a higher relative weight for the operational phase due to resistive losses in conductors [11]. However, as the European electricity system incorporates an increasing share of renewable generation, the warming impact attributable to network losses

diminishes proportionally, further consolidating the primacy of embodied carbon. This shift has a direct strategic implication: improvements in material sourcing, particularly through the use of recycled-content metals, represent the most impactful lever available to a grid operator.

Beyond the primary material flows, sulphur hexafluoride (SF₆) leakage constitutes a critical environmental hotspot in substation switchgear. Owing to its global warming potential of approximately 24 300 times that of CO₂, even fractional leakage rates over an asset's service life can rival the entire manufacturing footprint [32]. This has driven significant research into alternative gas mixtures, such as Fluoronitriles/CO₂, which offer comparable dielectric strength with a fraction of the environmental impact [33–35].

2.3.2 Material Flow Analysis and In-Use Stocks

Material Flow Analysis (MFA) is an accounting methodology that tracks and quantifies the flows and stocks of specific materials within a defined system boundary [36]. Unlike LCA, MFA focuses on mass balance. A key insight from dynamic MFA applied to long-lived infrastructure is the concept of the **Anthropogenic Sink** or *In-Use Stock*. Human well-being relies heavily on the physical services provided by buildings and infrastructure, which act as massive reservoirs of locked-in materials [36].

Studies show that per capita in-use metal stocks in industrialised economies tend to saturate, and the future availability of secondary material depends critically on the age distribution of the existing stock rather than on current production rates [37, 38]. The global electricity infrastructure, in particular, represents a massive and continuously growing material stock [39]. Although metals are infinitely recyclable in principle, practical recycling rates remain substantially below theoretical limits owing to losses in collection and thermodynamic constraints in separating dissimilar materials [40]. For infrastructure operators, dynamic MFA allows viewing the existing grid as an "Urban Mine", providing a forward-looking picture of material availability as assets age [41].

2.3.3 Integration of LCA and Circular Economy

The relationship between LCA and the CE is characterised in the literature as both complementary and methodologically tensional [9, 30]. From a complementarity perspective, LCA provides the empirical evidence needed to verify whether a circular strategy genuinely delivers environmental benefits. A refurbishment strategy may preserve material value but consume significant energy, and only LCA can determine the net balance. From a trade-off perspective, strategies that improve circularity metrics (e.g., transporting scrap metal over long distances) may worsen the carbon footprint [28]. Despite these tensions, the prevailing direction in the literature is toward the integration of circularity indicators within LCA frameworks, since neither tool alone is sufficient for capital-intensive infrastructure [30].

2.4 Carbon Footprint and Circularity

2.4.1 Carbon Footprint Methodology and Accounting Standards

The carbon footprint of an organisation or asset is a quantitative measure of the total greenhouse gas (GHG) emissions associated with its activities, expressed in tonnes of carbon dioxide equivalent (tCO₂eq). The most widely adopted framework for organisational carbon accounting is the **GHG Protocol Corporate Standard**, developed jointly by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) [8]. This standard organises emissions into three scopes that together cover the full value chain of any organisation:

- **Scope 1** covers direct emissions from sources owned or controlled by the organisation, such as fuel combustion in company vehicles or on-site equipment.
- **Scope 2** covers indirect emissions from the consumption of purchased electricity, heat, or steam, attributed to the organisation based on its energy purchases.
- **Scope 3** encompasses all other indirect emissions occurring throughout the value chain, both upstream and downstream, including those associated with the extraction and processing of purchased materials (Category 1), capital goods (Category 2), transportation (Category 4), waste generated in operations (Category 5), and the end-of-life treatment of sold products (Category 12), among fifteen categories in total [8].

Complementary to the GHG Protocol, the ISO 14064 standard family provides a framework for quantifying, reporting, and verifying GHG emissions at organisational and project level [42]. These standards are increasingly required under the Corporate Sustainability Reporting Directive (CSRD) and the European Sustainability Reporting Standards (ESRS), which mandate disclosure of Scope 1, 2, and 3 emissions as part of mandatory corporate sustainability reporting across the EU [43].

For grid operators and infrastructure developers, **Scope 3 is typically the largest and least visible part of the carbon footprint**. The extraction, refining, and fabrication of the metals used to build and maintain transmission networks are among the most energy- and carbon-intensive industrial processes, placing them squarely within the Scope 3 boundary of any infrastructure operator. This makes material procurement decisions a primary lever for reducing total value chain emissions [8, 44].

2.4.2 Embodied Carbon in Transmission Infrastructure

Within the context of electricity transmission, **embodied carbon** refers to the GHG emissions associated with the manufacturing, transport, installation, maintenance, and end-of-life management of physical infrastructure components, in contrast to operational carbon, which arises from energy losses during use. As the electricity grid decarbonises and operational emissions fall with

the growing share of renewable generation, embodied carbon becomes a progressively dominant share of the total life cycle carbon footprint of transmission assets [11].

The embodied carbon intensity of the main materials used in transmission infrastructure varies considerably. Steel produced through the conventional blast furnace route emits approximately 2.0 to 2.5 tCO₂eq per tonne, while secondary steel via electric arc furnace (EAF) from scrap reduces this by 60 to 80% [44]. Aluminium produced from bauxite ore via the Hall-Héroult process carries an emission factor of approximately 11 to 17 kgCO₂eq/kg, and secondary aluminium from recycled scrap reduces this by 90 to 95% [45]. Copper from primary smelting carries approximately 3 to 5 kgCO₂eq/kg, with secondary copper from recycled sources reducing this by 65 to 85% [46]. These figures illustrate the substantial carbon leverage that changes in material sourcing can generate within a transmission network's supply chain, and they establish a direct quantitative link between the choice of recycled or virgin material and the Scope 3 emission profile of each infrastructure investment (as illustrated in Figure 2.3).

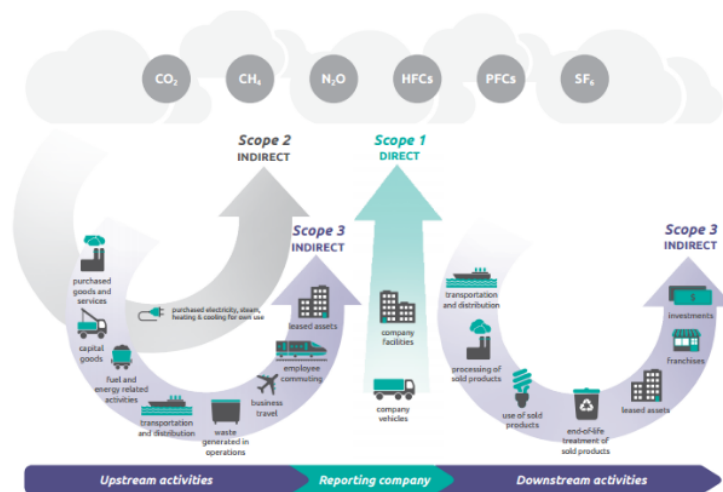


Figure 2.3: GHG Protocol scopes across the value chain. Adapted from [47].

2.4.3 The Link Between Circularity and Carbon Footprint

The connection between circularity performance and carbon footprint is direct and increasingly well-documented in the literature. Circular strategies that reduce the consumption of primary materials simultaneously reduce the GHG emissions associated with their extraction, concentration, and refining, all of which are among the most carbon-intensive steps of any manufacturing supply chain [9, 30]. Conversely, a low circularity index in a material-intensive asset signals high dependence on virgin feedstock, which translates directly into elevated Scope 3 emissions attributable to purchased materials.

This relationship operates at multiple scales. At the **material level**, increasing the recycled content of a purchased component systematically reduces its emission factor, since secondary production requires substantially less energy than primary production for all major metals. At the **asset level**, extending the operational life of existing infrastructure through refurbishment or

condition-based maintenance avoids the embodied carbon cost of manufacturing and installing a replacement. At the **network level**, higher overall circularity means that a larger share of the material stock circulates within a closed loop rather than being continuously replaced with newly extracted resources, compounding emission savings over successive asset life cycles.

It has further been quantified that metal dissipation and inefficient end-of-life collection intensify climate forcing by perpetuating the energy demand of primary production across the global material system [48, 49]. A comprehensive analysis of recycling rates across 60 metals concluded that for most technically complex metals, end-of-life recycling rates remain below 50%, and for many specialty metals below 1%, revealing a vast and largely untapped potential for carbon reduction through improved circular management [49]. From a material efficiency perspective, closing this gap is among the most impactful levers available to reduce industrial GHG emissions, since avoided primary metal production carries a substantially larger emissions benefit per tonne than most energy efficiency improvements within existing processes [18]. Further evidence confirms that the GHG emission reduction potential of circular economy strategies is material-specific and non-trivial: for bulk metals, even modest improvements in recycled content and end-of-life recovery rates translate into reductions in embodied emissions that are comparable in magnitude to typical operational efficiency measures [30, 40].

This relationship is of direct relevance to ESG disclosure frameworks. Improvements in circularity, when quantified at the material and project level, can be translated into avoided Scope 3 emissions, providing a tangible and reportable climate co-benefit alongside the resource efficiency rationale. The model developed in the present dissertation explicitly incorporates this carbon dimension, calculating alongside the circularity index the associated global warming potential (GWP) implications for each material class and lifecycle phase, enabling organisations to communicate the climate benefits of circular procurement within their integrated sustainability reporting.

Beyond disclosure, avoided emissions carry a direct economic value through carbon pricing. The European Union Emissions Trading System, established in 2005 and now the largest carbon market in the world, places a price on each tonne of CO₂ equivalent emitted by the power and industrial sectors through a cap-and-trade mechanism [50]. The allowance price assigns a monetary value to the emissions that circular procurement avoids, and it converts a reduction in embodied carbon into a quantifiable financial saving. This economic layer complements the environmental rationale for circularity and provides the basis for the monetary valuation of avoided emissions adopted in the framework of Chapter 4.

2.5 Thermodynamic Resource Accounting and Exergy

While the mass-based indicators and Life Cycle Assessment methodologies discussed in the previous sections provide essential frameworks for tracking material flows and environmental impacts, they share a fundamental blind spot: they do not inherently distinguish the thermodynamic quality or the "effort" required to extract and refine different resources. A pure mass balance treats

one kilogram of concrete equivalently to one kilogram of refined aluminium, despite the vastly different energy requirements and environmental burdens associated with their production.

To address this qualitative disparity, thermodynamic accounting relies on the concept of **exergy**. Exergy is defined as the maximum useful work that can be obtained from a system as it is brought into thermodynamic equilibrium with its surrounding environment [51]. Unlike mass and energy, which are strictly conserved according to the First Law of Thermodynamics, exergy is consumed or destroyed in every real (irreversible) physical and chemical process, as dictated by the Second Law of Thermodynamics and the Gouy-Stodola theorem [52]. Exergy destruction is thus a true, directional measure of resource depletion.

From a Mechanical Engineering perspective, exergy has historically been employed to assess the efficiency of thermal plants, engines, and energy conversion systems, where minimizing irreversibilities translates directly to operational efficiency [53]. However, its application has progressively expanded into industrial ecology and material science, providing a rigorous physical basis for valuing materials. The extraction and metallurgical refinement of metal ores into high-purity conductors represents a massive concentration of exergy. Conversely, when materials are dissipated into the environment, sent to landfill, or mixed in complex assemblies that prevent effective recycling, their embedded exergy is destroyed. This represents a permanent, thermodynamically irreversible loss of resource quality that mass-based metrics fail to capture.

To quantify this at the life-cycle level, the **Cumulative Exergy Demand (CExD)** indicator was developed. CExD measures the total exergy removal from nature required to provide a product, aggregating the exergy of all energy and material resources consumed along the supply chain [54]. Integrating CExD with circularity frameworks provides a powerful corrective mechanism against the "mass dominance" problem common in infrastructure assessments. By weighting material flows not by their physical mass, but by their thermodynamic value (embodied exergy), decision-makers can prioritise the recovery of high-quality, energy-intensive materials. This thermodynamic extension elevates Circular Economy from purely environmental accounting to a rigorous engineering discipline based on the Second Law, and forms a core methodological pillar of the framework developed in Chapter 4.

2.6 Circular Economy in Electricity Infrastructure

The application of CE frameworks to physical infrastructure systems, and to electricity transmission networks in particular, represents an emerging and still limited body of work in the literature. Studies applying LCA to power grid components [11] and reviews of CE indicators in capital-intensive sectors [25] have begun to establish the analytical foundations, but sector-specific circularity assessment models calibrated for transmission infrastructure remain largely absent from the published literature. This gap is partly attributable to the characteristics that make transmission infrastructure distinctive: asset lifetimes typically ranging from 30 to 50 years, a diverse material portfolio spanning bulk metals, specialised dielectric fluids, engineering polymers, and gases such as SF₆, and the coexistence of multiple end-of-life pathways within the same asset.

The circularity of transmission infrastructure is also a question of supply security. Several of the materials that dominate the grid, in particular aluminium and copper, are classified by the European Union as strategic or critical, on the basis of their economic importance and the concentration of their supply [55, 56]. The Critical Raw Materials Act of 2024 sets explicit targets for domestic extraction, processing, and recycling, and identifies secondary production as a central instrument for reducing external dependence [55]. For a transmission system operator, this reframes recycled content as more than an environmental lever, since it also mitigates exposure to volatile primary markets and to geopolitical supply risk. The circular economy and the critical raw materials agenda are therefore convergent, and the recovery of high-value metals from ageing assets contributes to both [57, 58]. This dual rationale, environmental and strategic, reinforces the case for a project-level circularity model calibrated to the material profile of the network.

At the sectoral level, the European Network of Transmission System Operators for Electricity has identified circular economy and life cycle assessment as innovation priorities still to be consolidated in transmission asset management. Its research and innovation roadmap lists the establishment of eco-design and life cycle assessment methods in the TSO context, the inclusion of circular economy and environmentally friendly components in network planning and asset management, and the deployment of SF₆-free solutions, as missions to be developed over the coming decade [59]. This positions the present work within an explicit and recognised sectoral research gap.

These characteristics mean that the standard MCI framework, designed for shorter-lived consumer or manufactured products, cannot be applied directly without adaptation [5, 21]. Long replacement cycles introduce a temporal mismatch between procurement decisions (which set the recycled content of materials entering the stock) and decommissioning events (which determine the availability of secondary materials). Stock-driven dynamic MFA models have demonstrated that this lag between investment and recovery is a defining structural feature of material cycles in long-lived infrastructure, and one that conventional static circularity assessments are structurally unable to capture [60, 61]. The practical barriers to improving recycling rates in complex infrastructure assets, ranging from material mixing in multi-component assemblies to inadequate end-of-life collection infrastructure, have been systematically documented in the literature and apply with particular force to capital-intensive systems with long in-use lifetimes [40].

The Portuguese electricity transmission network managed by *REN, Redes Energéticas Nacionais, S.A.* concentrates each of these characteristics in a single operational context: a grid spanning approximately 9 985 km with assets ranging from mid-twentieth-century 150 kV overhead lines to recently commissioned 400 kV corridors, a material composition dominated by steel and aluminium in bulk but punctuated by high-entropy substation equipment, and an operator with explicit circular economy and Scope 3 reduction commitments that currently lack project-level measurement tools. This combination of long asset cycles, material complexity, and an active regulatory and sustainability agenda makes the REN portfolio a well-defined and operationally grounded context for the development and calibration of a transmission-specific circularity model. Chapter 3 characterises this context in detail.

3 Circularity Challenges in Energy Networks

Following the theoretical framework established in the previous chapter, this chapter examines the application of circularity concepts to the specific infrastructure challenges addressed in this study. It begins by characterising the operations and assets of REN, followed by an analysis of current material stocks and lifecycle dynamics. It then evaluates existing assessment methodologies and identifies gaps through a sectoral benchmarking exercise. The chapter concludes by defining the research gap that the methodology developed in Chapter 4 is designed to address.

3.1 Characterization of REN’s Operations and Infrastructure

REN is the Portuguese concession holder for bulk electricity transmission and the overall technical manager of the national natural gas system. The organisation manages a capital-intensive portfolio of long-lived assets across two structurally distinct infrastructure networks and is regulated by the *Entidade Reguladora dos Serviços Energéticos (ERSE)*. Service lives across this portfolio typically span several decades, a characteristic that defines both the scale of the material stock at stake and the complexity of its circular management.

3.1.1 Regulatory Context and Business Structure

REN is the Portuguese national energy transmission operator, responsible for bulk electricity transmission at very high voltage and for the overall technical management of both the National Electricity System (SEN) and the National Natural Gas System [4]. The organisation operates under a concession contract with the Portuguese State, which grants it the exclusive right to plan, construct, operate, and maintain the transmission infrastructure across the continental territory [62].

From a regulatory standpoint, REN is subject to the oversight of ERSE, the independent national energy regulator. This institutional framework is consistent with the requirements of the European Union’s Third Energy Package, which mandated the full legal, organisational, and functional separation of transmission system operators from entities engaged in the production or supply of energy [63]. The unbundling regime was formally certified for REN by ERSE in 2015, in accordance with Article 3 of Regulation (EC) 714/2009 [64].

Within the European context, REN is the certified Transmission System Operator (TSO) for electricity and a member of ENTSO-E, the body established under Regulation (EC) 714/2009 to

coordinate pan-European grid operations and network development planning [65]. For the natural gas sector, REN operates within the ENTSOG framework. These memberships ensure that REN's investment planning and operational standards are benchmarked against a European reference, most notably through the Ten-Year Network Development Plan (TYNDP) [66].

The organisational structure is divided into two primary business areas, electricity transmission and natural gas infrastructure. The gas domain is articulated across four specialised units, covering LNG reception and regasification at Sines, high-pressure transmission, underground storage at Carriço, and regional distribution in the northern coastal region [62]. Each business area encompasses distinct asset typologies with different material compositions, operational lifetimes, and end-of-life recovery pathways, which is significant for a material lifecycle analysis [67].

3.1.2 The National Electricity Transmission Network (RNT)

The electricity transmission infrastructure constitutes the core physical asset base of REN and is the primary focus of this dissertation. Its function is to transport electrical energy in bulk from large generation centres to the delivery points of the distribution network and to manage interconnections with the Spanish grid [68]. According to the 2024 technical data published by REN, the National Electricity Transmission Network (RNT) comprises approximately 9 985 km of circuit length, distributed across overhead lines and underground cables [4, 69] (a geographical map of the network is provided in Appendix A).

The grid is structured across three primary voltage levels. The 400 kV network forms the backbone of the system, carrying the highest power flows over long distances and interconnecting with Spain. The 220 kV level serves as an intermediate transmission tier, while the 150 kV network, much of which was constructed in the mid-twentieth century, provides regional coverage and connects older generation assets. The physical infrastructure is anchored by 71 substations with a total installed transformation capacity exceeding 41 200 MVA [4].

3.1.2.1 Material Composition of Transmission Lines

From a materials perspective, overhead lines represent the most material-intensive component of the RNT in terms of total mass. The conductors deployed on the Portuguese grid are predominantly of the Aluminium Conductor Steel Reinforced (ACSR) type, in which stranded aluminium provides the primary electrical conduction pathway while a central steel core provides the tensile strength for long spans between towers [70]. This dual-material configuration is the dominant design in high-voltage transmission networks worldwide.

Support structures are predominantly steel lattice towers fabricated from hot-dip galvanised structural steel, chosen for its high strength-to-weight ratio, structural rigidity, and long service life under outdoor exposure conditions [71]. The total mass of steel embedded in transmission towers constitutes a significant fraction of the anthropogenic material stock of the grid. The RNT also incorporates underground and submarine cables, predominantly deployed in urban corridors

and environmentally sensitive zones, using copper or aluminium conductors insulated with cross-linked polyethylene (XLPE) or, in older installations, oil-impregnated paper [70].

3.1.2.2 Material Composition of Substations

Substations are the most materially complex nodes of the transmission network, integrating equipment with distinct material profiles. The principal asset families are the following.

- **Power transformers and autotransformers**, which combine copper windings, grain-oriented electrical steel in the magnetic core, and large volumes of mineral insulating oil [72].
- **Switchgear and circuit breakers**, which may contain sulphur hexafluoride (SF₆) as an insulating and arc-quenching medium [73].
- **Support structures and civil works**, comprising reinforced concrete foundations and steel structural frames, which account for the majority of mass at substation sites [71].
- **Insulators and bushings**, manufactured from porcelain, glass, or polymeric composite materials, each with very different recyclability profiles at end of life.

The way these material families interact across the asset lifecycle, and the circular barriers that result, is examined in Section 3.2.3.

3.1.3 The National Natural Gas Infrastructure (RNTIAT)

The natural gas infrastructure managed by REN, designated RNTIAT, comprises the high-pressure transmission grid of 1 375 km of carbon steel pipelines, the Sines LNG terminal, and the Carriço underground storage facility [4, 62]. Carbon steel dominates the pipeline mass, while the terminal relies on specialised cryogenic alloys. A strategically relevant dimension is the potential repurposing of the pipeline network for hydrogen transport, which is constrained by the embrittlement of high-strength steels and therefore introduces uncertainty about the timing of eventual decommissioning [74, 75]. These downstream and storage assets fall outside the primary scope of this dissertation, which concentrates on electricity transmission, but they form part of REN's total managed material base.

3.1.4 Strategic Role in the National Energy Transition

Beyond its role as a physical asset manager, REN's strategic importance in Portugal's energy transition provides the policy context that makes circularity a pressing operational concern. In 2024, renewable energy sources supplied 71% of Portugal's electricity consumption, reaching a record production of 36.7 TWh [69, 76]. In 2025, this figure was surpassed, with renewables generating 37 TWh and meeting 68% of national demand, which itself reached an all-time high of 53.1 TWh [3].

This accelerating integration of variable renewable energy has a direct material consequence for the transmission operator. The connection of large volumes of dispersed generation requires the continuous reinforcement and expansion of the 400 kV network, driving significant procurement of new steel, aluminium, copper, and concrete [66]. Simultaneously, the oldest segments of the 150 kV network, installed in the 1950s and 1960s, are progressively reaching the end of their designed service lives, generating large volumes of secondary material. Portugal's National Energy and Climate Plan (PNEC 2030) translates these dynamics into a sustained and large-scale capital investment programme for the RNT over the coming decade [1]. The material procurement and disposal flows resulting from this investment programme are, in aggregate, the primary object of the circularity assessment framework developed in this dissertation. As the literature on energy transition material requirements has demonstrated, the low-carbon transition is intrinsically a material-intensive undertaking, where the environmental and resource-security implications of infrastructure deployment are inseparable from the question of how those materials are managed throughout their lifecycle [71, 77].

3.2 Characterization of REN's Current Situation

The operational profile presented in the preceding section describes what REN does. This section addresses what REN holds. It covers the physical material accumulated across decades of infrastructure construction, the way that material is currently managed across its lifecycle, and the performance and limitations of the organisation's existing circularity practices. Together, these dimensions define the material baseline against which the assessment framework developed in Chapter 4 is designed to operate.

3.2.1 The Transmission Grid as an Anthropogenic Material Sink

A defining physical characteristic of transmission infrastructure is that it does not consume materials in operation but locks them in. Unlike industrial processes that transform or release materials through production, energy transmission assets function as long-lived reservoirs. Materials enter through construction, remain in service for decades, and exit only through decommissioning. This pattern of extended accumulation is captured in the literature through the concept of *in-use material stock*, or *anthropogenic stock*, defined as the aggregate mass of materials embedded in the built environment at any given point in time [78–80].

The strategic relevance of this concept for an operator such as REN lies in its temporal dimension. Multi-scale spatial analyses have demonstrated that infrastructure stocks in developed economies represent a dominant fraction of the total anthropogenic material reservoir, and that the timing of their re-entry into the economic cycle as secondary material flows is determined by the age structure of the asset base rather than by market conditions alone [78]. For REN, this means that decisions made today about what materials are procured, and in what configuration they are assembled, will determine the volume and quality of secondary materials available for recovery in

the 2040s and 2050s. Circularity is not only a current reporting obligation but a forward-looking resource management problem.

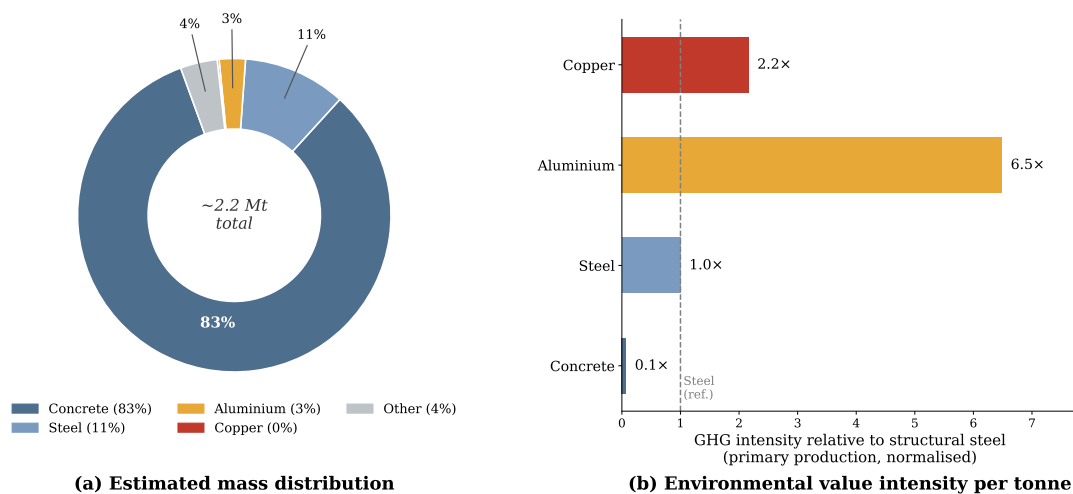
Based on standard material intensity data for high-voltage transmission infrastructure [71, 77], the Portuguese transmission network represents an estimated in-use stock on the order of 400 000 tonnes of steel, 120 000 tonnes of aluminium, and over one million cubic metres of reinforced concrete. This concentration is confirmed at the corporate scale by REN's own material flow analysis, which found that reinforced concrete and ferrous metals together account for 96.7% of the total material mass of its assets, with the electricity business unit alone concentrating around 75% of those flows [81]. Copper, while present in smaller absolute volumes, represents a disproportionate share of economic value and environmental significance, particularly in transformer windings and high-voltage cabling [48]. Dynamic MFA studies of the global steel cycle have shown that in-use steel stocks per capita in industrialised economies tend to saturate at levels of 11 to 16 tonnes, and that the timing of secondary material availability is governed by the age structure of the stock rather than by production or recycling capacity alone [61]. This insight directly applies to the Portuguese grid: the oldest 150 kV segments are progressively reaching or exceeding their designed service lives [72], while the 400 kV corridors commissioned in the 1990s and 2000s will only release their material stocks from the 2040s onwards. The result is a dual and simultaneous challenge: managing ageing assets approaching end of life while procuring massive quantities of new materials to reinforce the grid for variable renewable integration [66]. It is this coexistence of large-scale inflows and outflows within the same planning horizon that makes circularity a first-order operational priority.

3.2.2 Material Composition and the Pareto Concentration Principle

A critical insight for the design of any circularity assessment tool is that the material composition of transmission infrastructure is heavily concentrated. A small number of material categories accounts for the overwhelming majority of total mass, while the remaining materials, though potentially complex, valuable, or hazardous, represent a small physical fraction of the total stock. This concentration follows the empirical Pareto pattern [82]: roughly 20% of the material categories account for more than 80% of the total mass.

Reinforced concrete and structural steel together constitute approximately 80 to 90% of the total mass of the grid, concentrated primarily in tower foundations, civil works, and support structures. Aluminium, predominantly in overhead conductors, and copper, concentrated in transformer windings and high-voltage cabling, represent comparatively small mass fractions but carry a fundamentally different environmental significance: the carbon cost per tonne of primary aluminium production is approximately 6 to 7 times greater than that of structural steel, while primary copper carries around double the emission intensity of steel [48, 71]. As shown in Figure 3.1, this creates a key asymmetry between mass share and circular relevance: the materials that dominate by weight are not those that drive the majority of the environmental impact, and vice versa.

The practical implication of this Pareto distribution for the design of a circularity assessment tool is significant. Restricting the quantitative assessment to the four dominant material streams,



Note: Estimates based on literature intensity factors applied to REN Technical Data (2024). GHG intensities from Ciacchi et al. (2016) and World Steel Association (2023).

Figure 3.1: Material composition of high-voltage transmission infrastructure. (a) Mass share by category. (b) Environmental value intensity per tonne, normalised to steel. Percentages in (a) are rounded to the nearest whole number and may therefore not sum exactly to 100%. Adapted from [48, 71, 77].

concrete, steel, aluminium, and copper, makes it possible to capture over 90% of the total material circularity performance of a given project while maintaining a data collection scope that is operationally feasible within REN's existing reporting infrastructure [71]. This mass-weighted simplification does not eliminate the need to address complex or hazardous materials such as SF₆ or mineral oils. It channels those into qualitative or compliance-based assessments within the same framework, while preserving quantitative rigour for the bulk material streams. This design choice is formalised in the methodology presented in Chapter 4.

3.2.3 Project Typologies and Lifecycle Phases

The challenge of circularity management at REN is not uniform across its portfolio. This dissertation focuses on the two most representative typologies, overhead transmission lines (LMAT) and substations. They present different material profiles, different lifecycle dynamics, and critically different circularity barriers, and recognising this distinction is essential for an assessment framework that is both accurate and applicable.

REN structures the project lifecycle into five phases for greenhouse gas accounting: right-of-way or site establishment (A), construction (B), operation and maintenance (C), forest balance (D), and decommissioning (E). This phased view spans the entire carbon footprint, including land-use and forestry effects that lie beyond the material boundary of the present work, which concentrates on the components introduced during construction.

3.2.3.1 Overhead Transmission Lines (LMAT)

The construction of an overhead line introduces its principal materials in a single stage, namely the aluminium-steel conductors, the galvanised steel lattice towers, the reinforced concrete foundations, the reinforcement steel, and the insulator strings. Over a service life of fifty years or more the line requires periodic inspection, vegetation management, and the replacement of deteriorated components such as insulator strings, before decommissioning returns the cables, insulators, towers, and foundations to the material system.



Figure 3.2: Example of REN overhead transmission line. Adapted from [68].

Overhead lines are therefore characterised by large material volumes across extensive corridors. The principal streams, ACSR conductors and galvanised steel towers, are bulk commodities with well-established secondary markets. At end of life, systematic dismantling generates predictable, high-purity ferrous and non-ferrous scrap that flows efficiently into conventional recycling. The high valorisation rates achieved by REN follow directly from the physical properties of these bulk metal streams [40, 83].

The circularity challenge for LMAT is therefore input-side rather than output-side. The unresolved question is not whether decommissioned aluminium is recycled, but whether newly procured conductor and tower steel specifies and verifies a minimum recycled content. This leading indicator connects present procurement with the circular flows of the future, and it is currently absent from REN's project-level monitoring.

3.2.3.2 Substations

The construction of a substation introduces concrete and metallic structures, power transformers and autotransformers, current, auxiliary, and capacitive voltage transformers, circuit breakers, disconnectors, protection and control systems, insulators, and batteries. During operation the substation is dominated by the electrical losses of the autotransformer, the main source of emissions over its service life, before decommissioning dismantles the installed equipment.

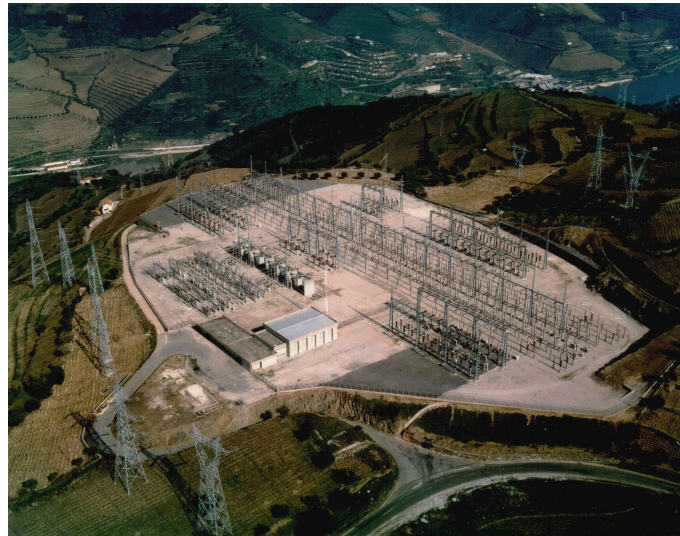


Figure 3.3: Example of a REN high-voltage substation, located in Valdigem. Adapted from [62].

Substations present a more complex challenge than lines, defined by high *material entropy*, the degree to which dissimilar materials are mixed or co-assembled in ways that degrade their separability at end of life [40]. Power transformers are the canonical example. A single high-voltage transformer integrates copper windings, grain-oriented electrical steel, cellulose insulation impregnated with mineral oil, and several thousand litres of liquid insulating medium within a sealed steel tank [11]. About 75% of the mass of a liquid-filled transformer is compatible with circular recovery, but the remainder, including impregnated insulation, composite seals, and polymer bushings, requires specialised processing to avoid cross-contamination [11, 40]. The possible presence of Polychlorinated Biphenyls (PCBs) in oil from transformers made before 1987 further classifies this stream as hazardous under European Directive 96/59/EC [84]. These thermodynamic and collection constraints keep practical recycling rates for complex metals far below what is technically achievable [40].

Switchgear adds a further dimension. SF_6 , with a global warming potential about 24 300 times that of CO_2 over a 100-year horizon, is subject to mandatory phase-out in new equipment under the revised EU F-Gas Regulation [32, 73], which sets replacement timelines decoupled from physical service life.

The contrast between the two typologies reveals a fundamental asymmetry. The assets simplest to assess already perform well at end of life, while the assets hardest to assess are precisely those where the circularity performance gap is greatest. The circularity and embodied carbon of the construction-phase components, and their connection to REN's project-level accounting, are quantified in the methodology of Chapter 4.

3.2.4 Current Resource Management Performance

REN's current resource management performance is strong by the primary metric applied. The organisation has consistently maintained a waste valorisation rate exceeding 90% across recent

reporting cycles [4]. This reflects genuine operational competence in end-of-life recovery, driven by the systematic dismantling of decommissioned overhead lines and the regeneration of mineral insulating oils from power transformers.

This metric is, however, a *lagging indicator*. It measures outcomes at the end of the asset lifecycle, not the conditions that shape circular performance at the design and procurement stages. A high end-of-life recovery rate does not prevent the procurement of materials with low recycled content, creates no incentive for suppliers to adopt circular design, and cannot compare the circular merits of two alternative projects before construction. The distinction between lagging and leading indicators is central to the framework established in Chapter 2 and has direct practical consequences for REN's ability to improve its circularity trajectory [25]. The boundaries this creates for project-level decision-making are examined in Section 3.3.

3.2.5 Sustainability Strategy and ESG Commitments

REN's resource management performance is embedded within a formal sustainability strategy. The Strategic Plan for 2027, published in 2024, establishes climate targets aligned with a 1.5 °C pathway. As summarised in Figure 3.4, these commit REN to a 60% reduction in Scope 1 and 2 emissions by 2030 relative to a 2019 baseline, a 30% reduction in Scope 3 emissions relative to 2021, and net-zero operational emissions by 2040 [7]. These targets are supported by dedicated green financing, including a 300-million-euro green bond issued in 2024 [7].

Within the circular economy domain, REN has formalised its approach through the *Circular Economy Roadmap* (2023), which defines strategic axes for integrating circular principles into asset management, procurement specification, and contractor engagement [81]. The roadmap moves beyond end-of-life waste management toward circular procurement and design-for-disassembly, recognising the input-side gap identified above. The Scope 3 target is central here, since capital goods and infrastructure materials dominate REN's indirect emissions, so a 30% reduction by 2030 depends largely on increasing the recycled content of procured materials.



Figure 3.4: REN 2030 climate commitments and 2040 neutrality target. Adapted from [7].

The roadmap is a strategic document. It defines directions and objectives but does not yet provide the quantitative, project-level tools required to operationalise them or to demonstrate compliance with ESRS E5 at the asset level. A gap therefore remains between strategic ambition and the measurement of circularity performance in practice, and addressing this gap is the main objective of this dissertation.

3.3 Analysis of the Current Assessment Model

Following the characterisation of REN's material profile, it is necessary to understand the tools currently used to monitor and project its circularity indicators. This section details the existing internal framework, describes its operational scope, and situates its maturity within the broader European transmission sector.

3.3.1 The Existing Internal Framework

The Circular Economy Roadmap introduced above is operationalised through an internal Resource Use Assessment Tool [81]. As disclosed in the 2024 Integrated Report, this tool consolidates and monitors a defined set of environmental and waste management indicators at the corporate level [4].

The framework tracks total waste generation, hazardous and non-hazardous valorisation rates, end-of-life recovery volumes by material stream, and the recycled content of key material inputs. Aggregating this data generates the outputs required to align REN's reporting with ESRS E5 and the Global Reporting Initiative (GRI 306) [43]. At the corporate level the framework provides a consistent and auditable baseline, capturing genuine achievements such as the waste valorisation rate exceeding 90% discussed in Section 3.2.4. It is the appropriate operational starting point for a more advanced circularity assessment.

The roadmap also reported a first corporate-level circularity score, computed with the EMF Material Circularity Indicator [81]. The aggregate value reached $MCI = 0.31$, a low result driven by the dominance of concrete and other mineral materials, which carry virgin content close to unity and negligible end-of-life recovery. The assessment weighted representative equipment models by mass, providing a macro-level snapshot rather than a project-level diagnostic. This figure is the quantitative starting point that the present dissertation refines and extends.

3.3.2 Operational Boundaries of the Current Model

While the existing tool fulfils its purpose of corporate reporting, its structure reveals specific boundaries when applied to project-level engineering and procurement decisions.

The model operates at an aggregated asset scale designed for a macro-level corporate overview. Its architecture is not adapted to isolate and compare alternative design options or procurement choices for a specific investment [24]. Its intentionally broad material categorisation also limits diagnostic resolution, since a single corporate valorisation rate can be dominated by bulk ACSR conductor scrap while masking the much lower performance of SF₆ switchgear, dry-type transformers, or composite insulators [23].

The framework tracks material flows in mass terms and does not simultaneously track the greenhouse gas emissions associated with those flows. The carbon dimension of circularity, particularly the avoided Scope 3 emissions from substituting primary by secondary production, cannot be quantified within the same tool [30]. The magnitude of this co-benefit is significant, since

secondary aluminium requires approximately 5 to 10% of the energy of primary production [45]. As established in Chapter 2, this disconnection between circularity and carbon is a recognised limitation in material-intensive industries.

The temporal scope is limited to annual corporate snapshots rather than the full lifecycle of long-lived infrastructure. Component replacement cycles, which occur on 15 to 25-year intervals within a 50-year design life, are therefore not integrated into the circularity calculations [5]. The tool also relies on manual data collection, which limits scalability and prevents systematic integration into procurement specifications.

3.3.3 Sectoral Benchmarking: European TSO Landscape

The operational boundaries identified in the preceding subsection are not anomalous but reflect the current stage of methodological development across the European transmission sector. An analysis of sustainability reports, circular economy roadmaps, and procurement frameworks from major European Transmission System Operators for the 2023 and 2024 reporting cycles reveals a consistent pattern.

Operators such as TenneT, Elia, National Grid, Redeia, Statnett, and RTE share a common baseline: all have formalised circular economy strategies and align their macro-level reporting with ESRS E5 requirements [85–88]. Leading organisations have begun introducing targeted initiatives, such as embedding Life Cycle Assessment (LCA) criteria into procurement, specifying minimum recycled content thresholds, and launching pilot projects for material reuse. Despite this strategic ambition, these initiatives remain largely fragmented. No operator currently operates an integrated tool capable of evaluating circularity at the project level, incorporating component substitution cycles, systematically linking material circularity metrics with quantified carbon avoidance, or automating EPD data management.

This fragmentation is reinforced by the policy context. The European and national circular economy action plans concentrate on high-consumption goods and on sectors with a large material footprint, such as construction, and do not yet define concrete measures for the energy transmission sector. The adaptation of transmission infrastructure to circular principles therefore remains a largely open opportunity, only partially addressed by current strategic instruments [81].

The current structure of REN's model places the organisation fully within the European industry baseline [25]. Transitioning from a corporate reporting mechanism to an active, project-level decision-support instrument, however, requires methodological updates of the kind developed in Chapter 4.

3.4 Strategic Targets and Asset Replacement Outlook

REN's strategic actions are aligned with the Portuguese National Energy and Climate Plan (PNEC 2030) and the broader European carbon neutrality agenda. Its updated Sustainability Policy emphasises the entire value chain, linking the transition from linear to circular material

management to the decarbonisation of the supply chain and the modernisation of national energy infrastructure.

3.4.1 Strategic Sustainability and Supply Chain Targets

The headline climate commitments of REN, presented in Section 3.2.5, are complemented by more granular 2030 commitments that are directly relevant to the material and operational dimensions characterised in this chapter. These include a 50% reduction in SF₆ emissions and a 30% reduction in CH₄ emissions relative to 2023 levels, alongside a 40% reduction in water consumption and a 35% reduction in energy consumption [7].

Of particular strategic significance for the present dissertation is the supply chain procurement target. REN aims to ensure that **50% of contracted procurement volume** is allocated to suppliers operating under Science Based Targets initiative (SBTi)-aligned decarbonisation pathways [7]. This target places circularity firmly within the supply chain decisions that determine the embodied carbon of each procurement decision. A project-level tool that scores material circularity without simultaneously quantifying embodied carbon avoidance cannot support this commitment in a consistent or auditable way, which is precisely the gap addressed in Chapter 4.

3.4.2 Asset Replacement Dynamics and Future Material Flows

The REN Circular Economy Roadmap identified the extension of asset service life as the circularity area with the greatest development potential for the organisation, and the one where its position is weakest, with dispersed and largely uncoordinated actions across asset classes, as shown in Figure 3.5 [81]. This assessment provides a direct institutional motivation for the service life extension module developed in this dissertation, which translates that strategic priority into a quantitative and physically bounded analysis. A dimension of the circularity problem that extends beyond the assessment of current material stocks is the forecasting of future material availability from asset decommissioning. Both electricity and gas transmission infrastructure have long and irregular replacement cycles. Power transformers may remain in service for 40 years or more, overhead lines for 50 years or longer, and high-pressure gas pipelines for comparable periods. Certain components are replaced at much shorter intervals due to technological evolution or regulatory changes, as is currently the case with SF₆-containing equipment under the F-Gas Regulation phase-out schedule [72, 73]. Dynamic material flow analysis and stock-driven modelling provide the methodological foundation for forecasting these flows [36, 60]. By modelling the age distribution and service life of the current stock, it is possible to project when specific materials will reach end of life and become available as secondary feedstock, which supports both recovery logistics and the alignment of procurement with domestic secondary supply. End-of-life recycling rates vary widely across metals, from above 50% for bulk steel and aluminium to below 1% for many specialty metals, constrained by collection losses, disassembly deficiencies, and thermodynamic separation limits [40, 49]. For bulk structural metals, the decommissioning wave anticipated in

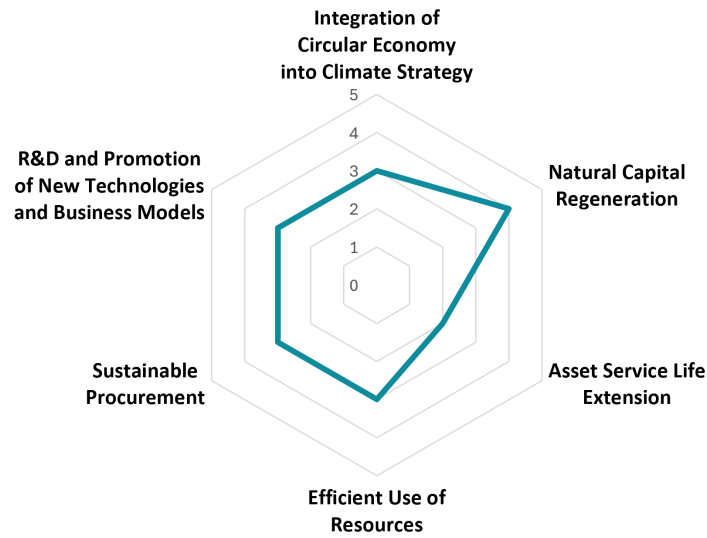


Figure 3.5: REN's position across six circular economy areas. Adapted from [81].

the Portuguese grid represents a substantial opportunity to reduce primary demand and the embodied carbon of new infrastructure [30, 44]. In the Portuguese context, a significant wave of infrastructure renewal is anticipated over the coming decades. As characterised in Section 3.2.1, the ageing of the oldest 150 kV segments and the later release of the 400 kV stock create a temporal mismatch between the current wave of new construction and the availability of domestic secondary material. For the gas infrastructure, the potential repurposing of natural gas pipelines for hydrogen transport introduces additional uncertainty about the exact timing and nature of end-of-life material flows. This temporal mismatch between current procurement decisions and future decommissioning flows is a defining structural feature of the circularity challenge in energy networks [60]. The framework developed in Chapter 4 addresses this temporal dimension through the replacement-cycle structure of its indicators. Projecting the resulting secondary material availability against REN's procurement plan to 2030 was an initial objective of this work, intended to quantify the associated variation in circularity and its emission implications. The procurement and decommissioning volumes required for that projection did not become available in time. The full stock-flow analysis is therefore carried forward as a direction for future development in Chapter 6.

3.5 Circularity Assessment Optimization Strategy

The analysis presented in this chapter demonstrates that the circularity challenge in energy transmission infrastructure is not primarily a question of technological feasibility, but of measurement, integration, and decision-making. While REN operates within a system where large volumes of technically recyclable materials are already recovered at end of life, the operational boundaries

identified in Section 3.3.2 prevent circularity from being embedded upstream at the design and procurement stages, and prevent its carbon co-benefits from being quantified and reported.

The core gap can be formally stated as follows. REN currently lacks a quantitative, project-level methodology capable of integrating material composition, recycled content, component replacement cycles, greenhouse gas emissions, and benchmarking against achievable targets into a single decision-support instrument. This results in three structural inefficiencies. Circularity remains a retrospective reporting metric rather than an active design parameter. Material flows are evaluated in terms of mass alone, which disconnects procurement decisions from their associated carbon footprint. The temporal dynamics of the infrastructure are not captured, so the organisation cannot account for variable component service lives across the project horizon.

To address this problem, the optimisation strategy proposed in this dissertation is structured around the development of a project-level circularity and carbon assessment model. The model is designed around five core requirements:

- **Project-level applicability:** the methodology must operate at the scale of individual infrastructure projects, enabling the quantitative comparison of alternative designs and procurement options [24].
- **High-resolution material categorisation:** the model must account for the distinct physical and circularity profiles of specific material streams, rather than relying on broad aggregate groupings [23].
- **Carbon-circularity integration:** the assessment must bridge material flows and their environmental impact by quantifying the avoided GHG emissions associated with different circularity strategies, directly supporting Scope 3 reporting [30].
- **Lifecycle and temporal dynamics:** the framework must incorporate the full temporal structure of the assets, integrating component replacement cycles and distinct service lives into the core MCI calculations [5].
- **Systematic benchmarking against achievable targets:** the model must situate the performance of each material stream against best-practice recycled content and end-of-life recovery rates, quantifying the circularity and carbon improvement potential that realistic procurement action can deliver [25].

Conceptually, this approach represents a shift from a waste management paradigm to a circular engineering paradigm, in which material flows and their carbon implications are treated as active design variables from the earliest stages of project planning. The quantitative methodology that operationalises these five requirements is developed in full in Chapter 4.

4 Proposed Solution and Model Development

Chapter 3 concluded that REN lacks a quantitative, project-level methodology capable of integrating material composition, recycled content, replacement cycles, greenhouse gas emissions, and benchmarking potential into a single decision-support instrument. This chapter develops the assessment framework that closes this gap, covering the adapted circularity indicators, the lifecycle carbon module, the benchmarking layer, and the verification and sensitivity procedures embedded in the computational tool.

4.1 Framework Architecture and Design Principles

The proposed framework is a project-level assessment tool designed to operate at the scale of individual transmission infrastructure projects, covering both overhead line (LMAT) and substation typologies as characterised in Chapter 3. It produces decision-ready outputs that can be directly integrated into procurement specifications and sustainability disclosures.

The assessment is organised around three primary input categories. Project parameters define the asset typology, the total design life L_{proj} , and the reference year for environmental data. The material inventory specifies the as-installed mass and declared service life L_i of each component stream, drawn from the applicable Environmental Product Declaration (EPD) or technical specification. Environmental data provides the stream-level parameters required by the circularity and carbon modules: recycled content fraction F_R , effective end-of-life recovery rate E_c , upstream recycling efficiency E_F , cumulative exergy demand CExD, and global warming potential factors GWP_{vir} and GWP_{rec} . Project-specific EPDs take precedence over sector-average literature values where available. Datasets exceeding the five-year validity period defined under EN 15804 are flagged automatically and excluded from unverified calculations.

From these inputs, the tool generates five categories of output, as illustrated in Figure 4.1. The mass-weighted circularity score MCI^{mass} is computed under two variants, one including all material streams and one excluding concrete foundations, to isolate the effect of civil works on the headline result. The exergy-weighted score MCI_{ex} reweights each stream by its thermodynamic resource intensity, providing a complementary view of circularity performance anchored in material quality rather than physical mass. The component-level MCI is evaluated as a function of the utility factor X , up to the physically bounded ceiling $X_{\text{max},i}$ defined in Section 4.2.2, to support asset management prioritisation. The total lifecycle carbon footprint GWP_{proj} covers Modules A through D of EN 15978, expressed as Scope 3 emissions. The benchmarking outputs ΔMCI_i and

$\Delta GWP_{i,\text{total}}$ quantify the circularity and carbon gains achievable by adopting best-practice recycled content and end-of-life recovery rates for each material stream.

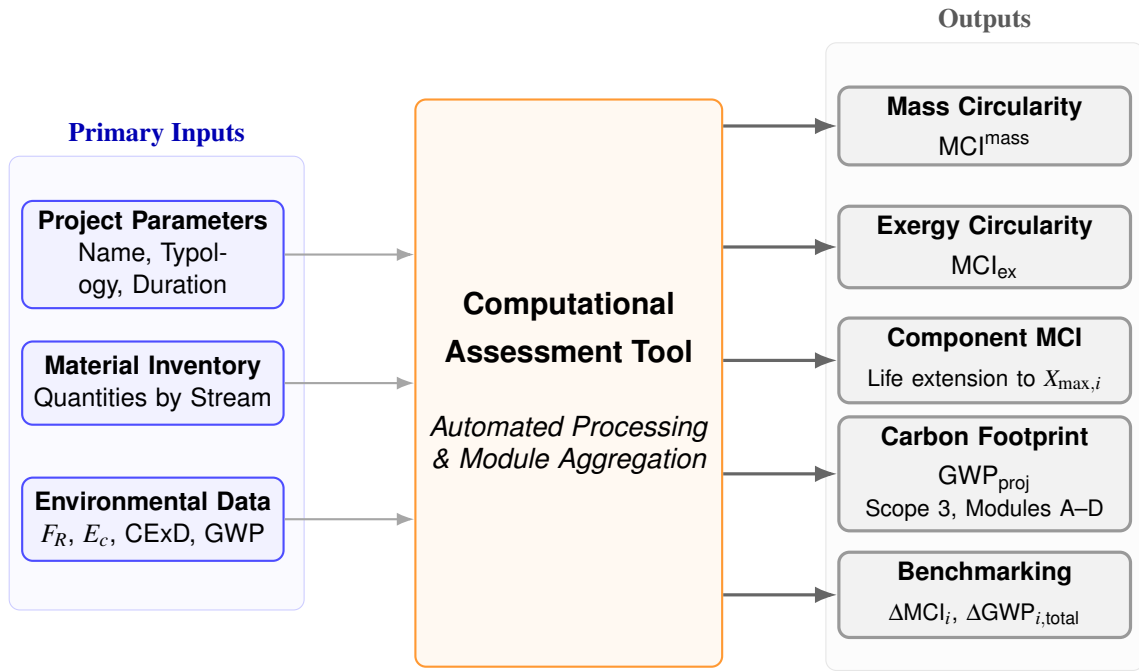


Figure 4.1: Information flow and outputs of the proposed assessment framework.

The framework covers twenty material streams organised into five functional groups: structural and conductive metals (steel, aluminium, copper, silver, tin, zinc, and lead), dielectric and insulating media (mineral oil, SF₆, and insulating paper), non-metallic bulk materials (concrete, glass, ceramics, and composites), polymers (equipment housing, cabling, and PE piping), and a residual category. This disaggregation ensures that streams sharing a base material but exhibiting distinct recovery pathways, such as structural steel in lattice towers versus steel in internal equipment components, are assigned independently calibrated parameters. The same formulation is applied uniformly across all twenty streams regardless of mass fraction. SF₆, for instance, carries a global warming potential of approximately 24 300 kg CO₂eq kg⁻¹ [32] and constitutes one of the most environmentally critical streams in substation projects despite its small mass presence. Excluding it on mass grounds would introduce a systematic blind spot in the environmental assessment.

To operationalise the framework for direct use by REN’s engineering teams, the computational model is implemented as a structured spreadsheet workbook in *Microsoft Excel*, which constitutes the primary calculation engine of the framework. All circularity and carbon modules are embedded in the workbook, with parameter inputs, intermediate calculations, and output dashboards organised across dedicated worksheets. A complementary web-based interface, developed in *Python* with the *Streamlit* library, runs the model in the background and presents the results without requiring direct manipulation of the spreadsheet. This interface supports practical adoption within REN’s engineering workflows. Its implementation is described in Section 5.1.

The carbon accounting boundary follows EN 15978:2011, covering Modules A through D. This cradle-to-grave scope aligns with REN's formally adopted target of a 30% reduction in Scope 3 emissions by 2030 relative to a 2021 baseline and with ESRS E5 disclosure obligations. The circularity modules operate on a consistent but analytically distinct boundary: the MCI characterises the degree to which material inputs are sourced from secondary feedstocks and outputs are recovered at end of life, independently of their carbon implications. The two analytical layers are complementary and their outputs are presented in parallel throughout the assessment.

4.2 Baseline Circularity Assessment: The Adapted MCI

The Material Circularity Indicator provides the quantitative backbone of the circularity assessment module. Its standard formulation, introduced in Chapter 2, was designed for single-material, single-lifecycle manufactured products and requires two structural adaptations before it can be applied to long-lived, multi-component transmission infrastructure assets. First, individual components within the same asset operate under service horizons ranging from 20 to more than 60 years and undergo independent replacement cycles, which the standard formulation does not account for. Second, the diversity of material streams across LMAT and substation typologies requires that aggregation weights reflect more than physical mass. The following subsections develop the standard formulation, introduce the temporal adaptations, and establish the mass-weighted aggregation method that delivers the baseline composite score.

4.2.1 Standard MCI Formulation

The MCI is constructed sequentially from a set of intermediate variables, each representing a physically distinct and measurable material flow [5]. Together, they capture two symmetric sources of linearity: resource extraction on the input side, measured through the virgin material term V , and material loss on the output side, measured through the total waste term W . The complete material flow structure is illustrated in Figure 4.2.

Virgin material input (V)

V quantifies the mass of primary resources incorporated into the product system [5]:

$$V = M \cdot (1 - F_R - F_U - F_B) \quad (4.1)$$

where M is the total input mass (kg), F_R the recycled content fraction, F_U the reused content fraction, and F_B the fraction from certified biological feedstocks, all in $[0, 1]$ and mutually exclusive. Here $F_U = F_B = 0$, reducing the expression to $V = M(1 - F_R)$. The recycled content F_R , declared in the applicable EPD, is the primary input-side lever.

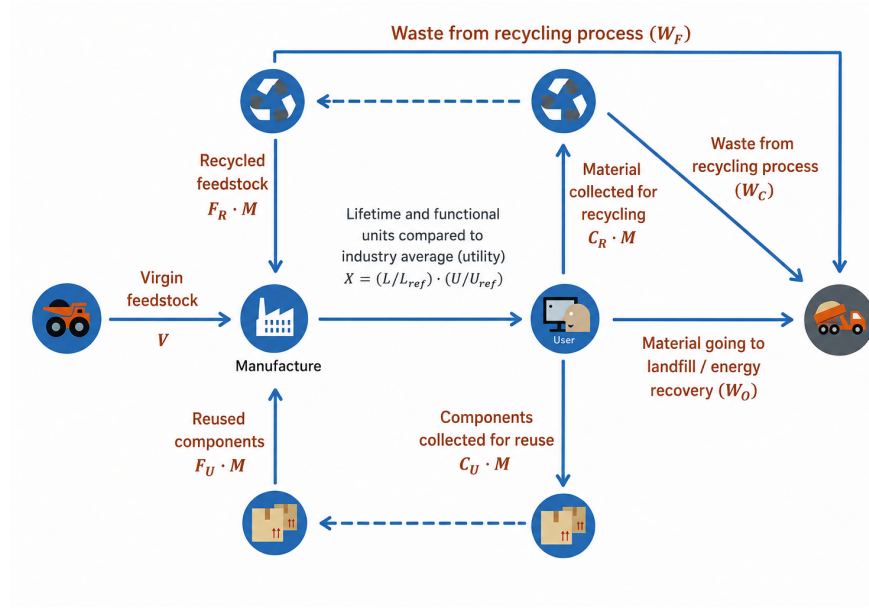


Figure 4.2: Material flow structure underlying the Material Circularity Indicator, adapted from [5].

Unrecoverable waste at end of life (W_o)

W_o quantifies the mass that irreversibly exits the system at end of life [5]:

$$W_o = M \cdot (1 - C_R - C_U - C_C - C_E) \quad (4.2)$$

where C_R , C_U , C_C , and C_E are the fractions directed to recycling, reuse, composting, and energy recovery. For the primary structural streams $C_U \approx C_C \approx C_E \approx 0$, reducing the expression to $W_o = M(1 - C_R)$. Here C_R is a binary flag. A stream with no viable recovery pathway is assigned $C_R = 0$ and its full mass flows to W_o , while a stream with an established pathway is assigned $C_R = 1$, with its in-process losses captured through the recycling efficiency E_c .

End-of-life recycling process losses (W_c)

W_c quantifies the mass lost within the recycling operation at end of life [5]:

$$W_c = M \cdot (1 - E_c) \cdot C_R \quad (4.3)$$

where $E_c \in [0, 1]$ is the technical efficiency of the end-of-life recycling process, estimated from material-specific recovery statistics [5]. Materials with no viable recovery pathway, such as concrete foundations and impregnated insulating paper, are assigned $C_R = 0$.

Upstream recycling process losses (W_F)

W_F accounts for the material mass consumed during the upstream recycling operations that produced the secondary feedstock F_R . Omitting this term would overstate the circularity of products with high recycled content [5, 10]:

$$W_F = M \cdot \frac{(1 - E_F) \cdot F_R}{E_F} \quad (4.4)$$

where $E_F \in [0, 1]$ is the upstream recycling efficiency. The case $E_F = 0$ implies $F_R = 0$ and the term vanishes. In a closed loop $E_c = E_F$, but the methodology does not require one, so the recycled feedstock may be sourced on the open market independently of the product's own end-of-life stream [5].

Total unrecoverable waste (W)

W aggregates all material losses that cannot be reintegrated into productive circular flows [5]:

$$W = W_o + \frac{W_F + W_c}{2} \quad (4.5)$$

The 50:50 averaging follows the EMF symmetry convention, which distributes responsibility for recycling losses equally between the system that generated the recycled feedstock and the system that will produce end-of-life scrap, preventing double counting [5, 10].

Linear Flow Index (LFI)

The LFI normalises the combined linear flows into a single dimensionless ratio [5], expressed in equation (4.6):

$$\text{LFI} = \frac{V + W}{2M + \frac{W_F - W_c}{2}} \quad (4.6)$$

The correction term $(W_F - W_c)/2$ maintains consistency with the 50:50 convention of equation (4.5) and vanishes when the recycling system is symmetric ($W_F = W_c$). The LFI ranges from 0 for a fully circular system to 1 for complete linearity.

Utility factor (X and $F(X)$)

The utility factor X introduces a temporal dimension by relating the actual service life of the asset to a sector reference [5]:

$$X = \frac{L}{L_{\text{ref}}} \cdot \frac{U}{U_{\text{ref}}} \quad (4.7)$$

where L and L_{ref} are the actual and reference service lives (years), and U and U_{ref} the actual and reference utilisation intensities. For transmission infrastructure, which operates continuously at design capacity, $U/U_{\text{ref}} = 1$ and the expression reduces to $X = L/L_{\text{ref}}$. The utility factor enters the MCI through:

$$F(X) = \frac{0.9}{X} \quad (4.8)$$

The coefficient 0.9 is set such that a fully linear product ($LFI = 1$) at the sector average ($X = 1$) receives $MCI = 0.1$ by convention [5]. Lifetime extension beyond the reference ($X > 1$) reduces $F(X)$ and directly improves the MCI, constituting a quantifiable circular strategy independent of material sourcing decisions [89, 90]. Figure 4.3 illustrates the MCI response for three representative recovery scenarios. A fully restorative product achieves $MCI = 1$ regardless of X , confirming that circular material flows dominate the utility factor effect.

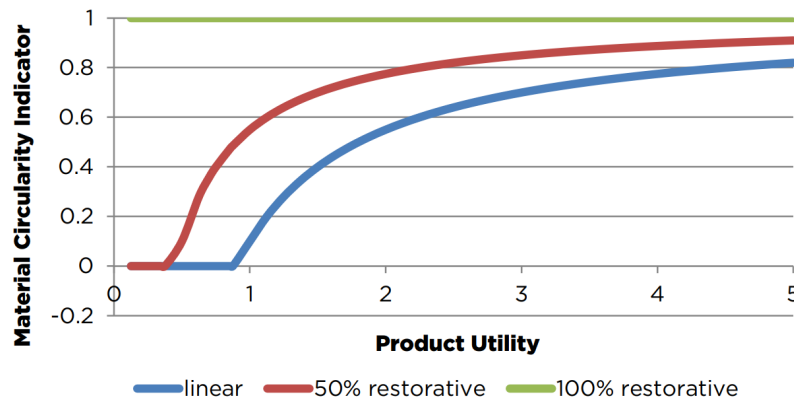


Figure 4.3: MCI as a function of the Utility Factor X . Adapted from [5].

Material Circularity Indicator (MCI)

The MCI synthesises the foregoing into a single scalar score [5]:

$$MCI = \max(0, 1 - LFI \cdot F(X)) \quad (4.9)$$

The floor at zero prevents negative values for assets with very high linearity and $X < 1$. At or above the sector reference lifetime ($X \geq 1$), the minimum attainable value is $MCI = 0.10$, corresponding to a fully linear system ($F_R = 0$, $E_c = 0$, $X = 1$). A score of 1 is achieved only when $LFI = 0$, corresponding to a system with no virgin inputs and no unrecoverable waste. Table 4.1 summarises all variables.

4.2.2 Temporal Adaptations: Effective Mass and Service Life Extension

The standard MCI assumes a product is manufactured once and reaching end of life as a unified system. Transmission infrastructure violates this assumption because individual components within the same asset operate under service horizons ranging from 20 to more than 60 years and undergo independent replacement cycles throughout the project lifetime. A circularity assessment restricted to the initial material composition at commissioning would therefore capture only a fraction of the material flows that actually occur over the project horizon.

Table 4.1: MCI variables in the TSO infrastructure context.

Parameter	Symbol	Definition
Total mass	M	As-installed mass of the component stream (kg)
Recycled content fraction	F_R	Fraction of input mass from secondary material
Upstream recycling efficiency	E_F	Yield of the recycling process supplying F_R
Virgin mass	V	Mass of primary material in the input
Recovery pathway flag	C_R	Fraction of mass sent to recycling at end of life, binary in this framework
Recycling process efficiency	E_c	Yield of the end-of-life recycling process
Upstream process losses	W_F	Mass lost in the upstream recycling process
Downstream process losses	W_c	Mass lost in the end-of-life recycling process
Unrecoverable waste	W_o	Mass not recovered at end of life
Total waste	W	Combined linear output flows
Linear Flow Index	LFI	Linear flows as a fraction of total mass throughput
Utility factor	X	Actual service life relative to the reference

Effective mass and replacement cycles

The framework addresses this by introducing an effective mass m_i^{eff} for each component i :

$$m_i^{\text{eff}} = m_i \cdot \left\lceil \frac{L_{\text{proj}}}{L_i} \right\rceil \quad (4.10)$$

where m_i is the nominal as-installed mass (kg), L_i is the declared service life (years) from the applicable EPD or technical specification, L_{proj} is the project design life (years), and $\lceil \cdot \rceil$ is the ceiling function. The ceiling operator reflects the discrete nature of infrastructure procurement: a partial replacement cycle incurs the full material burden of a complete unit. This effective mass replaces m_i in all downstream calculations, and the project-level score weights each component by m_i^{eff} rather than by its nominal mass. Figure 4.4 illustrates the replacement cycle logic for a representative transformer asset.

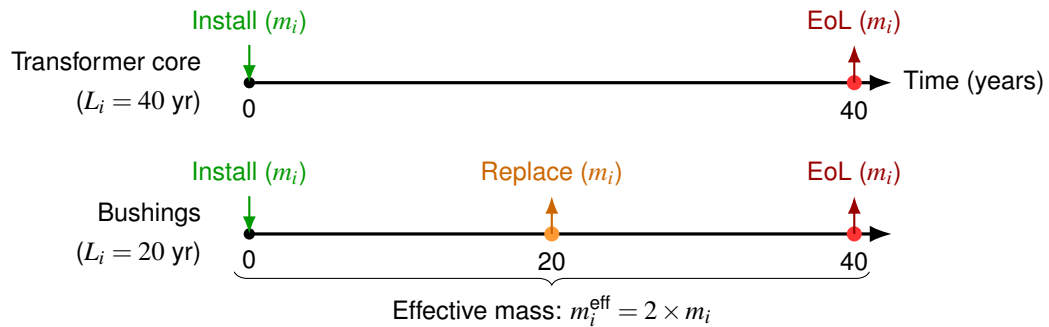


Figure 4.4: Effective mass approach example.

Service life extension and the utility factor

The effective mass formulation models each component as operating for exactly its declared service life and being replaced by an identical unit at every cycle. This is the conservative baseline. The utility factor X quantifies the circularity benefit of extending a component's service life beyond its declared reference, reducing the number of replacement cycles required across the project horizon. The component-level MCI is evaluated as a function of X to support asset management prioritisation, separately from the baseline project indicators.

The range over which X may be increased is not arbitrary. Two distinct limits bound it. The first is the project horizon. Extending a component beyond the point where a single installed unit already spans the full project life yields no further benefit within the assessment boundary, because the additional durability materialises only after decommissioning. This defines a project-bounded ceiling:

$$X_{\text{proj},i} = \frac{L_{\text{proj}}}{L_{\text{ref},i}} \quad (4.11)$$

The second limit is physical. Every component reaches an ultimate service life imposed by the irreversible degradation of its materials, independent of the project to which it belongs. Thermal creep, wind-induced fatigue, and atmospheric corrosion do not adjust to a design horizon. They impose a maximum attainable life $L_{\text{phys},i}$ beyond which the component cannot be safely retained, regardless of maintenance intent. This defines a physically-grounded ceiling:

$$X_{\text{phys},i} = \frac{L_{\text{phys},i}}{L_{\text{ref},i}} \quad (4.12)$$

The degradation mechanism that governs $L_{\text{phys},i}$ differs by component and by service environment. Three families dominate transmission infrastructure. Thermal creep is the slow accumulation of permanent strain in metals held under sustained mechanical load at elevated temperature, relevant to current-carrying conductors heated by the Joule effect. High-cycle fatigue is the progressive cracking of fixation points and accessories under cyclic loading, driven in overhead lines by wind-induced vibration. Atmospheric corrosion is the loss of protective coatings and subsequent attack of the base metal, strongly accelerated in coastal environments by airborne salinity. Under the chloride load of a C5 marine atmosphere, the zinc carbonate layer that protects galvanised steel is progressively converted into soluble zinc chlorides that offer little protection, so the sacrificial coating is consumed faster than in inland exposure [91]. A fourth consideration is whether the limiting mechanism is recoverable. A protective coating that can be restored through scheduled maintenance, such as the galvanising on a steel structure, does not impose a hard life limit. A degradation internal to a sealed or non-serviceable element, such as the corrosion of a conductor steel core, cannot be reversed and therefore governs the ultimate life. The specific mechanism, reference life, and physical life adopted for each material stream are derived and tabulated in Chapter 5, where the case-study material inventories are presented.

The applicable maximum utility factor is the more restrictive of the two ceilings, with a floor at unity:

$$X_{\text{max},i} = \max(1, \min(X_{\text{phys},i}, X_{\text{proj},i})) \quad (4.13)$$

The floor at unity reflects a deliberate modelling choice. A component whose reference life already exceeds the project horizon ($L_{\text{ref},i} \geq L_{\text{proj}}$) yields $X_{\text{proj},i} \leq 1$. Applying a utility factor below unity in equation (4.8) would increase $F(X)$ and penalise the component for outlasting the project, which is not physically meaningful. Such a component is instead modelled as covering the full project life with a single unit and no replacement, for which the relevant utility is $X = 1$. The residual life beyond the project horizon is not credited to the present assessment. It is accounted for separately, as the component remains available as a spare or reserve asset after decommissioning.

When $X_{\text{phys},i} < X_{\text{proj},i}$, the physical limit binds. The component cannot be extended to fill the project horizon because its materials degrade first. This is the characteristic case for short-lived components in aggressive environments. When $X_{\text{proj},i} < X_{\text{phys},i}$, the project limit binds and the component could physically last longer than the assessment can credit. Replacing the earlier purely geometric ceiling, equal to the project ceiling $X_{\text{proj},i}$ alone, with equation (4.13) ensures that the extension analysis is constrained by material reality rather than by the arithmetic of the project horizon alone.

The component-level MCI is therefore evaluated across the interval $X \in [1, X_{\text{max},i}]$. The MCI curve is monotonically increasing up to $X_{\text{max},i}$ and constant beyond it, the plateau marking the point at which no further life extension is attainable. This analysis operates exclusively at the component level and serves as a decision-support instrument for asset management. The baseline project indicators of Section 4.2.3 and Section 4.3.2 remain anchored at $X = 1$, using the effective mass of equation (4.10) with each component operating for its declared service life.

4.2.3 Mass-Weighted Project Aggregation

With stream-level MCI values and effective masses established for all material streams, the framework aggregates the component scores into a project-level composite indicator by weighting each stream by its effective mass fraction:

$$\text{MCI}^{\text{mass}} = \sum_{i=1}^n \frac{m_i^{\text{eff}}}{M_{\text{total}}^{\text{eff}}} \cdot \text{MCI}_i \quad (4.14)$$

where $M_{\text{total}}^{\text{eff}} = \sum_{i=1}^n m_i^{\text{eff}}$. The weights sum to unity by construction, bounding the composite score within $[0, 1]$ and rendering it independent of project scale. Mass weighting is adopted as the baseline method because the weights are directly observable from procurement bills of materials and because it preserves comparability with EMF-compliant benchmarks [5].

To make the influence of civil works explicitly visible, the framework additionally computes MCI^{mass} with all concrete streams excluded. The difference between the full and foundations-excluded scores quantifies the mass dilution effect of structural civil works on the headline result, isolating the circularity performance of the electrical and mechanical equipment where procurement leverage is greatest.

Mass weighting is, however, blind to thermodynamic significance. In a typical LMAT project, reinforced concrete foundations may represent over 60% of total effective mass and dominate the composite score, while aluminium conductors, which require nearly two orders of magnitude

more energy per kilogram to produce, contribute a fraction of that weight. Assigning influence in proportion to physical quantity rather than resource intensity means that the streams most critical from a thermodynamic standpoint exert the least influence on the headline indicator. This structural limitation motivates the thermodynamic extension developed in the following section.

4.3 Thermodynamic Extension: The Exergy-Weighted Circularity Indicator

The mass-weighted aggregation of Section 4.2.3 satisfies the structural requirements of the EMF methodology but treats all materials as thermodynamically equivalent per kilogram. This equivalence is not physically justified. The First Law conserves mass and energy across any transformation, but it says nothing about their quality. It is the Second Law that governs quality degradation, as every irreversible process destroys part of the capacity to perform useful work. That capacity is the true thermodynamic cost of producing a material. A mass-weighted indicator therefore measures how much material circulates, but not how much thermodynamic work society must invest to reproduce it if recovery fails. In a typical LMAT project, reinforced concrete represents 50 to 60% of effective mass yet requires only 0.28 kWh/kg to produce, while aluminium conductors represent 10 to 15% of mass but require 48.6 kWh/kg, nearly two orders of magnitude more. Mass weighting thus marginalises the stream that carries the greatest embedded thermodynamic cost and for which circular recovery avoids the greatest future exergy consumption. This section introduces the Exergy-Weighted Material Circularity Indicator (MCI_{ex}) as an extension that reanchors circularity in resource quality rather than physical quantity.

4.3.1 Cumulative Exergy Demand as a Thermodynamic Proxy

Exergy is the maximum useful work extractable from a system as it reaches equilibrium with its reference environment, the dead state [51]. Unlike energy, which is conserved by the First Law, exergy is partially or fully destroyed in every irreversible process by the Second Law. The destruction is proportional to the entropy generated, as stated by the Gouy-Stodola theorem:

$$\dot{E}x_{dest} = T_0 \cdot \dot{S}_{gen} \quad (4.15)$$

where $\dot{E}x_{dest}$ is the rate of exergy destruction, T_0 the dead-state temperature, and $\dot{S}_{gen}$ the rate of entropy generation. Every step of a material production chain, from ore extraction and concentration to smelting, refining, and fabrication, generates entropy and destroys exergy. The further a material is refined from its natural dispersed state, the greater the cumulative exergy irreversibly committed to produce it.

The Cumulative Exergy Demand (CExD), developed by Bösch et al. [54] within the thermodynamic framework of Szargut [51], quantifies this total exergetic consumption across all flows required to produce one kilogram of a material from its natural state. It covers chemical, fossil, nuclear, kinetic, and potential exergy and is originally expressed in MJ/kg, although values in this

dissertation are reported in kWh/kg. Circular recovery of a high-CExD material avoids the greatest quantity of future primary exergy consumption and the associated entropy generation. Two properties make CExD an appropriate aggregation basis. Its values share a single thermodynamic unit and are directly comparable without normalisation. It also captures production irreversibility more completely than primary energy demand, because it accounts for the quality degradation of energy across every transformation step rather than merely its quantity.

4.3.2 Two-Level Exergy-Weighted Formulation

The extension operates at two hierarchical levels. At the sub-material level, the CExD of each constituent modifies the linear flow terms of the component LFI. At the inter-component level, the aggregation weight of each component reflects its share of total project exergy. This structure captures thermodynamic significance both within heterogeneous components and across the full material inventory.

For a component i with sub-material composition $\{f_{i,k}\}$, where $f_{i,k}$ is the mass fraction of sub-material k , the mass-based flow terms of Section 4.2.1 are replaced by their exergy-weighted equivalents. The embodied exergy of component i per unit mass is:

$$e_i = \sum_k f_{i,k} \cdot \text{CExD}_k \quad (4.16)$$

The exergy-weighted linear flow terms are then defined as:

$$V_i^{\text{ex}} = m_i \cdot \sum_k f_{i,k} \cdot \text{CExD}_k \cdot (1 - F_{R,k}) \quad (4.17)$$

$$W_{o,i}^{\text{ex}} = m_i \cdot \sum_{k \in \mathcal{K}_0} f_{i,k} \cdot \text{CExD}_k \quad (4.18)$$

$$W_{c,i}^{\text{ex}} = m_i \cdot \sum_{k \in \mathcal{K}_R} f_{i,k} \cdot \text{CExD}_k \cdot C_{R,k} \cdot (1 - E_{c,k}) \quad (4.19)$$

$$W_{F,i}^{\text{ex}} = m_i \cdot \sum_{k \in \mathcal{K}_R} f_{i,k} \cdot \text{CExD}_k \cdot F_{R,k} \cdot \frac{1 - E_{F,k}}{E_{F,k}} \quad (4.20)$$

where $\mathcal{K}_0$ denotes the sub-materials with no viable recovery pathway ($C_{R,k} = 0$), $\mathcal{K}_R$ those with an established pathway, $F_{R,k}$ the recycled content, $E_{c,k}$ the end-of-life recovery, and $E_{F,k}$ the upstream recycling efficiency of sub-material k . The total exergy-weighted waste term follows the convention of equation (4.5):

$$W_i^{\text{ex}} = W_{o,i}^{\text{ex}} + \frac{W_{F,i}^{\text{ex}} + W_{c,i}^{\text{ex}}}{2} \quad (4.21)$$

The exergetic LFI and the component-level exergetic MCI are then:

$$\text{LFI}_i^{\text{ex}} = \frac{V_i^{\text{ex}} + W_i^{\text{ex}}}{2m_i e_i + \frac{W_{F,i}^{\text{ex}} - W_{c,i}^{\text{ex}}}{2}} \quad (4.22)$$

$$\text{MCI}_i^{\text{ex}} = \max(0, 1 - \text{LFI}_i^{\text{ex}} \cdot F(X)) \quad (4.23)$$

For single-material components, $f_{i,k} = 1$ and CExD_k cancels in the ratio of equation (4.22), giving $\text{MCI}_i^{\text{ex}} = \text{MCI}_i^{\text{mass}}$. For multi-material components the result differs, as sub-materials with high CExD exert proportionally greater influence even at a modest mass fraction. In an ACSR conductor of aluminium (48.6 kWh/kg) over a steel core (7.5 kWh/kg), the aluminium drives the exergetic LFI with a weight about 6.5 times its mass share. Its low recycled content ($F_R = 10\%$) therefore depresses $\text{MCI}_{\text{ACSR}}^{\text{ex}}$ below its mass-based value, correctly reflecting the thermodynamic cost of sourcing that fraction from virgin production.

The project-level indicator aggregates the component scores using effective exergy as the weighting basis:

$$w_i^{\text{ex}} = \frac{m_i^{\text{eff}} \cdot e_i}{\sum_j m_j^{\text{eff}} \cdot e_j} \quad (4.24)$$

$$\text{MCI}_{\text{ex}} = \sum_i w_i^{\text{ex}} \cdot \text{MCI}_i^{\text{ex}} \quad (4.25)$$

where m_i^{eff} is the effective mass of equation (4.10), incorporating replacement cycles at the current value of X . The CExD reference values for all material streams are presented in Table 4.2, ordered by ascending thermodynamic significance.

The concrete-to-aluminium ratio of 1:175 quantifies the thermodynamic blind spot that mass weighting introduces when concrete dominates by physical quantity but aluminium dominates by resource intensity. SF_6 , at 86.1 kWh/kg, carries a high exergetic cost despite its negligible mass fraction in substation switchgear, receiving a weight that mass-based aggregation would otherwise render invisible.

4.3.3 Diagnostic Interpretation: Mass versus Exergy Convergence

The two indicators are computed in parallel because their relationship carries diagnostic information that neither score conveys alone. When $\text{MCI}_{\text{ex}} \approx \text{MCI}^{\text{mass}}$, the mass and exergy distributions are aligned, the streams that dominate by quantity also dominate by thermodynamic cost, and the two methods agree. When $\text{MCI}_{\text{ex}} < \text{MCI}^{\text{mass}}$, the thermodynamically intensive streams perform below the mass average, whether through lower recycled content, lower collection rates, or both. This signals that procurement effort must target the high-exergy streams even where they hold a modest mass share. From a Second Law perspective this is the most critical case, since the materials whose loss is most costly are the least circular. When $\text{MCI}_{\text{ex}} > \text{MCI}^{\text{mass}}$, the lower headline score is driven by poor performance in bulk, low-exergy materials. This is the typical LMAT pattern, where concrete depresses MCI^{mass} while contributing negligible exergetic weight, and MCI_{ex} gives the more representative picture of resource-quality circularity.

MCI^{mass} remains the primary metric for regulatory reporting and cross-project benchmarking, given its direct alignment with the EMF methodology. MCI_{ex} is the appropriate instrument for internal procurement prioritisation, directing circular improvement actions toward the streams where they generate the greatest thermodynamic return.

Table 4.2: Cumulative Exergy Demand by material stream.

Material stream	CExD (kWh/kg)
Concrete	0.28
Glass	3.89
Ceramics	4.17
Insulating paper	6.94
Steel (structural)	7.50
Lead	8.33
Zinc	11.11
Mineral oil	12.22
Steel (components)	13.33
Others (proxy)	13.89
Copper (piping)	17.22
Plastic (cables)	18.89
Copper (electronics)	21.67
Plastic (PE piping)	22.22
Plastic (equipment)	23.06
Aluminium	48.61
Tin	63.89
Composites	80.56
SF ₆	86.11
Silver	486.11

Values converted from MJ/kg at 1 MJ = 0.2778 kWh. Compiled from [44, 46, 51, 54, 92–95] and ecoinvent 3.8.

4.4 Carbon Accounting and Lifecycle Emissions

Circularity indicators measure the degree to which material flows remain within restorative loops but do not capture the climate implications of those flows. Two configurations may share the same MCI while generating very different emissions, owing to differences in production route, energy intensity, or composition. For aluminium and copper, where the carbon intensity gap between primary and secondary routes exceeds 90%, a marginal gain in recycled content produces a disproportionate reduction in embodied emissions. The carbon accounting module complements the MCI by quantifying the climate implications of procurement, replacement, and end-of-life decisions across the infrastructure lifecycle.

The module follows EN 15978:2011 over Modules A to D and is deliberately restricted to the physical components of the asset and their declared lifecycle stages. It covers the manufacturing, transport, installation, operation, and end-of-life processing of the inventoried material streams. It does not encompass land clearance, right-of-way establishment, vegetation removal, earthworks, or temporary construction activities, which fall outside the material boundary and are not captured by EPD-based inventories. The outputs should therefore be read as the component-embodied and operational carbon footprint of the asset, not as a complete project-level environmental assessment.

To extend the assessment toward that complete footprint, a project-level greenhouse gas tool developed by REN's Operational Sustainability Department was integrated into the model. This tool estimates the emissions of a project across its five lifecycle phases, from right-of-way establishment to forest balance, as characterised in Section 3.2.3. Within that structure, the component-level assessment developed in this work corresponds to the construction phase. The integration automated the tool to connect directly with the model inputs and the web interface of Section 5.1, improved its usability for REN's engineering workflows, and updated its emission factors, notably the grid factor in tCO₂eq per MWh. A single assessment then reports both the component-level performance and the total project-level emissions, while preserving the distinct boundary of each layer.

4.4.1 Emission Inventory Structure

Emissions are quantified separately for each lifecycle stage, consistent with the EN 15978 module classification. For each component i , the unitary lifecycle emissions are:

$$\text{GWP}_{i,\text{unit}} = \text{GWP}_{i,\text{fab}} + \text{GWP}_{i,\text{dist}} + \text{GWP}_{i,\text{inst}} + \text{GWP}_{i,\text{use,unit}} + \text{GWP}_{i,\text{eol,unit}} \quad (4.26)$$

where each term is obtained from EPD datasets or equivalent inventories. Fabrication ($\text{GWP}_{i,\text{fab}}$) covers raw material extraction and manufacturing (Modules A1–A3). Distribution and installation cover transport to site and installation works (Modules A4–A5). The use-phase term covers operational emissions such as electrical losses in conductors or fugitive gas leakage in switchgear. The end-of-life term covers dismantling, transport, and waste processing at decommissioning (Modules C1–C4). The framework relies primarily on project-specific EPDs, with sector-average declarations or peer-reviewed values as secondary sources.

4.4.2 GWP Calculation with Replacement Cycles

Conventional embodied carbon assessments assume a single procurement event at the start of the lifecycle. This is insufficient for transmission infrastructure, where components with heterogeneous service lives undergo asynchronous replacement cycles across the project horizon. The methodology therefore applies a distinct temporal operator to each lifecycle stage, reflecting the physical nature of the emissions it models. The total component-embodied and operational footprint is:

$$\text{GWP}_{\text{proj}} = \sum_{i=1}^n (\text{GWP}_{i,\text{embodied}} + \text{GWP}_{i,\text{use}} + \text{GWP}_{i,\text{eol}}) \quad (4.27)$$

Embodied impacts (Modules A1–A5) occur discretely whenever a component is procured and installed. They are scaled with the ceiling operator, consistent with the effective mass of equation (4.10):

$$\text{GWP}_{i,\text{embodied}} = \left\lceil \frac{L_{\text{proj}}}{L_i} \right\rceil \cdot Q_i \cdot (\text{GWP}_{i,\text{fab}} + \text{GWP}_{i,\text{dist}} + \text{GWP}_{i,\text{inst}}) \quad (4.28)$$

where Q_i is the project quantity of component i . The ceiling operator treats a partial replacement cycle as a complete procurement event, reflecting the indivisibility of infrastructure components. Use-phase impacts (Module B), including electrical losses, insulating fluid leakage, and fugitive SF_6 emissions, accumulate continuously and scale with the exact fractional ratio of lifetimes:

$$\text{GWP}_{i,\text{use}} = \frac{L_{\text{proj}}}{L_i} \cdot Q_i \cdot \text{GWP}_{i,\text{use,unit}} \quad (4.29)$$

End-of-life impacts (Modules C1–C4) are attributed only to components that complete their service life within the horizon, and are scaled with the floor operator:

$$\text{GWP}_{i,\text{eol}} = \left\lfloor \frac{L_{\text{proj}}}{L_i} \right\rfloor \cdot Q_i \cdot \text{GWP}_{i,\text{eol,unit}} \quad (4.30)$$

The floor operator ensures that a final incomplete cycle, whose decommissioning falls outside the horizon, incurs no end-of-life charge. The three operators, ceiling for embodied, fractional for use, and floor for end-of-life, constitute the core methodological adaptation for long-lived infrastructure carbon accounting. Together they attribute to each stage only the emissions that genuinely occur within the project boundary, without double counting or omission.

4.4.3 Scope 3 Reporting Linkage

The component-embodied and operational emissions integrate directly into organisational greenhouse gas inventories under the GHG Protocol Corporate Standard, within Scope 3 Category 1 (Purchased Goods and Services) and Category 2 (Capital Goods) [8]. For REN, whose Scope 3 inventory is dominated by infrastructure procurement rather than direct operational emissions, project-level outputs flow into corporate disclosures without a separate accounting exercise. The framework isolates the contribution of Modules A1–A3, the stage most responsive to circular procurement levers through the substitution of primary by secondary production. Modules A4 and A5 are governed by logistics and contracted works and are less sensitive to material sourcing. The outputs are structured for disclosure under ESRS E5 and align with REN's formally adopted Scope 3 target of a 30% reduction by 2030 relative to a 2021 baseline.

4.5 Benchmarking: Circularity and Carbon Improvement Potential

The MCI and GWP calculations established in the preceding sections quantify the absolute environmental performance of a project under its actual procurement and recovery conditions. A decision-support framework additionally requires a comparative reference layer that situates that performance relative to what is technically achievable within the sector. The benchmarking

module serves this function: it defines best-practice targets for recycled content and end-of-life recovery derived from demonstrated European TSO procurement practice, and uses them to quantify the circularity and carbon improvement potential of each material stream.

4.5.1 Circularity Benchmarking: Baseline and Best-Practice Targets

For each material stream i , two reference parameters are defined. The best-practice recycled content fraction F_R^{best} represents the proportion of secondary material incorporated during manufacturing under leading procurement conditions. The best-practice effective end-of-life recovery rate E_c^{best} represents the proportion of material effectively recovered and reintroduced into industrial material loops after decommissioning, incorporating both collection logistics and process efficiency. The baseline values reflect current average procurement and recovery conditions observed in REN's transmission infrastructure programme. The best-practice benchmarks represent technically demonstrated performance achievable by 2030 to 2040, derived from European TSO procurement specifications, supplier-declared EPD datasets, and sector-specific circular economy literature. Both sets of values are presented in Table 4.3.

Table 4.3: Current and best-practice circularity parameters by material stream.

Material stream	Current (%)		Best-practice (%)	
	F_R	E_c	F_R	E_c
Steel (components)	50	90	70	95
Steel (structural)	100	95	100	98
Aluminium (components)	40	85	50	90
Aluminium (cables/ACSR)	10	85	30	90
Copper (electronics)	50	80	60	90
Copper (piping)	60	90	80	97
Silver	0	0	5	50
Tin	0	0	33	33
Zinc	100	60	100	75
Glass	0	0	40	50
Composite	0	0	0	10
Ceramics	0	0	10	50
Plastics (equipment)	0	10	10	30
Plastics (cables)	0	50	10	60
Plastics (PE)	0	25	0	65
Oil	0	55	85	95
SF ₆	0	60	0	99
Insulating paper	0	0	0	0
Lead	60	80	80	90
Concrete	0	0	30	70
Others	0	0	0	0

The circularity improvement potential for each material stream is defined as the difference between the stream-level MCI computed under best-practice parameters and that computed under actual conditions, with the utility factor X held constant:

$$\Delta \text{MCI}_i = \text{MCI}_i(F_R^{\text{best}}, E_c^{\text{best}}, X) - \text{MCI}_i(F_R^{\text{actual}}, E_c^{\text{actual}}, X) \quad (4.31)$$

where MCI_i is computed from equation (4.9) using the full variable chain defined in Section 4.2.1. Holding X constant isolates the contribution of procurement and recovery decisions from that of service life extension, allowing the two improvement levers to be analysed independently.

4.5.2 Carbon Improvement Potential and Material Sensitivity

The carbon benchmarking layer estimates the avoided emissions achievable by transitioning from actual to best-practice procurement conditions. Rather than relying on component-specific EPD datasets, this layer uses generic cradle-to-gate emission factors for virgin and recycled production routes, compiled in Appendix B, Table B.1. SF₆ is excluded from this analysis. With a global warming potential of 24 300 kg CO₂eq/kg [32], its climate significance is dominated by operational fugitive emissions rather than by its production route, and is treated separately in Section 4.4.2.

Aluminium exhibits the largest differential between production routes at 94 to 96%, meaning that small improvements in recycled content generate disproportionately large reductions in embodied emissions. This result is consistent with the thermodynamic significance of aluminium established in Section 4.3.2: the high CExD of aluminium reflects the same energy-intensive production process that drives its large carbon differential between primary and secondary routes. The two analytical layers of the framework therefore converge on the same material priority from independent perspectives.

The avoided emissions from improved recycled content are computed by comparing the embodied carbon under actual and benchmark procurement conditions:

$$\Delta \text{GWP}_{i,\text{RC}} = \text{GWP}_{i,\text{actual}} - \text{GWP}_{i,\text{benchmark}} \quad (4.32)$$

where the actual and benchmark embodied emissions per stream are respectively:

$$\text{GWP}_{i,\text{actual}} = Q_i \cdot [F_R^{\text{actual}} \cdot \text{GWP}_{i,\text{rec}} + (1 - F_R^{\text{actual}}) \cdot \text{GWP}_{i,\text{vir}}] \cdot 10^{-3} \quad (4.33)$$

$$\text{GWP}_{i,\text{benchmark}} = Q_i \cdot [F_R^{\text{best}} \cdot \text{GWP}_{i,\text{rec}} + (1 - F_R^{\text{best}}) \cdot \text{GWP}_{i,\text{vir}}] \cdot 10^{-3} \quad (4.34)$$

where Q_i is the material quantity in tonnes and $\text{GWP}_{i,\text{vir}}$ and $\text{GWP}_{i,\text{rec}}$ are the emission factors from Table B.1. The factor 10^{-3} converts kg CO₂eq/kg to t CO₂eq/t.

Avoided emissions from improved end-of-life recovery are estimated independently. An improvement in E_c increases the share of material that re-enters secondary production rather than going to landfill or incineration, thereby displacing future primary production and its associated emissions:

$$\Delta\text{GWP}_{i,\text{EoL}} = Q_i \cdot (E_c^{\text{best}} - E_c^{\text{actual}}) \cdot (\text{GWP}_{i,\text{vir}} - \text{GWP}_{i,\text{rec}}) \cdot 10^{-3} \quad (4.35)$$

The total avoided emissions per stream are the sum of both contributions:

$$\Delta\text{GWP}_{i,\text{total}} = \Delta\text{GWP}_{i,\text{RC}} + \Delta\text{GWP}_{i,\text{EoL}} \quad (4.36)$$

This decomposition distinguishes between upstream improvements in recycled content procurement and downstream gains from enhanced end-of-life recovery. By presenting ΔMCI_i and $\Delta\text{GWP}_{i,\text{total}}$ side by side for each material stream, the framework identifies the streams where circularity improvements yield simultaneous gains in both resource circularity and carbon reduction. These are the priority targets for procurement action, particularly for energy-intensive streams such as aluminium and copper where the circularity and carbon dimensions are strongly correlated.

To express the avoided emissions in economic terms, the framework applies a reference carbon price to the total avoided GWP of each stream. The value adopted is 80 €/tCO₂e, a representative level for the European Union Emissions Trading System over the 2025 period, during which the allowance price fluctuated broadly between 60 and 80 €/tCO₂e [96]. This figure is used as a transparent reference rather than as a forecast, since the allowance price is set by a regulated market and varies over time. The monetised saving for each stream is the product of this reference price and its total avoided emissions, and it provides a common economic basis for comparing circularity interventions across streams and case studies.

4.5.3 Scenario Construction

The benchmarking of the preceding sections is a per-stream and static analysis. It measures, for each material in isolation, the distance between current practice and the best-practice ceiling. It does not describe how the asset as a whole behaves under a coherent level of effort applied to every stream at once. The scenarios provide that complementary view. A scenario is a complete set of recycled content and end-of-life recovery rates, one for every material in the asset, and each scenario fixes those rates under a distinct assumption about the level of deliberate effort. The model recomputes the global indicators from the rates of each scenario, which places the levels of ambition on a common and directly comparable basis. The Regulatory Compliance scenario coincides with the best-practice ceiling of the benchmarking, which is the point where the two analyses meet. Three scenarios are constructed, from the least to the most ambitious.

- **Business as Usual.** The assumption is that no new policy or procurement decision is taken. Recycled content and recovery rates improve only marginally, through the autonomous growth of the background markets for secondary material, so this scenario is the conservative baseline that shows where circularity settles without deliberate action.
- **Regulatory Compliance.** The assumption is that the sector meets every binding requirement and announced commitment, and no more. Each rate is anchored to a dated instrument

that already exists, namely the removal of SF₆ from new high-voltage switchgear under the F-Gas Regulation [73], the recycled share of strategic metals required by the Critical Raw Materials Act [55], the recycled aggregate limits of EN 206 for structural concrete [97], and the recycled aluminium target announced by a European transmission operator [85]. This scenario reaches the best-practice ceiling of Section 4.5.

- **Circular Ambition.** The assumption is that the sector adopts the best available technology beyond the legal minimum, with each rate following a published industry roadmap. Recycled aluminium content follows the 2050 target of the European aluminium industry [45], and transformer oil follows the performance of a fully re-refined product compliant with IEC 60296:2020 Type A [98]. This scenario defines the technical ceiling of the assessment.

Each scenario is defined by its level of ambition and is associated with an indicative horizon rather than an exact year, so the set is a comparison of trajectories and not a time series. The dated instruments of the Compliance scenario place it around 2040, and the Ambition scenario corresponds to the 2050 technology horizon. The binding milestones of the European Climate Law, a 55% emission cut by 2030 and climate neutrality by 2050 [2], together with the proposed 90% cut by 2040 [99], set the pace of the regulatory pressure that drives the transition.

4.6 Verification and Sensitivity Analysis

The reliability of the framework outputs depends on the quality of the input data and on the stability of the model under parameter uncertainty. Three verification layers are embedded in the computational tool. The first applies automated checks on the validity of the input data. The second tests the mathematical integrity of the model at its boundary conditions. The third quantifies how parameter uncertainty propagates into the headline indicators. Together they support the use of the outputs in procurement decisions and sustainability disclosures.

4.6.1 Automated Compliance and Data Quality Checks

The tool cross-references every EPD dataset against its declared publication date. Datasets that exceed the five-year validity period defined under EN 15804 are flagged automatically and excluded from verified outputs until an updated declaration is provided. This ensures that the emission factors and circularity parameters reflect current production technology rather than obsolete values.

A separate pathway applies to materials governed by regulation rather than by a commodity market. SF₆ is the primary example. Its end-of-life recovery is legally mandated under the F-Gas Regulation (EU) 2024/573 [73] and does not respond to the economic incentives that govern metal recycling. The tool therefore treats SF₆ recovery as a compliance variable rather than a market-driven circularity parameter. This prevents the regulatory obligation from inflating the circularity score. The environmental significance of SF₆ is still captured through its exergetic weight and its use-phase carbon contribution.

4.6.2 Mass Balance and Boundary Verification

The engine enforces a strict mass balance at the component level. For each stream, the total material throughput over the project horizon must equal the sum of circular flows, permanent losses, and the effective mass generated through replacement cycles. This confirms that no material is created or destroyed within the model boundary and that the effective mass formulation of equation (4.10) is applied consistently.

Two theoretical extremes test the model integrity. The fully circular case sets $F_R = 1$, $C_R = 1$, and $E_c = E_F = 1$. Every linear flow term vanishes, the linear flow index falls to zero, and the model returns $MCI = 1$ for every stream. The fully linear case sets $F_R = 0$, $C_R = 0$, and $X = 1$. The virgin input and the unrecoverable waste each equal the full mass, the linear flow index reaches unity, and the model returns $MCI = 0.10$, the conventional minimum of the EMF methodology [5]. These limits confirm that the ceiling operator of equation (4.10) and the floor operator of equation (4.9) behave consistently across the full range of component service lives.

4.6.3 Sensitivity and Uncertainty Analysis

The circularity indicators depend on the recycled content fraction F_R and the recycling efficiency E_c , both estimated from statistics, EPDs, and procurement specifications. Two complementary analyses address this. The sensitivity analysis identifies which parameters govern each indicator. The uncertainty propagation quantifies how precisely the baseline indicator is known. Both are kept separate from the benchmarking layer of Section 4.5, which measures a different quantity, namely the improvement available between current and best-practice procurement. This separation ensures that improvement potential is never mistaken for estimation uncertainty.

A variance-based global method is adopted in preference to a local one-at-a-time approach. The MCI combines F_R and E_c non-linearly through the linear flow index of equation (4.6), so a method that captures interactions is required. The Sobol method decomposes the total variance of the output into contributions from each parameter and from their interactions [100, 101]. The first-order index S_i measures the variance explained by parameter X_i alone:

$$S_i = \frac{\text{Var}_{X_{\sim i}}(E_{X_i}[Y | X_i])}{\text{Var}(Y)} \quad (4.37)$$

where $X_{\sim i}$ denotes all parameters except X_i . The total-effect index S_{Ti} measures the variance explained by X_i including its interactions:

$$S_{Ti} = 1 - \frac{\text{Var}_{X_{\sim i}}(E_{X_i}[Y | X_{\sim i}])}{\text{Var}(Y)} \quad (4.38)$$

A close agreement between the two indices marks an independent parameter. A first-order sum near unity marks an additive model with negligible interactions. The second-order index S_{ij} isolates the joint interaction of two parameters and is reported in Appendix F. Samples are generated with the Saltelli extension of the Sobol sequence and processed with the *SALib* library [101, 102]. Each parameter ranges from its current value to its European best-practice benchmark

rather than over the full interval $[0, 1]$. The upstream efficiency follows the closed-loop assumption $E_F = E_c$ of Section 4.2.1, and the utility factor X is treated deterministically through the service life extension of Section 4.2.2. The sample size is set to ensure convergence of the total-effect indices.

Raw Sobol indices depend on the width of the assigned range. A parameter with a wide range tends to produce a high index for that reason alone. To separate the range from the intrinsic sensitivity, the Index of Sensitivity, Amplitude-Normalised (ISAN) divides the total-effect index by the range width Δ_i :

$$\text{ISAN}_i = \frac{S_{Ti}}{\Delta_i} \quad (4.39)$$

The ISAN ranks parameters by their sensitivity per unit of variation. A parameter with a narrow range but a high ISAN is one where a small change produces a strong response, which carries a direct procurement implication. The ranking is cross-checked against the Spearman rank correlation between each parameter and the output, reported in Appendix F.

The uncertainty propagation answers a distinct question, namely the dispersion of the baseline indicator that follows from the estimation uncertainty of its inputs. A Monte Carlo sampling of the parameters within narrow intervals centred on their current values is propagated through the full MCI calculation [103, 104]. The reported band is the interval between the 5th and 95th percentiles. The half-width assigned to each parameter is the smaller of two quantities:

$$\delta_i = \min \left(\delta_i^{\text{phys}}, \frac{|p_i^{\text{best}} - p_i^{\text{cur}}|}{2} \right) \quad (4.40)$$

where δ_i^{phys} is the reference estimation uncertainty, taken as ± 10 percentage points for recycled content and ± 5 percentage points for recovery efficiencies, and p_i^{cur} and p_i^{best} are the current and benchmark values. The second term confines the uncertainty band to the first half of the margin separating the current value from its benchmark, which keeps the estimation uncertainty strictly apart from the improvement potential. Parameters whose current and benchmark values coincide are held fixed, and SF_6 is excluded as a regulated compliance variable. Both analyses are applied to MCI^{mass} and MCI_{ex} across both case studies, and the results are presented in Section 5.6.

This chapter developed the complete assessment framework that operationalises the five requirements established in Chapter 3. The adapted mass-based MCI introduced the effective mass formulation and the physically bounded service life extension required for long-lived, multi-component infrastructure. The exergy-weighted extension reanchored circularity in resource quality through the Cumulative Exergy Demand, exposing the thermodynamic significance that mass weighting conceals. The carbon accounting module quantified lifecycle emissions with distinct temporal operators for each phase, linked to REN's Scope 3 reporting. The benchmarking layer defined the improvement potential against best-practice targets, and the verification layer established the data quality, mass balance, and sensitivity procedures behind the outputs. The framework is applied to two REN transmission projects in Chapter 5.

5 Results and Discussion

5.1 Computational Implementation

The assessment framework is implemented as a structured spreadsheet workbook in *Microsoft Excel*, which constitutes the primary calculation engine. A bill of materials entered in the quantities input sheet triggers the automated calculation of all downstream modules, namely the mass-based and exergy-weighted circularity indicators, the lifecycle carbon footprint, the benchmarking analysis, and the eco-efficiency matrix. All parameter datasets, including EPD references, CExD values, emission factors, and service life declarations, are consolidated in a dedicated annex sheet that is updated independently of the calculation modules.

As a complementary interface, a web-based application was developed in *Python* using the *Streamlit* library. The application presents the model outputs interactively and requires no direct manipulation of the underlying spreadsheet, which facilitates adoption within REN's engineering workflows. It provides two dedicated modules, one for overhead transmission line (LMAT) projects and one for high-voltage substations, each pre-configured with the corresponding material streams and default parameters. The full web interface for the LMAT case study is shown in Appendix C.

5.2 Case Study 1: LMAT Overhead Transmission Line

The reference LMAT case study is the Viana do Castelo – Vila Fria 150 kV overhead transmission line, constructed in 2024 with a total investment of approximately 6.2 M€. The line spans 27.3 km across 71 steel lattice towers and carries a design life of 50 years. System boundaries follow EN 15978 Modules A1 through D for each material stream. Land clearance, right-of-way establishment, and earthworks are excluded from the material lifecycle boundary as defined in Section 4.1.

5.2.1 Material Inventory

The full bill of materials is reported in Appendix D, Table D.1. The line is dominated by three bulk streams. The concrete foundations are the largest at 2 974 t, 51.1% of the 5 821 t effective inventory, with a reference life of 65 years and no replacement over the horizon. The ACSR conductors follow at an effective 1 505 t, 25.9%, with a 40-year life that forces one replacement

within the horizon. The galvanised steel towers add 1 204 t, 20.7%, at a 63-year life and no replacement. Effective masses incorporate the ceiling-function replacement multiplier of equation (4.10) at $X = 1$. The conductors and ground wires are replaced once ($\lceil 50/40 \rceil = 2$), which doubles their effective mass, and the insulator chains undergo two replacements ($\lceil 50/20 \rceil = 3$), which triples their contribution.

5.2.2 Physical Service Life Limits

The service life extension of Section 4.2.2 requires a maximum utility factor for each stream. The earlier formulation bounded this factor by the project horizon alone. Each stream instead reaches an ultimate service life governed by an irreversible degradation mechanism, so its maximum utility factor is the more restrictive of the project ceiling and the physical ceiling, following equation (4.13). The line runs along the Atlantic shoreline at Viana do Castelo, where the structures meet direct marine aerosol. Under ISO 9223 this environment is corrosivity category C5 [105], and the chloride load drives the dominant ageing mechanism of every metallic stream [91]. Table 5.1 summarises the result.

The galvanised steel towers are limited not by fatigue but by the consumption of the sacrificial zinc layer. This mechanism is recoverable, since REN restores the coating through scheduled maintenance rather than replacing structures of this mass. The protected steel then exceeds a century of service [106, 107]. The reference life of 63 years already exceeds the 50-year horizon, so the project ceiling governs and the maximum utility factor is fixed at unity. The concrete foundations and their reinforcement carry reference lives above 50 years and are never replaced. Their degradation through carbonation and chloride-induced corrosion proceeds slowly and is addressed by the cover design. Both take a maximum utility factor of unity.

The ACSR phase conductors and the steel guard wire are aluminium over a galvanised steel core. Thermal creep, wind-induced fatigue, and atmospheric corrosion act on them, and in the C5 environment the corrosion of the galvanised core dominates. This mechanism is not recoverable, because the core sits sealed within the aluminium layers and cannot be re-galvanised in service. Once it loses section the conductor must be replaced. The physical life is taken as 45 years, a physical utility factor of 1.125 that falls below the project ceiling of 1.25, so the physical limit governs. The galvanising class is the principal source of uncertainty in this estimate and is addressed in the sensitivity analysis of Section 5.6.

The OPGW ground wire carries optical fibres within an aluminium-clad steel construction, which resists marine salinity better than a zinc coating. Its life is bounded instead by the functional ageing of the optical fibre, already reflected in the declared 40-year reference. The physical life is taken as 48 years, a utility factor of 1.20 below the project ceiling, so the physical limit governs. The insulator chains are composite units of high-temperature silicone rubber, an ECR glass-fibre core, and galvanised steel fittings, with a 20-year reference life. The silicone ages through loss of hydrophobicity and erosion under combined ultraviolet and salt exposure, the glass core is vulnerable to brittle fracture, and the fittings corrode under the same chloride load [108]. The physical life is taken as 28 years, a utility factor of 1.40 well below the geometric ceiling of 2.50.

This stream carries the largest correction, because that geometric bound had no physical basis for a coastal silicone composite.

Table 5.1: Physical service life limits by stream, Viana do Castelo - Vila Fria LMAT line.

Stream	L_{ref} (yr)	L_{phys} (yr)	X_{max}	Manuf. cycles	
				Base	Ext.
Steel towers	63	≥ 100	1.00	1	1
Concrete	65	> 50	1.00	1	1
Reinforcement	70	> 50	1.00	1	1
ACSR conductors	40	45	1.125	2	2
OPGW ground wire	40	48	1.20	2	2
Steel guard wire	40	45	1.125	2	2
Insulator chains	20	28	1.40	3	2

$X_{\text{max}} = \max(1, \min(L_{\text{phys}}/L_{\text{ref}}, L_{\text{proj}}/L_{\text{ref}}))$, with $L_{\text{proj}} = 50$ yr. Manufacturing cycles: $\lceil L_{\text{proj}}/L \rceil$, where $L = L_{\text{ref}}$ at baseline and $L = \min(L_{\text{phys}}, L_{\text{proj}})$ when extended.

A consistent pattern emerges from Table 5.1. The physical analysis disciplines the utility ceilings rather than inflating them. The long-lived structural streams confirm a unit ceiling justified by durability and maintenance. The conductors fall slightly below their previous ceiling, because the galvanised core cannot be recovered in a saline atmosphere, while the OPGW falls less owing to its aluminium cladding, a distinction the model captures through the difference between 1.20 and 1.125. The insulator chains carry the largest correction, from 2.50 to 1.40. The two metallic responses to the same salt load are opposite. The maintained tower gains durability while the sealed conductor core does not, and this asymmetry follows directly from whether the limiting mechanism is recoverable.

5.2.3 Material Circularity Indicator

The project mass-weighted indicator is $\text{MCI}^{\text{mass}} = 0.42$. Excluding the concrete and reinforcement foundations raises it to 0.76, a gap of 0.34 points that quantifies the mass dilution of civil works. Concrete holds 51% of the effective mass at an MCI of 0.10, the minimum for a stream with no declared recycled content and no established recovery pathway.

The exergy-weighted indicator is $\text{MCI}_{\text{ex}} = 0.60$, an uplift of 0.18 points that follows the diagnostic pattern of Section 4.3.3. The thermodynamically intensive streams outperform the mass average, and the mass score is depressed by concrete at 0.28 kWh/kg. For the ACSR conductors the aluminium sub-fraction carries a CExD of 48.6 kWh/kg against 7.5 kWh/kg for the steel core, which amplifies the aluminium contribution to the exergetic LFI. With only $F_R = 10\%$ recycled aluminium, $\text{MCI}_{\text{ACSR}}^{\text{ex}} = 0.56$ falls below its mass value of 0.59. The same mechanism applies to the OPGW and steel guard wire.

Steel towers achieve the highest score at 0.97 under both formulations, reflecting the recycled content of galvanised structural steel and its established recovery route. Insulator chains record

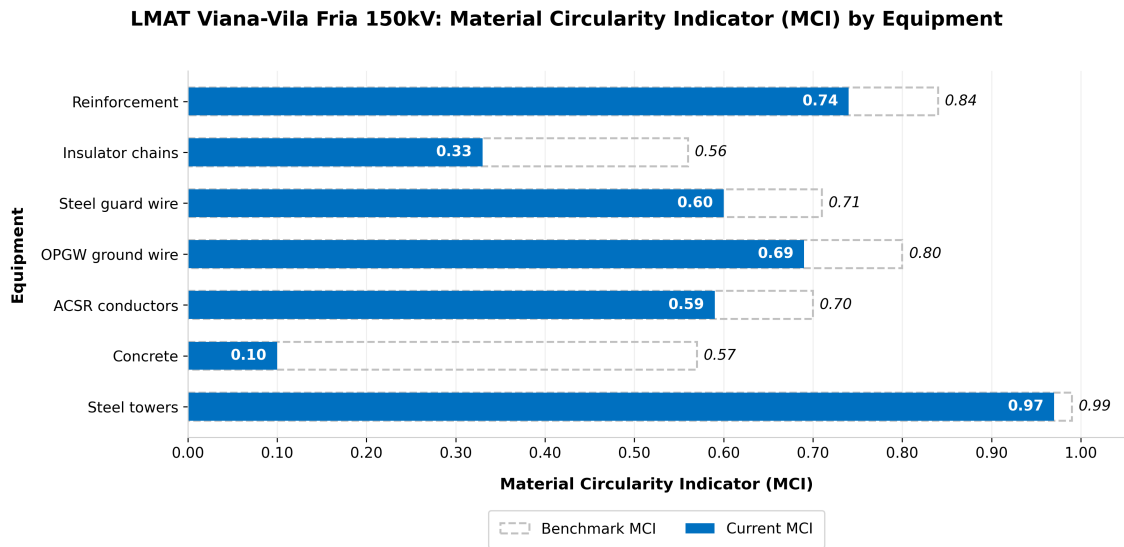


Figure 5.1: Stream-level MCI, current and best practice, Viana do Castelo - Vila Fria Overhead line.

the lowest score outside concrete at 0.33, from the absence of declared recycled ceramic content and the multiple replacements that amplify their linear flow. Table 5.2 and Figure 5.1 show current against best-practice values. The largest absolute improvements are concrete (+0.47) and insulator chains (+0.23), while the largest exergetically weighted gain is the ACSR conductors, rising from 0.56 to 0.66 on the dominant thermodynamic stream.

Table 5.2: Stream-level MCI at baseline and benchmark, Viana do Castelo - Vila Fria LMAT line.

Stream	MCI ^{mass}		MCI _{ex}	
	Baseline	Benchmark	Baseline	Benchmark
Concrete	0.10	0.57	0.10	0.57
Steel towers	0.97	0.99	0.97	0.99
Reinforcement	0.74	0.84	0.74	0.84
ACSR conductors	0.59	0.70	0.56	0.66
OPGW ground wire	0.69	0.80	0.63	0.74
Steel guard wire	0.60	0.71	0.56	0.67
Insulator chains	0.33	0.56	0.33	0.55
Project	0.42	0.70	0.60	0.70

The material-flow transformation of the Viana do Castelo - Vila Fria LMAT overhead line is presented in Appendix E through four Sankey diagrams. Two diagrams, Figures E.1 and E.2, illustrate the material inputs under the current and benchmark scenarios, while the remaining two, Figures E.3 and E.4, depict the corresponding output flows. This structure enables a direct comparison of how the benchmark assumptions affect both the origin of the materials entering the system and their end-of-life destinations.

5.2.4 Lifecycle Carbon

The total lifecycle carbon footprint over the 50-year horizon is $GWP_{proj} = 28\,341 \text{ tCO}_2\text{e}$. Manufacturing emissions (Modules A1–A3) account for 87 to 100% of the individual stream footprints, and no stream generates significant use-phase or installation emissions. Table 5.3 presents the breakdown.

Table 5.3: Lifecycle carbon by material stream, Viana do Castelo - Vila Fria LMAT line.

Stream	GWP per unit	Replacements	Total 50-yr (tCO ₂ e)	Share (%)
Steel towers	3.57 tCO ₂ /t	0	4 260	15.0
Concrete	0.75 tCO ₂ /t	0	2 230	7.9
Reinforcement	2.30 tCO ₂ /t	0	144	0.5
ACSR conductors	32.71 tCO ₂ /km	1	21 299	75.2
OPGW ground wire	3.61 tCO ₂ /km	1	196	0.7
Steel guard wire	1.57 tCO ₂ /km	1	83	0.3
Insulator chains	0.06 tCO ₂ /un	2	128	0.5
Total			28 341	100

Per-unit factors are rounded. Totals are computed at full precision, so rows may not sum exactly to the column total.

The ACSR conductors account for 75% of the total. Two factors compound. The manufacturing carbon intensity of primary aluminium is high at 16.5 kg CO₂eq/kg, and the single in-service replacement doubles the throughput. The initial installation generates 10 795 tCO₂e and the replacement a further 10 504 tCO₂e, a 50-year total of 21 299 tCO₂e. The replacement is lighter than the initial installation because the end-of-life stage of the second conductor set falls beyond the 50-year horizon and is excluded by the floor operator of Section 4.4.2.

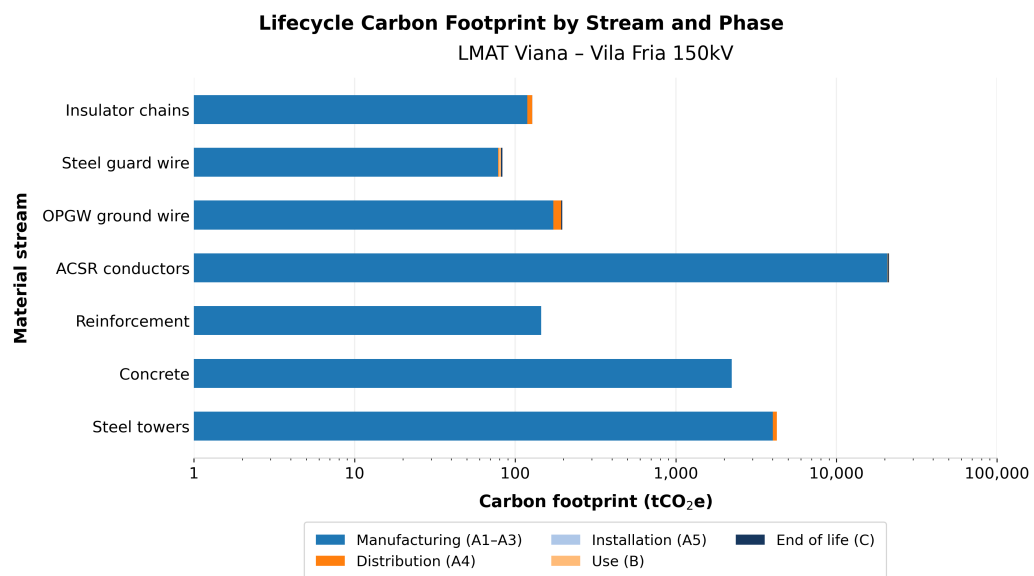


Figure 5.2: Lifecycle carbon by material stream, Viana do Castelo - Vila Fria LMAT line.

Steel towers rank second at 15%, through their installed mass of 1 204 t despite a lower unit factor. This manufacturing-dominated profile, with conductors and towers as the principal contributors, is consistent with recent lifecycle assessments of overhead transmission lines that attribute the large majority of the footprint to material production [12]. Figure 5.2 presents the component footprint on a logarithmic scale.

5.2.5 Service Life Extension

Table 5.4 reports the stream-level MCI at the baseline and at the physical ceiling of each stream, under both formulations. The baseline column is the conservative project indicator, with every component operating for its declared service life. The ceiling column is the maximum extension the governing mechanism permits.

Table 5.4: Stream-level MCI at baseline and physical ceiling, LMAT line.

Stream	MCI^{mass}		MCI_{ex}		X_{max}
	$X=1$	$X=X_{max}$	$X=1$	$X=X_{max}$	
Steel towers	0.97	0.97	0.97	0.97	1.00
Concrete	0.10	0.10	0.10	0.10	1.00
Reinforcement	0.74	0.74	0.74	0.74	1.00
ACSR conductors	0.59	0.64	0.56	0.61	1.125
OPGW ground wire	0.69	0.74	0.63	0.69	1.20
Steel guard wire	0.60	0.65	0.56	0.61	1.125
Insulator chains	0.33	0.52	0.33	0.52	1.40
Project	0.42	0.43	0.60	0.65	—

The largest stream gains occur in the insulator chains, from 0.33 to 0.52 under both formulations. This stream benefits most because it starts furthest from its ceiling and the extension from 20 to 28 years eliminates one replacement over the horizon. The conductors gain moderately, from 0.59 to 0.64 by mass, bounded by the limited extension the galvanised core permits. The structural streams do not move, since their utility factor is fixed at unity.

Figure 5.3 presents both project indicators against the utility factor, with each component capped at its physical ceiling and effective masses recomputed at each value. Both curves increase monotonically. The mass-weighted indicator rises from 0.42 to 0.43 and stabilises once every stream reaches its ceiling. The exergy-weighted indicator rises from 0.60 to 0.65 over the same range.

The mass-weighted curve no longer exhibits the non-monotonic dip of the earlier geometric ceiling. That dip arose when the conductors reached a utility factor of 1.25, at which a single installed unit spanned the full horizon and the replacement cycle was eliminated, lowering conductor effective mass and raising the relative share of concrete. The physical ceiling of 1.125 retains the replacement, because the galvanised core corrodes at 45 years, so the artefact disappears. The removal of this counter-intuitive feature is itself an argument for the physical formulation.

The two indicators respond by different amounts, one point by mass against five by exergy. Service life extension acts on the conductors and the insulators, which carry little mass but dominate embodied exergy, and the ACSR conductors alone account for the majority of the project exergy. Extension therefore moves the exergy-weighted indicator far more than the mass-weighted one, consistent with the diagnostic role established in Section 4.3.3.

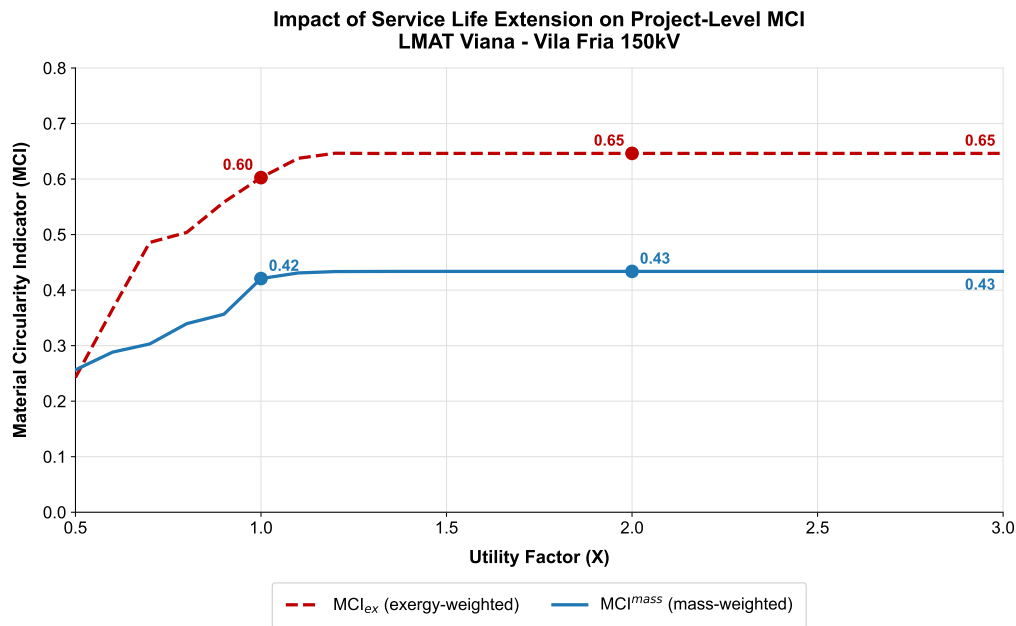


Figure 5.3: Project MCI against the utility factor, Viana do Castelo - Vila Fria LMAT line.

5.2.6 Eco-efficiency Matrix

Adopting best-practice procurement and recovery across all streams raises the project MCI from 0.42 to 0.70, a gain of +0.28 points. The GWP reduction potential is 4 984 tCO₂e, worth 398 720 € at the EU ETS reference price of 80 €/tCO₂e. The dominant contribution is the ACSR conductor stream, where a shift to 30% recycled-content aluminium with a 90% recovery rate produces the largest simultaneous gain in MCI and avoided carbon of any stream in the inventory.

Figure 5.4 presents the eco-efficiency matrix at baseline. A vertical threshold at MCI = 0.70 and a horizontal threshold at GWP = 1 000 tCO₂e define a critical zone of low circularity and high carbon and an excellence zone of the opposite. At baseline only the ACSR conductors and the concrete lie in the critical zone. ACSR enters it through its dominant carbon combined with a below-threshold MCI, and concrete through mass-driven carbon alone, since its circularity cannot improve without upstream procurement. Steel towers reach the high-MCI region but sit above the carbon threshold through their installed mass. Reinforcement occupies the excellence zone. The insulator chains, steel guard wires, and OPGW record carbon below the threshold but remain left of the MCI boundary.

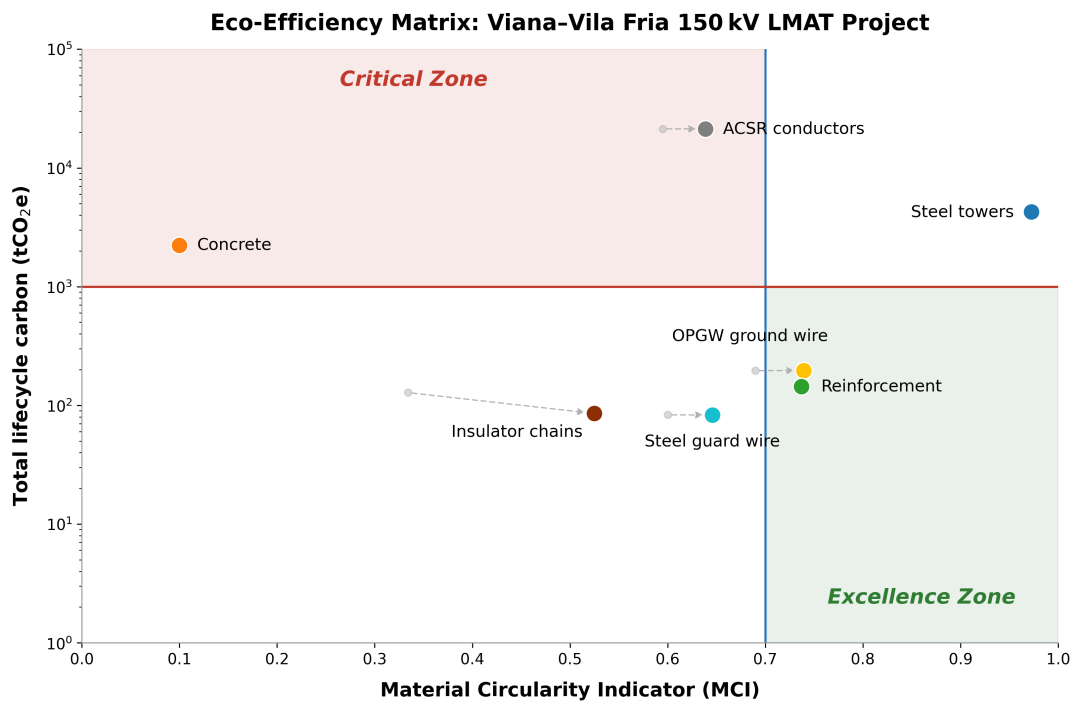


Figure 5.4: Eco-efficiency matrix at baseline, Viana do Castelo - Vila Fria Overhead line.

Life extension acts on both axes. The utility factor raises the stream MCI through the $F(X)$ correction, moving a stream right, while a longer life reduces replacement cycles and moves it down. The downward movement is discrete, since a cycle is avoided only once the extended life crosses an integer division of the horizon, and each stream advances only as far as its physical ceiling permits.

The ACSR conductors illustrate the bound. At their ceiling of 1.125 the conductor MCI improves from 0.59 to 0.64, but the extended life of 45 years stays below the horizon, the replacement is retained, and the carbon position does not improve. Crossing the MCI threshold therefore requires reducing the virgin aluminium content of the specification, not life extension. Concrete remains fixed on both axes, since its ceiling is unity.

The insulator chains show the clearest combined movement. At their ceiling of 1.40 the extension from 20 to 28 years removes one of three replacements, lowering embodied carbon, while the MCI rises from 0.33 to 0.52. The stream moves right and down but does not reach the excellence zone, because the composite ceiling bounds the attainable MCI below the threshold. The earlier geometric analysis allowed a factor of 2.50 and crossed both thresholds, an outcome not physically attainable for a coastal silicone composite.

By adjusting the utility factor up to the physical ceiling of each stream, REN's engineering teams can identify which streams migrate toward the excellence zone through maintenance alone and which require procurement intervention.

5.2.7 Project-Level Emissions Context

The carbon accounting above quantifies the embodied and operational footprint of the line components, the focus of this dissertation. The integrated project-level tool of Section 4.4 extends this to the full project across the five lifecycle phases of REN's accounting methodology. Table 5.5 reports the result over the 50-year horizon.

Table 5.5: Project-level emissions by phase, Viana do Castelo - Vila Fria LMAT line.

Phase	Description	Emissions (tCO ₂ e)
A	Right-of-way establishment	+109.0
B	Construction	+28 652.1
C	Operation and maintenance	−116 406.8
D	Forest balance	+105 736.6
E	Decommissioning	0.0
Net balance		+18 091.0

The construction phase confirms the boundary of the component-level assessment. Phase B totals 28 652.1 tCO₂e, split between the materials sub-component at 28 340.6 tCO₂e and the on-site works at 311.5 tCO₂e. The materials sub-component matches the $GWP_{proj} = 28\,341$ tCO₂e obtained independently above. The 311.5 tCO₂e remainder is on-site construction activity, namely worker transport, machinery, and waste handling, which falls outside the material boundary of Section 4.1. The component-level scope of this dissertation therefore corresponds to the materials sub-component of Phase B.

The remaining phases operate at a territorial and system scale. Phase C records a large negative contribution, the avoided emissions credited to the renewable generation the line integrates into the grid. Phase D records the forest balance of the land-use change along the right-of-way. These phases dominate the total in absolute terms, but they depend on land-use accounting and on the renewable integration trajectory of the national system rather than on procurement. The net balance is sensitive to the avoided-emissions trajectory of Phase C, a system-level variable revised periodically by the operator and outside the scope of this dissertation. The present work therefore does not treat the net project balance as a circularity or procurement result. The material circularity and embodied carbon assessed in this chapter remain the relevant levers for the decisions the framework supports.

5.3 Case Study 2: Ponte de Lima Substation

The second case study applies the framework to a high-voltage substation. The Ponte de Lima substation steps between the 400 kV and the 150 kV networks. The overall investment for the complete site, comprising the 400 kV and 150 kV line bays and the primary 400/150 kV

autotransformer, is approximately 45 M€, with the autotransformer alone near 4 M€. The project horizon is 42 years. The analysis follows the structure used for the overhead line.

5.3.1 Material Inventory

The inventory groups the assets into civil works, power transformers, switchgear, insulators, cabling, and control equipment. The full breakdown by category is reported in Appendix D, Table D.2. The mass is overwhelmingly civil. The concrete foundations account for 16 500 t, 88.7% of the 18 592 t effective mass, at a 63-year life and no replacement. The steel towers add a further 460 t. The power equipment is light by comparison. The autotransformer is the heaviest single power asset, at 345 t for one unit and 690 t over its two cycles across the horizon. The electrical equipment as a whole represents under 9% of the effective mass.

This distribution sets the central tension of the case. The mass concentrates in the concrete, while the exergy concentrates elsewhere. Concrete carries a low chemical exergy per unit mass, whereas the aluminium and copper conductors and the alloyed steel assemblies carry a high exergy per unit mass. The two weightings of the circularity indicator therefore describe different realities, and the contrast is sharper here than in the overhead line.

5.3.2 Physical Service Life Limits

The physical service life governs the utility factor ceiling $X_{\max,i}$ of each stream through equation (4.13), with a project horizon of 42 years. The site is milder than the coastal line. The substation lies inland in the Lima valley, about 25 to 30 km from the coast, with no marine aerosol, and classifies as C3 under ISO 9223 [105]. The C4 galvanisation required in the technical specifications is a uniform design class imposed across the grid rather than the measured corrosivity of the site. The lower corrosivity supports longer physical lives for the metallic components than the coastal line [106, 107]. Table 5.6 lists the values adopted.

The structural components carry reference lives above the horizon, so their utility factor is fixed at one. The current, voltage, and auxiliary transformers, along with the autotransformer, carry a manufacturer expected lifetime of 35 years, and a physical life of 48 years is adopted. The distinction must remain explicit, since the declared figure is a design expectation while the physical life reflects the duration achievable under active maintenance. REN maintains the oil by filtration, degassing, and passivation and records a reconditioning year in the asset register. The on-load tap changer is guaranteed for 600 000 operations, several decades at transmission duty. The ultimate limit is the solid insulation of the windings, which degrades by hydrolysis and oxidation and is not recovered. A physical life of 48 years is consistent with this regime and bounded by the insulation limit, and it is treated as an engineering estimate rather than a declared value [109, 110]. At 48 years the effective life under the project ceiling reaches 42 years, so the autotransformer requires a single unit over the horizon instead of two. As the dominant mass after the civil works, this removal of one manufacturing cycle is the single largest carbon reduction available from life extension.

Table 5.6: Reference and physical service lives, Ponte de Lima substation.

Asset	L_{ref} (yr)	L_{phys} (yr)	X_{max}	Manufacturing cycles	
				Base	Extended
Concrete	63	≥ 100	1.00	1	1
Steel towers	63	≥ 100	1.00	1	1
Current transformers	35	48	1.20	2	1
Auxiliary transformers	35	48	1.20	2	1
Capacitive voltage trans.	35	48	1.20	2	1
Autotransformer	35	48	1.20	2	1
Circuit breakers	20	30	1.50	3	2
Disconnectors	20	30	1.50	3	2
Insulators	20	32	1.60	3	2
Protection cabinets	20	28	1.40	3	2
Surge arresters	40	46	1.05	2	1
HV cables	40	46	1.05	2	1
Control cables	30	40	1.33	2	2
Station battery	10	13	1.30	5	4
Telecontrol	10	14	1.40	5	3

$X_{\text{max}} = \max(1, \min(L_{\text{phys}}/L_{\text{ref}}, L_{\text{proj}}/L_{\text{ref}}))$, with $L_{\text{proj}} = 42$ yr. Manufacturing cycles: $\lceil L_{\text{proj}}/L \rceil$, where $L = L_{\text{ref}}$ at baseline and $L = \min(L_{\text{phys}}, L_{\text{proj}})$ when extended.

The remaining metallic assets gain from the milder atmosphere and the condition-based maintenance. The circuit breakers and disconnectors extend from 20 to 30 years, which removes one of three cycles, and the insulators extend to 32 years with the same effect. The surge arresters and high-voltage cables extend modestly, capped at 1.05 by the project horizon. The station battery and control electronics are short-lived consumables whose small mass keeps their effect minor.

5.3.3 Material Circularity Indicator

The indicator is computed for each stream at the baseline utility factor and then aggregated by mass and by exergy. Figure 5.5 compares the current values against the best-practice benchmark.

The project mass-weighted indicator is 0.16 and the exergy-weighted indicator is 0.54. The gap is large and structural. Concrete holds an indicator of 0.10 and 88.7% of the effective mass, which pulls the mass-weighted average down to 0.16. The exergy weighting removes this dominance, since concrete contributes little exergy while the conductors, transformers, and switchgear dominate it and hold higher indicators, so the exergy-weighted indicator rises to 0.54. The benchmarks are 0.59 by mass and 0.70 by exergy, and the substation sits below both at baseline.

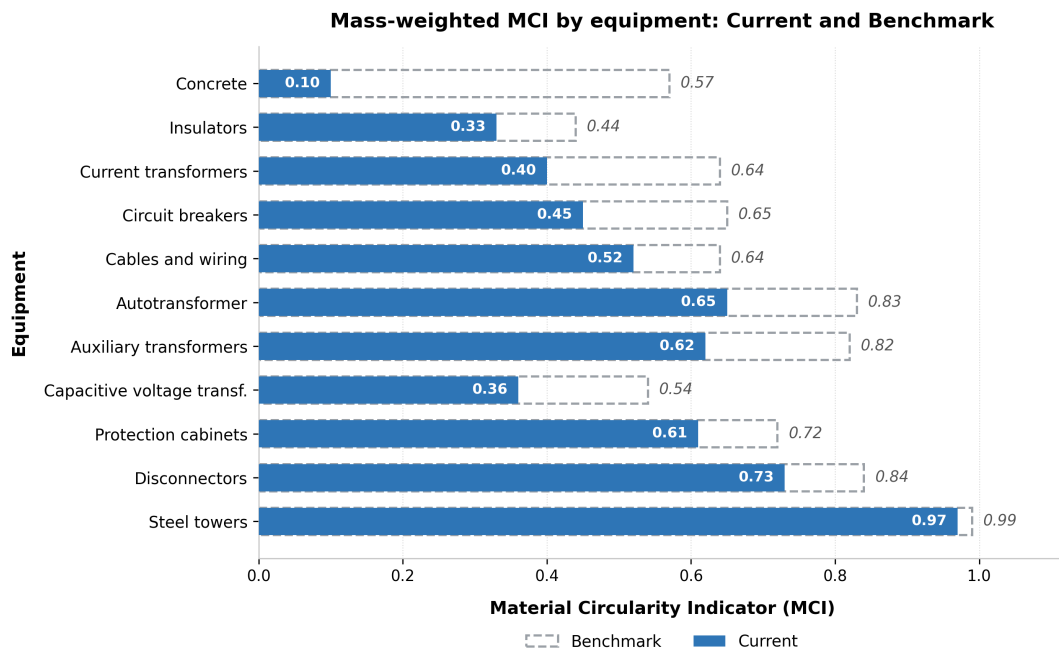


Figure 5.5: Mass-weighted circularity of the Ponte de Lima substation under current and best-practice conditions.

Table 5.7 reports the stream-level values under both formulations at baseline and benchmark.

Table 5.7: Stream-level MCI at baseline and benchmark, Ponte de Lima substation.

Stream	MCI^{mass}		MCI^{ex}	
	Baseline	Benchmark	Baseline	Benchmark
Concrete	0.10	0.57	0.10	0.57
Steel towers	0.97	0.99	0.97	0.99
Autotransformer	0.65	0.83	0.66	0.83
Circuit breakers	0.45	0.65	0.61	0.74
Disconnectors	0.73	0.84	0.73	0.83
Insulators	0.33	0.44	0.23	0.33
Current transformers	0.40	0.64	0.54	0.74
Auxiliary transformers	0.62	0.82	0.64	0.81
Capacitive voltage transf.	0.36	0.54	0.50	0.66
Protection cabinets	0.61	0.72	0.61	0.72
Surge arresters	0.57	0.68	0.44	0.55
Cables and wiring	0.52	0.64	0.52	0.64
Project	0.16	0.59	0.54	0.70

The steel towers are the best performer at 0.97 and the concrete the worst at 0.10. The autotransformer holds 0.65 by mass and 0.66 by exergy, the circuit breakers 0.45 and 0.61, and the insulators 0.33 and 0.23. The largest benchmark gaps are the concrete (+0.47) and the current transformers (+0.24 by mass), while the exergetically weighted improvement potential is distributed across the circuit breakers, the autotransformer, and the current transformers.

The material flow transformation of the Ponte de Lima substation under current and best-practice conditions is illustrated in Appendix E.

5.3.4 Lifecycle Carbon

The lifecycle carbon is computed over the 42-year horizon. Each stream re-incurs its manufacturing, distribution, and installation emissions at every replacement, the use phase scales with operating time, and the end of life applies only to units retired within the horizon. The project footprint is 35 114 tCO₂e. Table 5.8 reports the split by phase. Manufacturing dominates at 60.7%, the use phase follows at 29.8%, and the end of life accounts for 6.7%. Distribution and installation together stay below 3%.

Table 5.8: Ponte de Lima substation lifecycle carbon by phase.

Phase	Main contributors	Emissions (tCO ₂ e)	Share (%)
Manufacturing	Concrete and autotransformer	21 327	60.7
Distribution	Transport	515	1.5
Installation	Site works	452	1.3
Use	Transformer losses and SF ₆	10 478	29.8
End of life	Metal recovery	2 342	6.7
Total		35 114	100.0

Three streams carry most of the footprint, reported by asset category in Table 5.9. The concrete emits 12 375 tCO₂e (35.2%), the autotransformer 9 091 tCO₂e (25.9%) dominated by use-phase losses, and the circuit breakers 8 044 tCO₂e (22.9%) driven by the manufacturing of the switchgear and the high embodied impact of its SF₆ charge. Together these three account for 84% of the footprint. The steel towers and disconnectors follow at 1 627 and 1 500 tCO₂e, and the remaining streams contribute little. The prominence of the transformer and the switchgear in the substation footprint is consistent with lifecycle assessments of power transformers and of combined transmission and transformation projects [111, 112]. Figure 5.6 shows the distribution by stream and phase.

The use phase separates this case from the overhead line. The conductors of the line declared no use phase, since their losses depend on grid dispatch and not on the product. The autotransformer declares a use phase through its winding losses, which is kept inside the project footprint in line with the declared boundary. The available EPD for the circuit breakers declares no operational SF₆ leakage, an optimistic assumption whose true contribution could not be quantified and is reported qualitatively among the limitations of this work. The use phase scales with time and not with the number of replacements, so life extension acts on the embodied carbon and leaves the use phase untouched.

Table 5.9: Lifecycle carbon by asset category, Ponte de Lima substation.

Stream	Replacements	Total 42-yr (tCO ₂ e)	Share (%)
Concrete	0	12 375	35.2
Steel towers	0	1 627	4.6
Autotransformer	1	9 091	25.9
Circuit breakers	2	8 044	22.9
Disconnectors	2	1 500	4.3
Insulators	2	851	2.4
Current transformers	1	332	0.9
Auxiliary transformers	1	175	0.5
Capacitive voltage transf.	1	16	< 0.1
Protection cabinets	2	622	1.8
Cables and wiring	1	335	1.0
Other equipment	1–4	146	0.4
Total		35 114	100

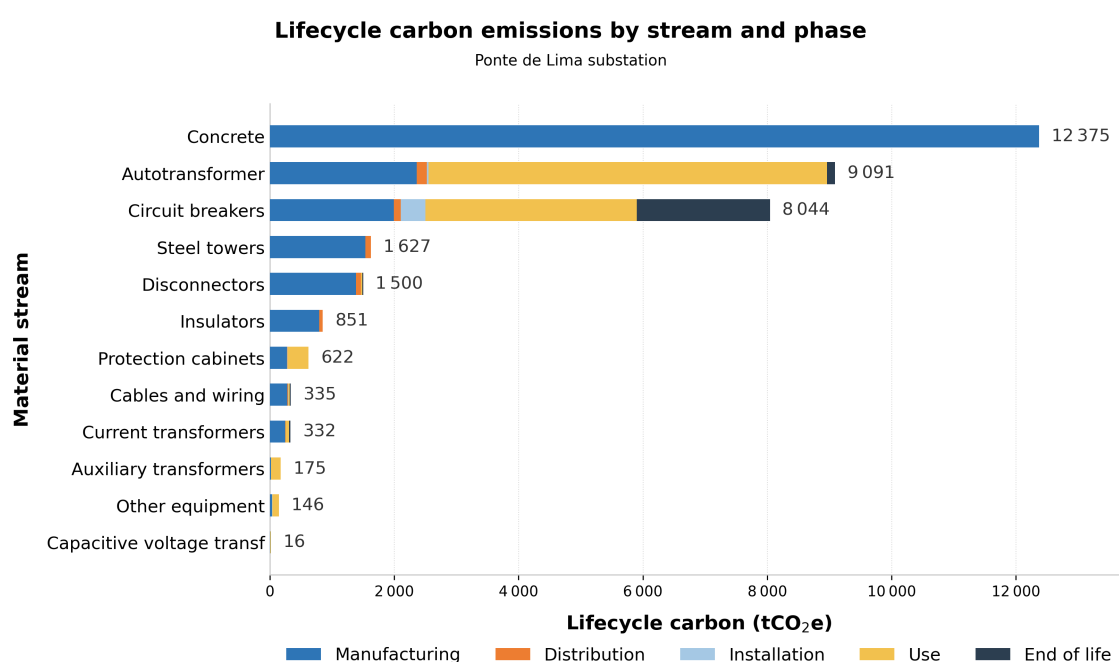


Figure 5.6: Ponte de Lima substation lifecycle carbon by stream and phase.

5.3.5 Service Life Extension

The service life extension applies the utility factor to every stream, with the effective mass recomputed at every value and each stream capped at its physical ceiling. Figure 5.7 shows the project indicator against the utility factor, and Table 5.10 reports the effect on each stream.

The two weightings diverge. The mass-weighted indicator starts at 0.16 and settles at 0.15 rather than rising. The reason is the concrete, fixed at one cycle. Table 5.10 makes this visible,

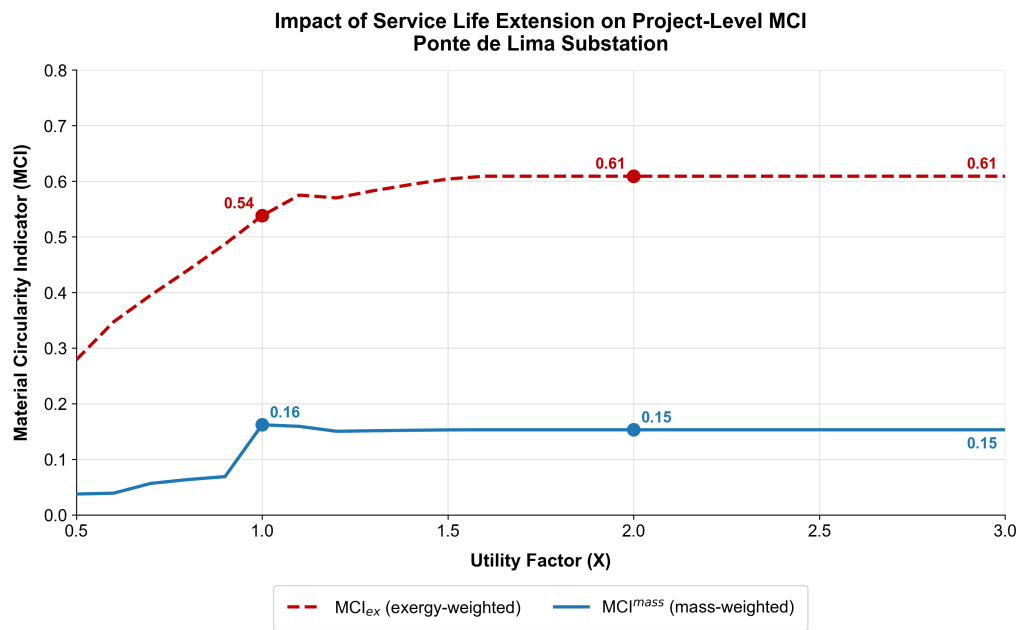


Figure 5.7: Substation circularity against the utility factor.

Table 5.10: Stream-level MCI at baseline and physical ceiling, Ponte de Lima substation.

Stream	MCI ^{mass}		MCI _{ex}		X _{max}
	X=1	X=X _{max}	X=1	X=X _{max}	
Concrete	0.10	0.10	0.10	0.10	1.00
Steel towers	0.97	0.97	0.97	0.97	1.00
Autotransformer	0.65	0.71	0.66	0.72	1.20
Current transformers	0.40	0.50	0.54	0.62	1.20
Auxiliary transformers	0.62	0.69	0.64	0.70	1.20
Capacitive voltage transf.	0.36	0.47	0.50	0.58	1.20
Circuit breakers	0.45	0.63	0.61	0.74	1.50
Disconnectors	0.73	0.82	0.73	0.82	1.50
Insulators	0.33	0.58	0.23	0.52	1.60
Protection cabinets	0.68	0.77	0.61	0.72	1.40
Surge arresters	0.57	0.59	0.44	0.47	1.05
HV cables	0.51	0.60	0.53	0.62	1.05
Control cables	0.47	0.55	0.48	0.56	1.33
Station battery	0.52	0.63	0.43	0.56	1.30
Telecontrol	0.68	0.77	0.68	0.77	1.40
Project	0.16	0.15	0.54	0.61	

$X_{\max} = \max(1, \min(L_{\text{phys}}/L_{\text{ref}}, L_{\text{proj}}/L_{\text{ref}}))$, with $L_{\text{proj}} = 42$ yr. The structural streams do not move, since their utility factor is fixed at one.

since the metallic streams climb from $X=1$ to $X_{\max}$ while the concrete stays fixed at 0.10. As the other streams extend their life they need fewer replacements, so their effective mass shrinks, the concrete then weighs even more in the average and it pulls the value down. The mass weighting hides the circularity gain. The exergy-weighted indicator starts at 0.54 and rises to 0.61, because the streams that benefit from extension are the metals, and the metals dominate the exergy. The

exergy weighting reveals the gain that the mass weighting conceals. The choice of weighting is not neutral. The plateau reflects the physical ceilings, with the transformers saturating at 1.20 and the insulators at 1.60.

Appendix E presents the evolution of the material flows associated with the Ponte de Lima substation by means of four Sankey diagrams. Figures E.5 and E.6 compare the material inputs for the current and benchmark scenarios, whereas Figures E.7 and E.8 show the corresponding output flows. Together, these diagrams highlight the changes introduced by the benchmark assumptions in both material sourcing and end-of-life allocation.

5.3.6 Eco-efficiency Matrix

The eco-efficiency places each stream on two axes, the circularity indicator and the lifecycle carbon. Figure 5.8 shows the streams. The concrete sits in the critical region, combining the lowest indicator at 0.10 with the highest carbon at 12 375 tCO₂e. The autotransformer and the circuit breakers also sit high on the carbon axis, between 8 000 and 9 000 tCO₂e, at indicators of 0.65 and 0.45, and are the priority targets after the concrete. The steel towers sit in a favourable position, at a high indicator of 0.97 and a moderate carbon of 1 627 tCO₂e. The remaining streams cluster at low carbon.

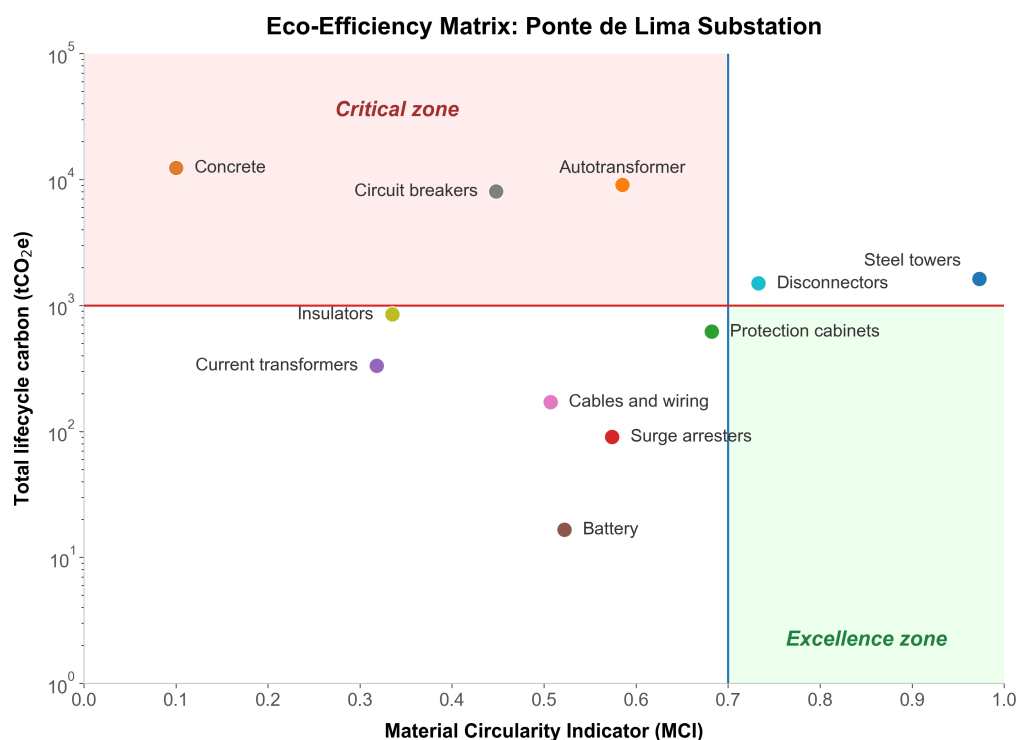


Figure 5.8: Eco-efficiency of the substation streams.

The eco-efficiency confirms the message of the carbon analysis. The footprint concentrates in a few streams. The civil works and the two largest power assets define the improvement potential.

Adopting best-practice conditions across the power equipment yields a GWP reduction potential of 2 179 tCO₂e, worth 174 320 € at the EU ETS reference price of 80 €/tCO₂e.

5.3.7 Project-Level Emissions Context

As for the overhead line, the integrated project-level tool of Section 4.4 extends the component carbon footprint to the full project across the five lifecycle phases of REN's accounting methodology. Table 5.11 reports the result over the 42-year horizon.

Table 5.11: Project-level emissions by phase, Ponte de Lima substation.

Phase	Description	Emissions (tCO ₂ e)
A	Site establishment	+7.3
B	Construction	+35 169.7
C	Operation and maintenance	+3 462.1
D	Forest balance	+26 103.3
E	Decommissioning	0.0
Net balance		+64 742.4

The substation differs from the line in its operation phase. The line integrates new renewable generation and carries a large avoided-emissions credit in Phase C. The substation integrates no new generation, so no such credit applies, and Phase C records a positive 3 462.1 tCO₂e for maintenance and inspection over the horizon. The electrical losses of the autotransformer are accounted within the Phase B equipment streams. Phase D records the forest balance of the land-use change at the site. Phase E is taken as zero, consistent with the carbon-neutrality assumption adopted by REN for decommissioning under the RNC 2050 roadmap. This convention concerns the on-site decommissioning activity and is distinct from the component end-of-life term of Section 5.3.4, which accounts for the material recovery of the equipment streams within the assessment boundary.

The net project balance is positive at 64 742.4 tCO₂e. Unlike the line, it does not depend on a volatile avoided-emissions trajectory, as the embodied and equipment emissions of Phase B and the land-use balance of Phase D dominate the total. As with the line, these project-level phases operate at a territorial and system scale that is complementary to the component-level material circularity that is the focus of this dissertation.

5.4 Comparative Analysis

The two case studies present distinct material profiles and circularity outcomes. This section compares them across three dimensions, namely circularity indicators, carbon accounting, and sensitivity, identifying the structural drivers of the divergence.

5.4.1 Circularity Comparison

Table 5.12 summarises the circularity indicators for both projects at baseline and under best-practice conditions.

Table 5.12: Circularity indicators, both case studies.

Indicator	LMAT		Substation	
	Baseline	Best-practice	Baseline	Best-practice
MCI^{mass}	0.42	0.70	0.16	0.59
MCI_{ex}	0.60	0.70	0.54	0.70

The two projects differ markedly at baseline. The LMAT scores $MCI^{\text{mass}} = 0.42$, driven by the high recycled content and recovery rates of the ACSR aluminium cables that dominate its mass. The substation scores 0.16, depressed by concrete foundations that account for 88.7% of effective mass at the minimum score of 0.10.

The exergy-weighted indicator partially closes this gap, at 0.60 for the LMAT and 0.54 for the substation, a difference of 0.06 points against 0.26 under the mass formulation. In the substation the electrically intensive streams carry high exergy demands and established recovery pathways, partially offsetting the concrete penalty, while in the LMAT the aluminium cables dominate embodied exergy and already perform well.

Under best-practice conditions both projects converge to the same exergetic level of 0.70. This convergence is not coincidental. It reflects that the exergetic ceiling is governed by the recovery potential of high-CExD materials, namely aluminium, copper, and structural steel, which are common to both typologies and share the same benchmark parameters. The mass-based best-practice scores diverge, 0.70 against 0.59, because concrete continues to depress MCI^{mass} in the substation even under best-practice conditions.

The best-practice improvement potential is higher for the substation under the mass formulation (+0.43 points against +0.28). Under the exergetic formulation, the substation also presents the greater improvement, at +0.16 points against +0.10. This confirms that the two indicators capture different dimensions of performance and that neither alone characterises the improvement potential of a project.

5.4.2 Carbon Profile Comparison

Table 5.13 presents the lifecycle carbon footprint of both projects across lifecycle phases.

The two projects present fundamentally different carbon profiles. Manufacturing dominates the LMAT at 97.2% of the total [12], while the substation assigns 60.7% to manufacturing and 29.8% to the use phase. The LMAT inventory is dominated by ACSR conductors, which concentrate their impact in the energy-intensive production of aluminium and steel, and use-phase losses in overhead lines are negligible in carbon terms.

Table 5.13: Lifecycle carbon by phase, both case studies.

Phase	LMAT (%)	Substation (%)
Manufacturing (A1-A3)	97.2	60.7
Distribution (A4)	1.6	1.5
Installation (A5)	0.1	1.3
Use (B)	–	29.8
End of life (C)	1.0	6.7
Total (tCO₂e)	28 341	35 114

The substation inventory contains two equipment categories with significant use-phase contributions. The autotransformer accounts for 25.9% of the total (9 091 tCO₂e) through its manufacturing footprint and the electrical losses declared over the servicing cycles. The circuit breakers account for 22.9% (8 044 tCO₂e) through manufacturing and the declared losses over the 42-year horizon. Together these two categories represent 48.8% of the substation total and are the only ones with a significant use-phase component. The end-of-life contribution is larger in the substation (6.7% against 1.0%), reflecting its greater material diversity and the processing of transformer oil and metallic components at decommissioning.

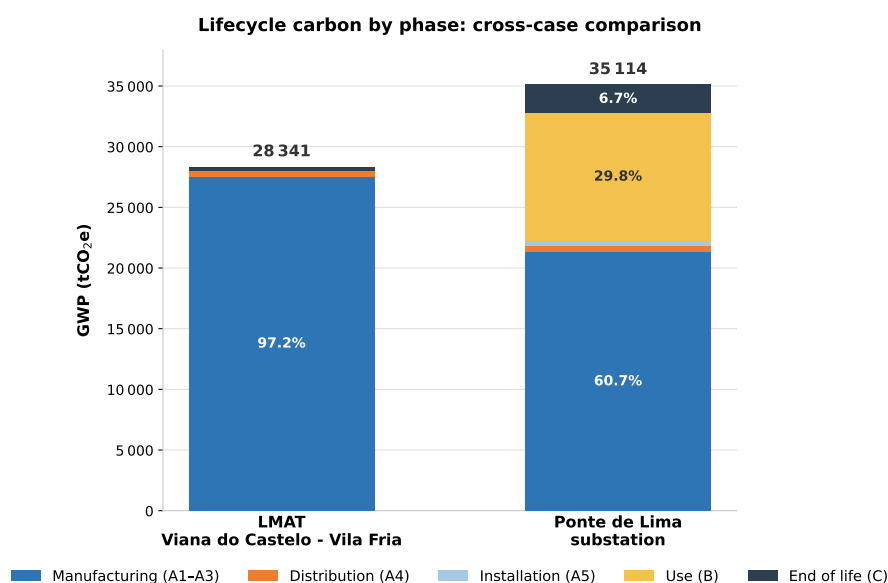


Figure 5.9: Lifecycle carbon by phase, both case studies.

The comparison illustrates a structural difference in decarbonisation levers. For the LMAT, reducing the footprint requires improving the manufacturing carbon intensity of conductors, primarily through increased recycled aluminium content. For the substation, the dominant lever is reducing use-phase emissions, where the declared losses set the magnitude and the transition to SF₆-free switchgear and to re-refined dielectric oil acts as a qualitative decarbonisation lever over

the asset life. Neither lever is captured by the circularity indicator alone, which reinforces the need for the parallel carbon accounting module of Section 4.4.

5.5 Circularity Improvement Potential

The preceding sections measured circularity at the present state and against the best-practice ceiling. This section quantifies the space between the two. It asks how much the circularity of each asset can improve, what level of effort each improvement requires, and which materials control the result. The analysis does not forecast a value for a given year, since a time-resolved forecast would require the projected procurement volumes of the network operator, which were not available for this work. It instead frames improvement as a function of ambition, which the model can support with the data at hand. The benchmarking quantified the improvement potential of each stream in isolation. The scenarios now combine those improvements into coherent trajectories for the asset as a whole.

5.5.1 Improvement Scenarios

The improvement potential is explored through the three scenarios constructed in Section 4.5.3, Business as Usual, Regulatory Compliance, and Circular Ambition, which span the range from no deliberate action to the technical ceiling of the sector. The model recomputes the global indicators under the recyclability rates of each scenario, with the present state included for reference.

5.5.2 Improvement by Asset and Component

Table 5.14 reports the global indicators of both assets under the three scenarios, with the present state included for reference. Each scenario is shown with its indicative horizon, the period in which it becomes realistic, which places each scenario on a common time reference rather than forecasting an exact year.

Table 5.14: Global circularity indicators by scenario.

Scenario	Horizon	LMAT		Substation	
		MCI ^{mass}	MCI _{ex}	MCI ^{mass}	MCI _{ex}
Current	2026	0.42	0.60	0.16	0.54
BAU	2050	0.48	0.62	0.26	0.57
Compliance	2040	0.70	0.70	0.59	0.70
Ambition	2050	0.79	0.79	0.71	0.79

The horizons clarify how the scenarios relate in time. Compliance is the state expected around 2040, once its regulatory instruments are in force. Ambition is the state reachable by 2050 with the best technology deployed. BAU is also a 2050 state, but the one reached through inertia rather

than effort. The contrast between BAU and Ambition is therefore a contrast between two versions of the same year, since by 2050 the asset can sit near the bottom or near the top of its circularity range, and the difference is the level of deliberate action taken.

The improvement potential is large for both assets. The mass-weighted indicator of the LMAT can rise from 0.42 to 0.79, and the substation from 0.16 to 0.71. The step from BAU to Compliance is the widest in both cases. For the substation mass-weighted indicator it spans 0.26 to 0.59. This gap carries the central message of the analysis. Most of the available improvement does not occur on its own. It depends on regulatory intervention and the active procurement of recycled content. The continuation of current trends alone reaches only a modest level.

For the LMAT, the steel towers and the reinforcement already sit near their ceiling and offer little additional gain. The concrete carries the largest potential, its mass-weighted indicator rising from 0.10 to 0.70 across the scenarios, bounded by the recycled aggregate limits of EN 206 [97]. The conductors improve through their aluminium content, the dominant driver of the exergy-weighted result. This pattern is consistent with the sensitivity analysis of Section 5.6, where the recyclability of aluminium in the cables emerged as the dominant parameter of the exergy-weighted indicator.

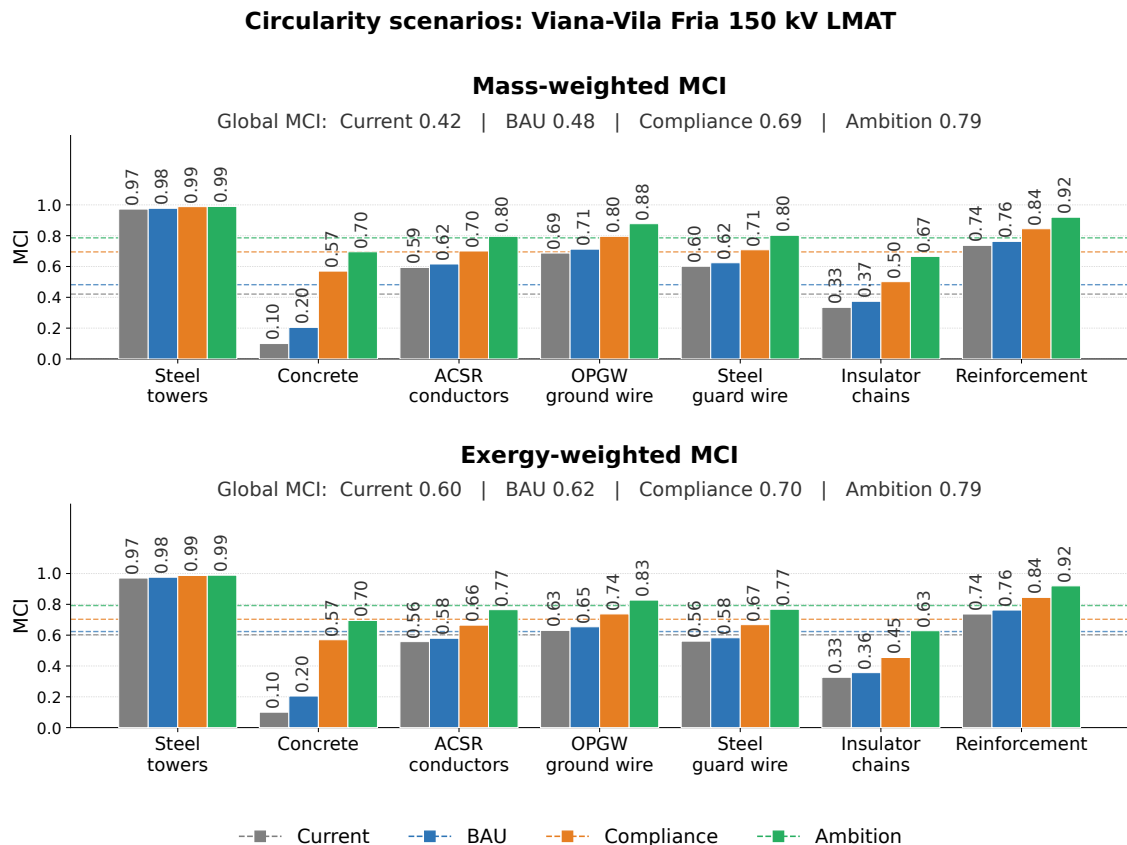


Figure 5.10: Component circularity by scenario, LMAT line.

For the substation, the steel towers and the disconnectors begin near their ceiling. The concrete, the current transformers, and the circuit breakers carry most of the potential. The concrete

shows the largest relative gain, rising from 0.10 to 0.70, which reflects its dominant mass share and its zero starting point. Any improvement in concrete recyclability moves the mass-weighted indicator of the whole asset strongly.

The two assets reach a similar ceiling through different routes. The LMAT gain is led by aluminium in the exergy-weighted view and by concrete in the mass-weighted view. The substation gain is dominated by concrete in both views. This difference follows from the distinct material composition of a line and a substation. It confirms that the circularity lever is asset-specific and that procurement strategy should target different materials in each case.

The improvement in circularity corresponds to the avoided carbon quantified in Sections 4.5.1 and 5.4.2. The same shift toward recycled content that raises the indicators is the shift that reduces the manufacturing carbon of each asset. Two further decarbonisation levers act on the use phase and fall outside the material circularity model. The F-Gas Regulation removes SF₆ from new high-voltage switchgear from 2032 [73]. Re-refined insulating oil reduces the carbon footprint of transformer oil by about 70% relative to virgin oil [98]. Neither lever is captured by the recyclability parameters of the model, and both reinforce the direction of the improvement scenarios.

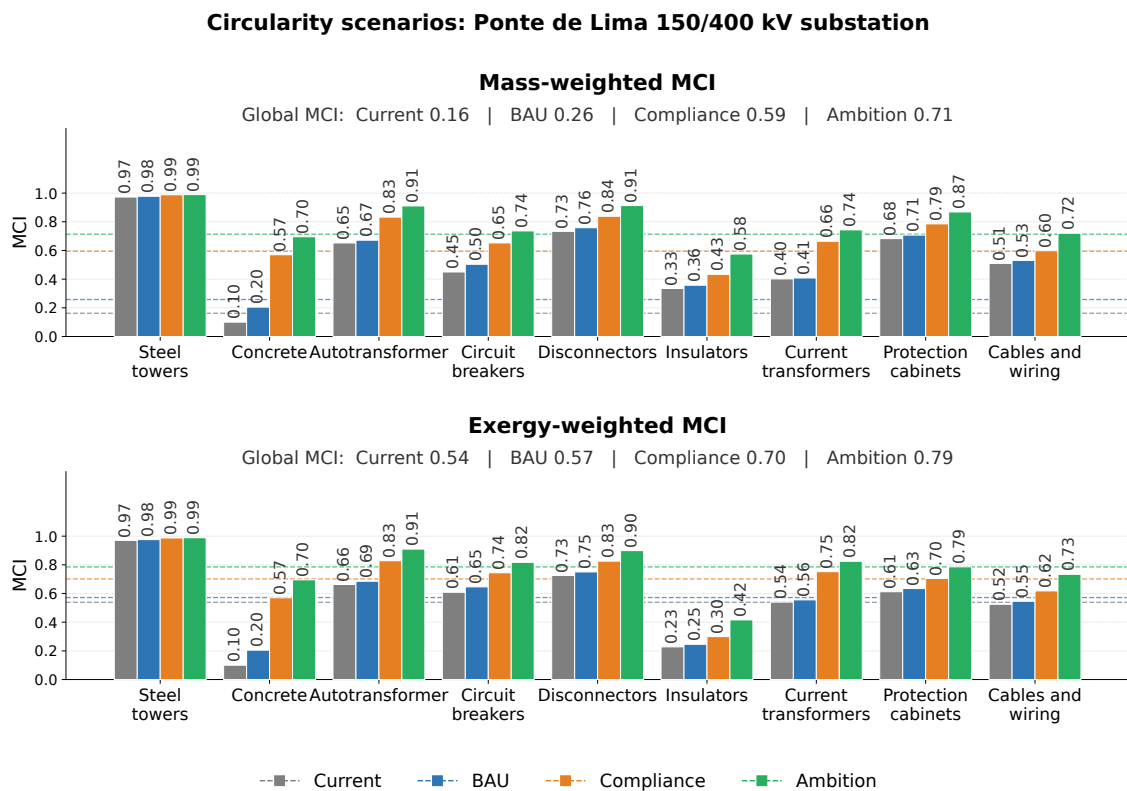


Figure 5.11: Component circularity by scenario, Ponte de Lima substation.

5.6 Sensitivity Analysis

A variance-based global sensitivity analysis identifies the parameters that most influence the circularity indicators, following the methodology of Section 4.6.3. It covers the recycled content fraction F_R and the end-of-life recycling efficiency E_c of every material above 1% of project mass or embodied exergy, each ranging from its current value to the European best-practice benchmark. The LMAT analysis uses $N = 4096$ base samples and the substation $N = 1024$, the smaller value justified by its larger parameter set and confirmed by the convergence assessment of Appendix F. Tables 5.15 and 5.16 report the dominant parameters of each project. The corresponding first-order and total-effect Sobol indices are presented in Appendix F. Parameters below the 5% threshold under both indicators are omitted.

Mass-Based Sensitivity

The mass-weighted indicator of both assets is governed by a single material. In the LMAT the end-of-life recycling efficiency of concrete dominates the variance at $S_T = 0.930 \pm 0.031$, followed by its recycled content, and no other parameter is significant. The substation shows the same structure, with the recycling efficiency of concrete leading at $S_T = 0.936 \pm 0.054$. The result follows directly from the mass share of concrete, 51% in the line and 89% in the substation.

Table 5.15: Dominant sensitivity indices, Viana do Castelo - Vila Fria LMAT line.

Parameter	MCI^{mass}		MCI_{ex}	
	S_T	ISAN	S_T	ISAN
E_c Concrete	0.930	0.487	0.004	0.001
F_R Concrete	0.069	0.490	0.000	0.001
F_R Aluminium cables	0.007	0.014	0.940	0.837
E_c Aluminium cables	0.000	0.002	0.040	0.142

Table 5.16: Dominant sensitivity indices, Ponte de Lima substation.

Parameter	MCI^{mass}		MCI_{ex}	
	S_T	ISAN	S_T	ISAN
E_c Concrete	0.936	0.851	0.478	0.176
F_R Concrete	0.070	0.148	0.036	0.031
F_R Steel components	0.000	0.000	0.160	0.211
E_c Steel components	0.000	0.000	0.135	0.178
E_c Composite	0.000	0.000	0.083	0.207

Exergetic Sensitivity

The exergetic formulation separates the two projects. In the LMAT a single parameter governs the indicator, the recycled content of aluminium cables at $S_T = 0.940 \pm 0.031$ with $S_1 = S_T$, which confirms that the cables concentrate over 90% of the embodied exergy and that interactions are negligible. The substation has no single dominant parameter. The end-of-life efficiency of concrete leads at $S_T = 0.478 \pm 0.041$, followed by the recycled content and recovery of steel components and the recovery of the composite, so the exergetic weight is shared across several electrically intensive streams. This contrast is itself a result. An overhead line can concentrate its circularity strategy on one material lever, whereas a substation requires coordinated action across several streams.

The sum of the first-order indices is close to unity throughout, at 0.995 and 1.000 for the LMAT and 0.993 and 0.974 for the substation. Both models are therefore predominantly additive, each material contributing almost independently, and the second-order indices reported in Appendix F confirm this.

Amplitude-Normalised Sensitivity

Raw Sobol indices reflect sensitivity within the assigned range, so a parameter with a wide range can score highly for that reason alone. The amplitude-normalised index (ISAN) of Section 4.6.3 corrects this bias, and is reported with the absolute Spearman rank correlation $|\rho|$ in Figures F.3 and F.4 of Appendix F.

For the mass-based indicator the correction confirms the dominance of concrete. In the LMAT its recycled content and recycling efficiency emerge as equally dominant per unit of variation (ISAN = 0.490 and 0.487), although the raw indices separated them by an order of magnitude. In the substation the recycling efficiency of concrete keeps the highest value (ISAN = 0.851), so its dominance is structural rather than an artefact of a wide range. The high Spearman correlations confirm direct and monotonic relationships. The procurement implication is direct, since a modest gain in the recycled content and recovery of concrete produces a disproportionate response in the mass-based indicator per unit of effort.

For the exergetic indicator the correction preserves the contrast. In the LMAT the recycled content of aluminium cables keeps its dominance (ISAN = 0.837, $|\rho| = 0.971$), confirming a near-linear direct effect. In the substation, the normalised ranking is led by the steel components and the composite rather than by concrete, whose recycling efficiency falls to fourth position. The apparent dominance of concrete in the raw exergetic indices was therefore partly a range effect, and the per-unit sensitivity is distributed across the metallic and composite streams.

Interaction Effects

Figures F.5 and F.6 in Appendix F examine the joint effect of the recycled content and the recycling efficiency of concrete on both indicators. The two parameters interact weakly and positively through the recycled feedstock waste term W_F of the linear flow index, an interaction secondary to

the main effects and consistent with the near-unity first-order sums. The same comparison quantifies the central divergence between the indicators. An identical concrete improvement moves the mass-based indicator far more than the exergetic one, by a factor of about 44 in the LMAT and 7 in the substation. This mirrors the weight of concrete in each formulation, 51% of the LMAT mass against 1% of its embodied exergy, and 89% against 13% in the substation.

The analysis confirms the complementary role of the two indicators. The mass-based indicator is governed by concrete in both projects, while the exergetic indicator is governed by a single aluminium parameter in the LMAT and by a distributed set of metallic and composite parameters in the substation. A strategy that targets only the mass-dominant stream leaves the exergetic performance largely unchanged.

6 Conclusions and Future Work

This final chapter summarises the main conclusions of the dissertation, identifies the limitations of the current model, and proposes improvements for future development.

6.1 Conclusions

The main objective of this dissertation was to develop a project-level model for the circularity index of REN's transmission infrastructure, closing the gap identified in Chapter 3. The goal was a quantitative, decision-oriented instrument that integrates material composition, recycled content, replacement cycles, greenhouse gas emissions, and benchmarking potential. The model was grounded in mechanical engineering, with a thermodynamic emphasis on the Second Law and on exergy as a measure of resource quality [51]. Five requirements framed the work. These were project-level applicability, high-resolution material categorisation, carbon-circularity integration, lifecycle and temporal dynamics, and systematic benchmarking against achievable targets.

All five requirements were met. The framework was implemented as a structured workbook in *Microsoft Excel*, which serves as the primary calculation engine. A complementary interface was developed in *Python* using the *Streamlit* library, with one module for overhead lines and one for substations. The model adapts the Material Circularity Indicator to long-lived, multi-component assets through an effective mass formulation and a physically-bounded service life extension. It extends the indicator with an exergy-weighted formulation based on the Cumulative Exergy Demand [54]. It computes the lifecycle carbon footprint over Modules A to D of EN 15978, reported as Scope 3 emissions. It quantifies the improvement potential of each material stream against best-practice benchmarks, and supports the result with a variance-based sensitivity analysis and an eco-efficiency matrix. One further initial aim, the projection of the circularity trajectory of REN's assets from its procurement volumes to 2030, could not be completed because those volumes did not become available in time. It is carried forward as a direction for future work.

The central methodological contribution is the parallel use of two circularity indicators. The mass-weighted indicator measures how much material circulates. The exergy-weighted indicator measures the thermodynamic quality of that material. The two are not interchangeable. Concrete dominates the mass of a transmission asset but carries a negligible exergetic weight. Aluminium dominates the embodied exergy but represents a small fraction of the mass. A strategy guided by mass alone would target the wrong material, and a strategy guided by exergy alone would

understate the headline score used for regulatory reporting. Computing both in parallel is therefore a requirement of the framework, not an option.

Main Results

The framework was applied to two REN projects. The first was the Viana do Castelo – Vila Fria 150 kV overhead line, assessed over a 50-year horizon. The line scored $MCI^{mass} = 0.42$ and $MCI_{ex} = 0.60$ at the baseline. Both indicators rise to 0.70 under best-practice conditions. The lifecycle carbon footprint is 28 341 tCO₂e, of which manufacturing accounts for 97.2%. The ACSR conductors alone represent 75% of the footprint, driven by the carbon intensity of primary aluminium and by a single in-service replacement. The avoided carbon under best-practice procurement reaches 4 984 tCO₂e, with an associated value of 398 720 € at the EU ETS reference price of 80 €/tCO₂e.

The second case was the Ponte de Lima substation, which steps between the 400 kV and 150 kV networks, assessed over a 42-year horizon. The substation scored $MCI^{mass} = 0.16$ and $MCI_{ex} = 0.54$ at the baseline. The mass indicator is depressed by the concrete foundations, which represent 88.7% of the effective mass. The exergy indicator removes this dominance and rises to 0.54, because the concrete carries little exergy while the power equipment carries most of it. The lifecycle carbon footprint is 35 114 tCO₂e. Manufacturing accounts for 60.7% and the use phase for 29.8%. Three streams carry most of the footprint, namely the concrete at 12 375 tCO₂e, the autotransformer at 9 091 tCO₂e, and the circuit breakers at 8 044 tCO₂e. The avoided carbon under best-practice procurement reaches 2 179 tCO₂e, with an associated value of 174 320 € at the same reference price.

The comparison of the two cases confirmed the complementary role of the two indicators. The mass-based indicator is governed by the recyclability of concrete in both assets. The exergetic indicator is governed by a single aluminium parameter in the line and by a distributed set of metallic and composite parameters in the substation. Under best-practice conditions the exergetic indicators converge to the same ceiling of 0.70, while the mass-based scores remain apart because concrete continues to weigh on the substation. The sensitivity analysis confirmed that both models are predominantly additive, with negligible interaction effects.

The improvement analysis showed that the available gain is large for both assets but does not occur on its own. The step from a business-as-usual trajectory to regulatory compliance is the widest in both cases. Most of the improvement depends on regulatory intervention and on the active procurement of recycled content, not on the continuation of current trends. The model therefore gives REN a single instrument to quantify, compare, and prioritise circularity and carbon actions at the scale of an individual project, in a form that feeds directly into procurement specifications and sustainability reporting.

6.2 Limitations of the Current Model

Despite the results obtained, several limitations were identified that should be addressed in future iterations.

The first limitation concerns the use phase. The carbon associated with the electrical losses of the transformers and with the SF₆ leakage of the switchgear could not be fully quantified from the available EPD data. These contributions were treated qualitatively. The same applies to the dielectric oil. As a consequence, the use-phase share of the substation footprint reflects what the declarations report rather than a complete operational inventory.

A related limitation is the treatment of SF₆. It was excluded from the Monte Carlo uncertainty propagation by design. Its end-of-life recovery is set by regulation rather than by a circular commodity market, so it was handled as a compliance variable rather than as a market-driven circularity parameter. This choice keeps the regulatory obligation from inflating the circularity score, but it means the uncertainty band does not cover this stream.

The circularity indicator does not capture use-phase carbon. Two assets with the same indicator can generate very different operational emissions. This is a structural feature of the Material Circularity Indicator, not an error of the implementation. The parallel carbon accounting module was developed precisely to address this gap, and the two layers must always be read together.

The physical service life adopted for each stream is an engineering estimate, not a declared value. It reflects the duration achievable on site under the maintenance regime applied. For the coastal conductors, the galvanising class is the principal source of uncertainty in this estimate. The distinction between the declared reference life and the adopted physical life was kept explicit throughout, but it remains an assumption that future field data could refine.

The system boundary is restricted to the material lifecycle of the asset. It excludes land clearance, right-of-way establishment, earthworks, and temporary construction activities. The outputs should therefore be read as the component-embodied and operational footprint of the asset, not as a complete project-level environmental assessment.

The improvement scenarios are presented as discrete ambition levels rather than as time-resolved curves. Converting them into dated trajectories would require the projected procurement volumes of the network operator and a carbon-intensity trajectory for the grid, neither of which were available for this work. Any continuous curve would therefore be partially speculative. The improvement potential was framed as a function of ambition, anchored to indicative regulatory and technology horizons, rather than as a dated prediction. The model presents ambition, not forecast.

Finally, the framework does not integrate the resistive losses of the overhead conductors. The Joule losses over the service life depend on the conductor cross-section, the load profile, and the loss factor. The EPD system boundary excludes these transmission losses from the use phase, and the 50-year load profile and grid carbon-intensity trajectory required to model them were not available. This dimension was therefore left outside the scope, and its integration is identified as future work.

6.3 Future Improvements

Beyond addressing the limitations identified above, several extensions could strengthen the model in future work.

The most direct extension is the integration of projected procurement volumes. With the network operator's deployment plans, the ambition-based scenarios could be converted into dated trajectories, allowing the model to report an expected circularity value and an avoided-carbon path for specific years.

The use phase should be quantified as the underlying declarations mature. As EPD datasets begin to report operational losses and gas leakage in a consistent form, the qualitative treatment of the transformer and switchgear use phase can be replaced by an explicit calculation, which would improve the carbon footprint of the substation in particular.

An economic layer would add a decision dimension that the present model does not cover. A cost-benefit analysis of each circularity intervention, comparing the procurement cost of recycled content against the value of the avoided carbon, would let REN rank actions by economic efficiency rather than by environmental gain alone.

A related extension is the integration of the trade-off between operational cost and carbon for overhead conductors. The resistive losses over the service life represent both an operational cost and a carbon source that depends on the grid's emission factor. Coupling these losses with the embodied carbon and the capital cost of the conductor would allow the model to recommend not only the recycled-content target but also the optimal conductor cross-section from a combined circularity, carbon, and cost perspective. This extension requires a load profile for the line, a loss factor, and a projected carbon-intensity curve for the electricity mix, all of which could be obtained from the network operator's planning data.

The framework could be extended to further asset typologies. The present work covered an overhead line and a substation. Underground cable systems and gas-insulated switchgear would broaden the coverage of the transmission network and test the model against different material profiles.

The outputs could be linked more directly to corporate reporting. The carbon results are already structured for Scope 3 disclosure under ESRS E5 [43]. A formal pipeline from the project-level assessment to the corporate inventory would remove the manual translation step and make the model a routine part of REN's reporting workflow.

The supporting datasets and visual outputs can also be progressively refined. Updating the Cumulative Exergy Demand values as the reference databases evolve, increasing the granularity of the sub-material composition, and consolidating the material flow diagrams would improve both the accuracy and the readability of the assessment.

Taken together, these extensions would move the framework from a project-level assessment instrument toward a planning tool for the circular management of the transmission network as a whole.

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Appendix A REN's Operations

This appendix provides supporting context on REN's operations. It presents the electricity and gas value chains and the geographical extent of the National Electricity Transmission Network (RNT), referenced in the characterisation of Chapter 3.

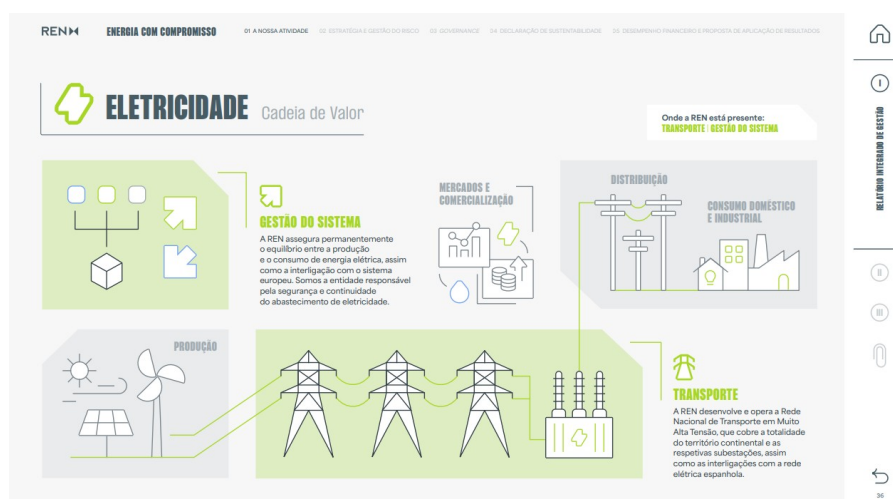


Figure A.1: REN electricity value chain.

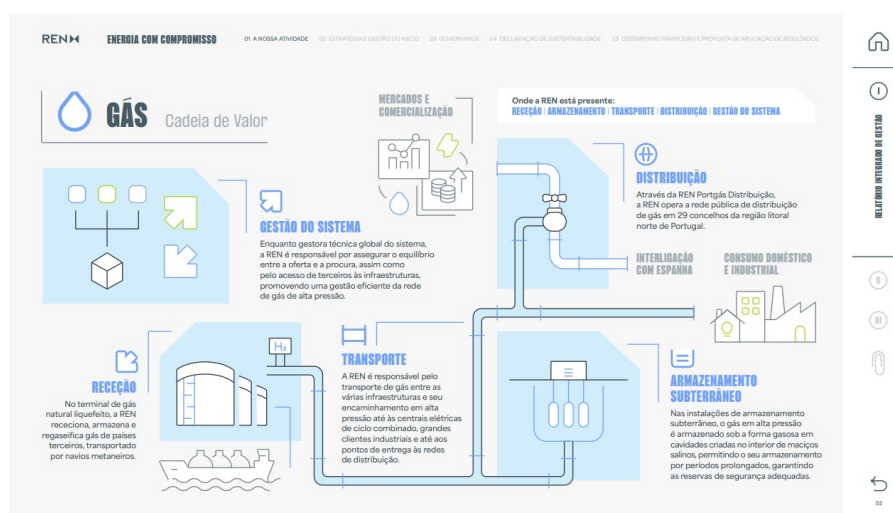


Figure A.2: REN gas value chain.

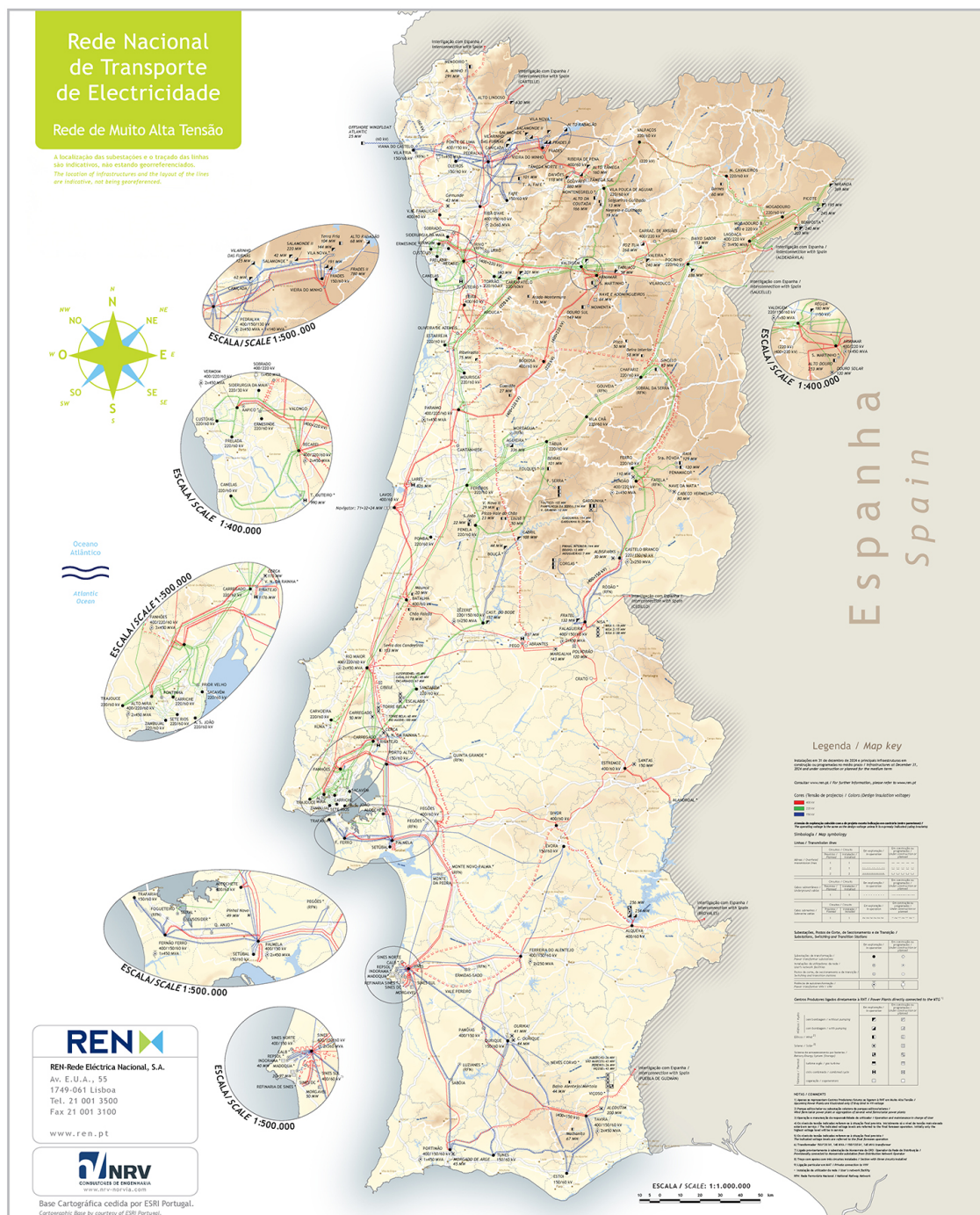


Figure A.3: Geographical map of the RNT. Adapted from [68].

Appendix B Material Emission Factors

Table B.1: Cradle-to-gate carbon intensity by production route (Modules A1-A3).

Material	GWP_{vir}	GWP_{rec}	Reduction (%)
Steel (components)	2.80	0.90	68
Steel (structural)	2.40	0.80	67
Aluminium (components)	14.00	0.50	96
Aluminium (cables)	16.50	1.00	94
Copper (electronics)	4.00	1.50	63
Copper (piping)	3.00	1.00	67
Silver	100.00	14.00	86
Tin	15.00	4.00	73
Zinc	3.89	1.10	72
Glass	1.00	0.40	60
Composite	4.50	3.20	29
Ceramics	1.20	0.60	50
Plastics (equipment)	3.50	1.20	66
Plastics (cables)	2.50	1.00	60
Plastics (PE)	2.50	1.00	60
Oil	2.00	0.60	70
Insulating paper	1.40	0.42	70
Lead	2.00	0.45	78
Concrete	0.15	0.08	47
Others	–	–	–

Values in kg CO₂eq/kg, compiled from [13, 44–46, 92–95, 113–116]. The figures are representative reference values from the cited datasets rather than exact, time-invariant factors. Their effect on the results is bounded by the sensitivity analysis of Section 5.6.

Appendix C Web Application Interface

This appendix presents the web application developed to implement the assessment model described in Section 5.1. For conciseness, the interface presented here illustrates the complete calculation workflow only for the LMAT case study. A corresponding module was also developed for the substation case study, using the same underlying architecture but adapted to its specific material inputs and service-life constraints. Although the application is demonstrated using the selected case studies, it was designed to be applicable to other projects within the same asset categories and is therefore not limited to the specific locations or projects analysed in this dissertation.

24/06/26, 17:37

REN | Ferramenta de Circularidade

Parâmetros do Projeto MAT

Nome do Projeto

Viana - Vila Fria

Tempo de Vida (Anos)

50 - +

Ano do Projeto

2024 - +

Preço do Carbono (€/tCO₂e)

80

Quantidades (Materiais)

Peso Apoios (t)

1204

Extensão Cabo Condutor (km)

330

Extensão Cabo de Guarda OPGW (km)

27,6

Extensão Cabo de Guarda Aço (km)

27,6

Nº Cadeias Isoladores

672 - +

Betão (t)

2973,6

Peso Armadura (t)

62,7

> Faixa de Servidão (ha)

> Dados PDIRT / Planeamento

Limpar

 Calcular

REN **Cálculo do Índice de Circularidade para projetos MAT**

Ferramenta de cálculo do Índice de Circularidade, Pegada Carbónica e ganhos relativos ao Benchmarking. Insira os dados técnicos do projeto no painel lateral para gerar os resultados e gráficos de apoio à decisão.

Resultados processados com sucesso para o projeto: Viana - Vila Fria

Desempenho de Circularidade



Impacto Ambiental & Valorização Económica

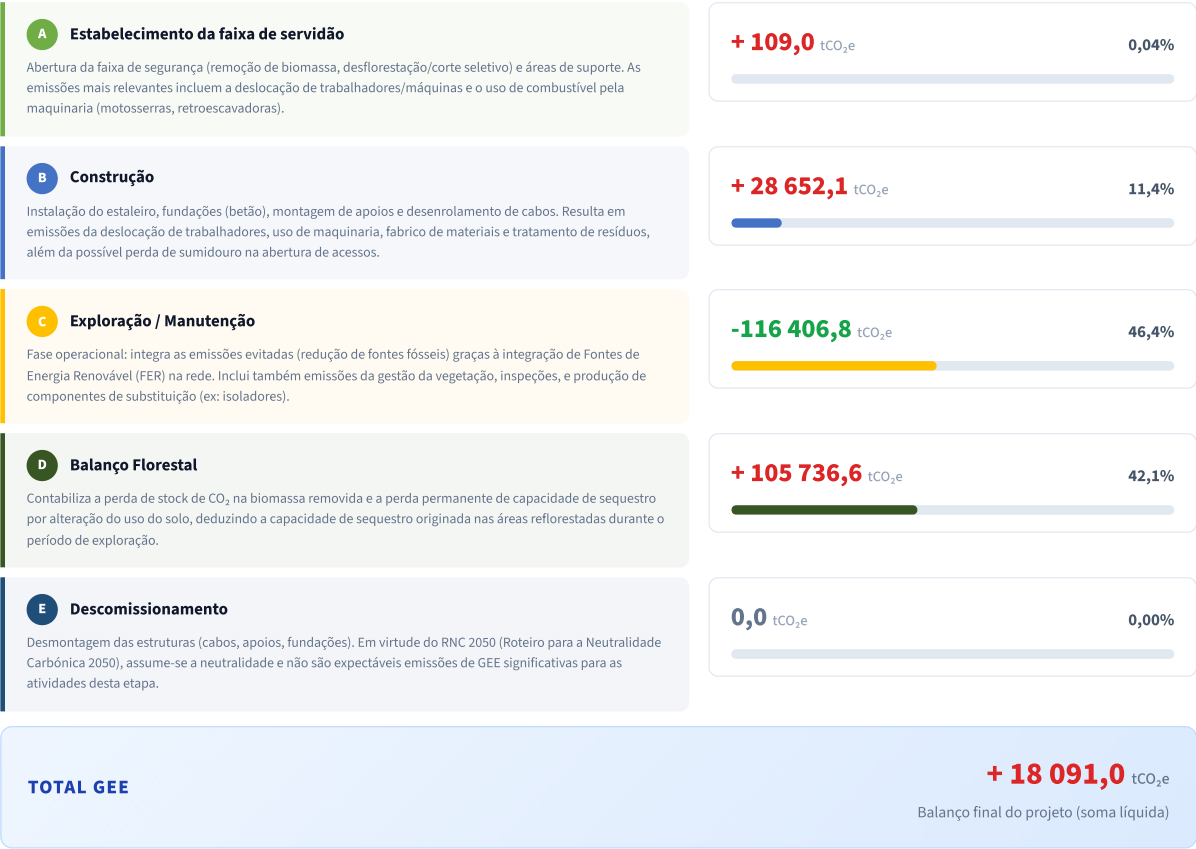


Emissões de Gases com Efeito de Estufa (GEE)

Contabilização das emissões GEE ao longo do ciclo de vida da linha, incluindo o impacto da alteração do uso do solo.



Detalhe por Fase do Projeto



Balanço Florestal: Alteração do Uso do Solo (Detalhe da Fase D)

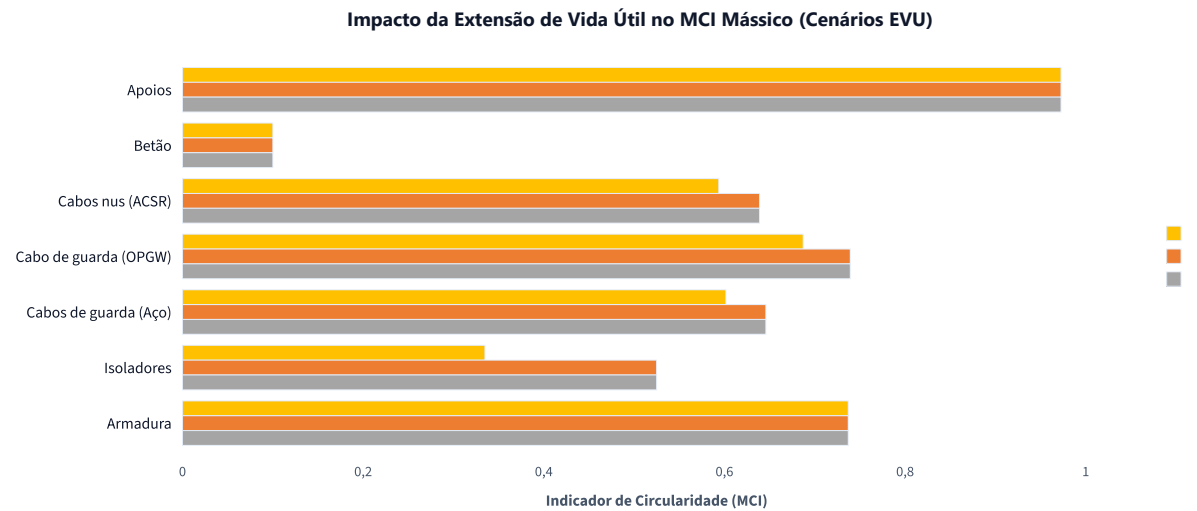
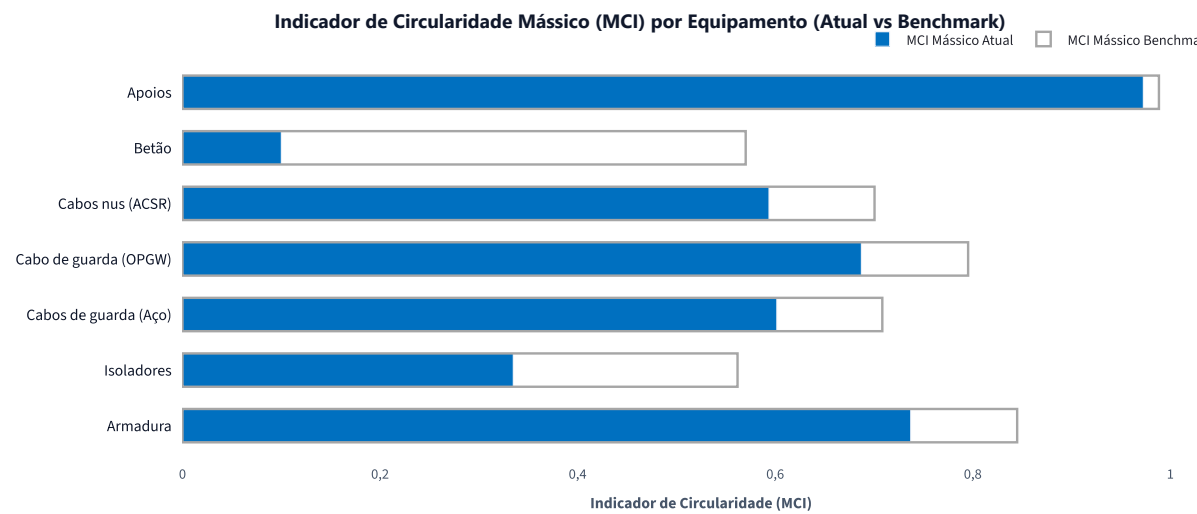


Análise Gráfica

Navegue pelos separadores abaixo para analisar o desempenho circular, explorar as emissões do projeto e simular cenários de extensão de vida útil.

Circularidade (MCI) Emissões GEE (Projeto Global) Pegada Carbónica (Infraestrutura) Matriz de Eco-Eficiência

Análise de Circularidade (MCI)

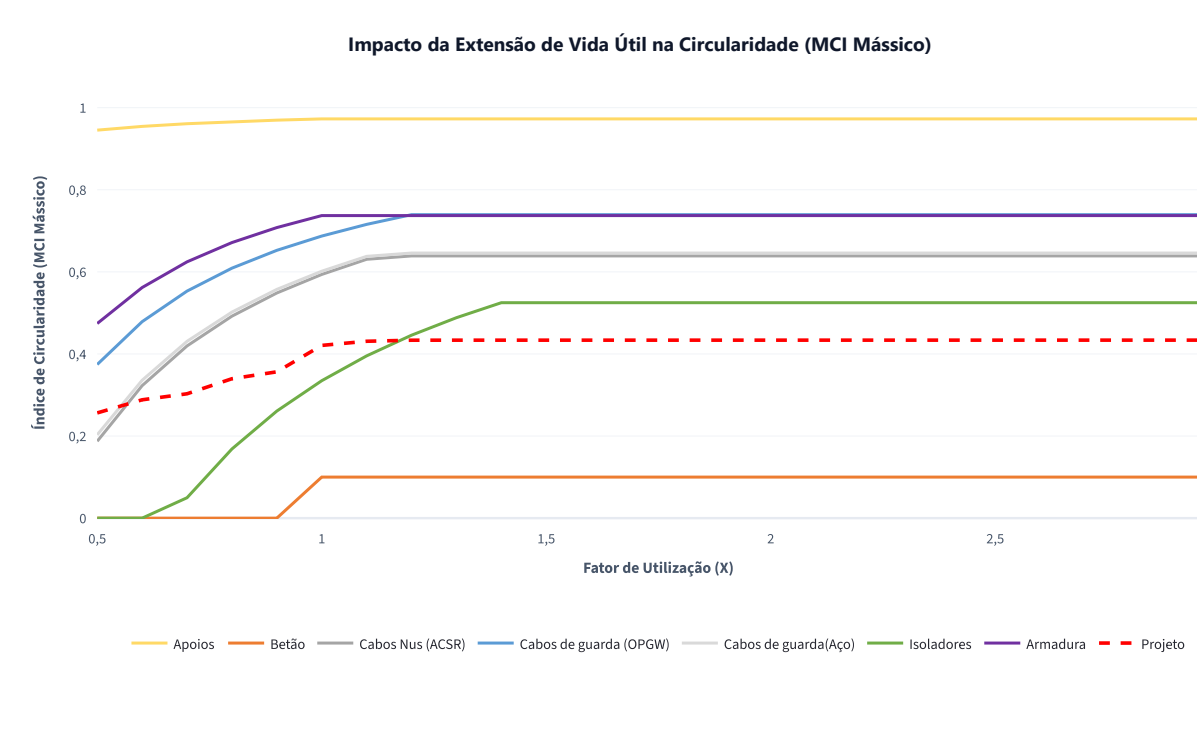


24/06/26, 17:37

REN | Ferramenta de Circularidade

Visão do Gráfico:

☒ MCI Mássico ☐ MCI Exergético



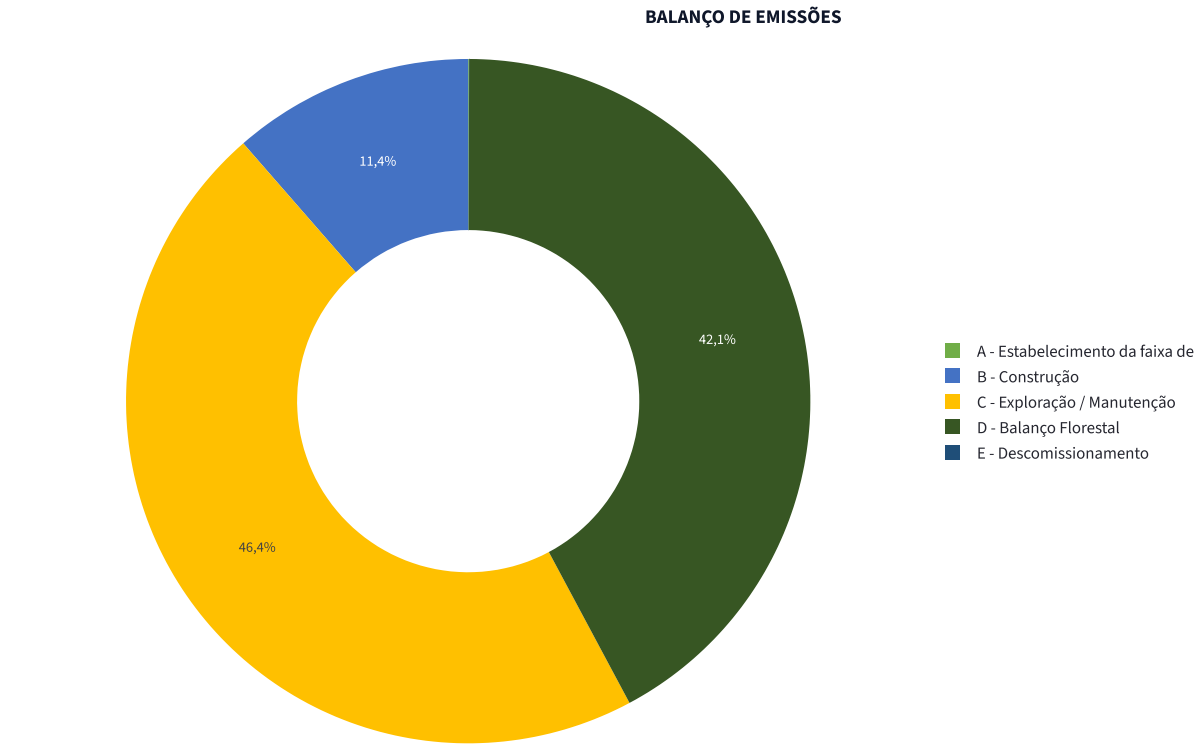
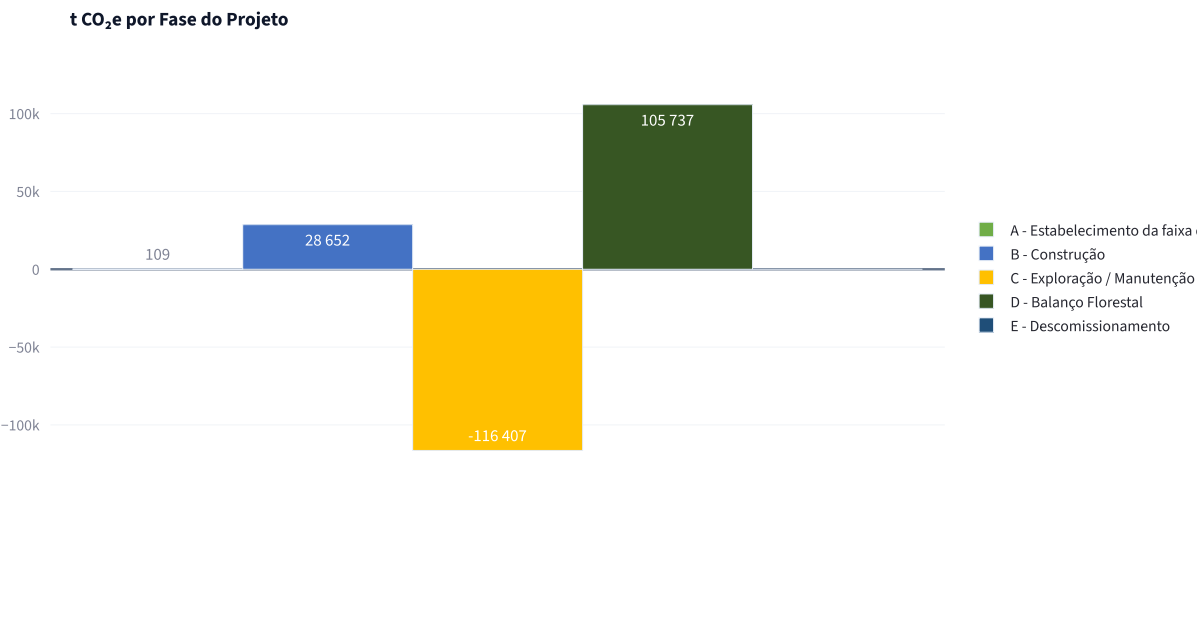
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Análise Gráfica

Navegue pelos separadores abaixo para analisar o desempenho circular, explorar as emissões do projeto e simular cenários de extensão de vida útil.

Circularidade (MCI) Emissões GEE (Projeto Global) Pegada Carbónica (Infraestrutura) Matriz de Eco-Eficiência

Resultados Globais de Emissões GEE



Análise Gráfica

Navegue pelos separadores abaixo para analisar o desempenho circular, explorar as emissões do projeto e simular cenários de extensão de vida útil.

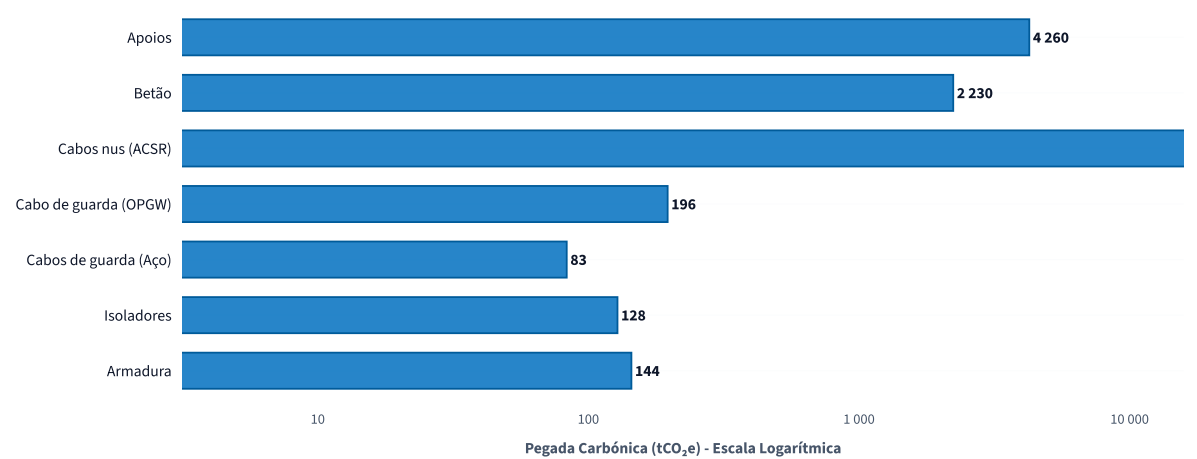
Circularidade (MCI) Emissões GEE (Projeto Global) Pegada Carbónica (Infraestrutura) Matriz de Eco-Eficiência

Avaliação de Ciclo de Vida (Pegada Carbónica)

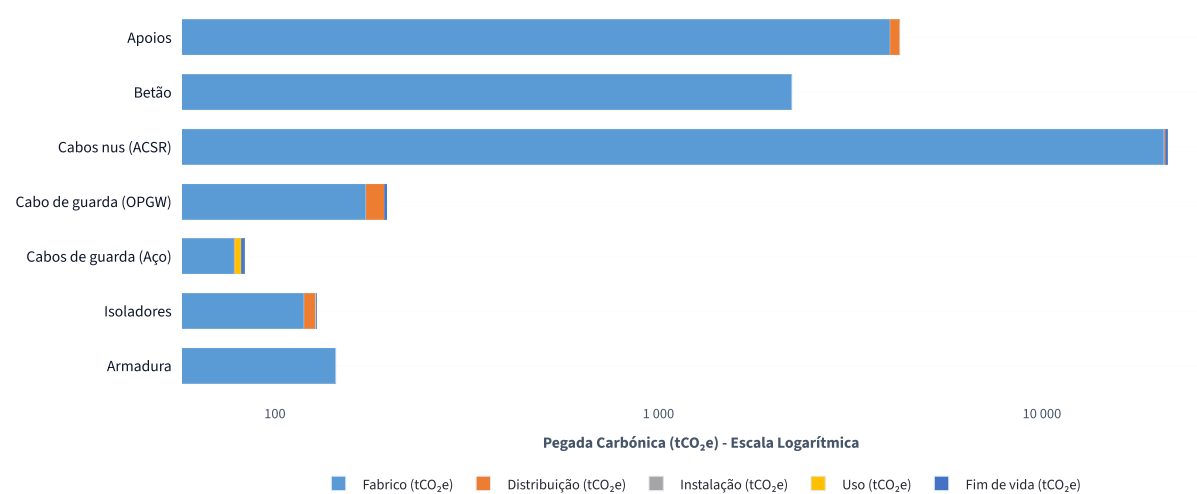
Escala do Eixo X:

Logarítmica Linear

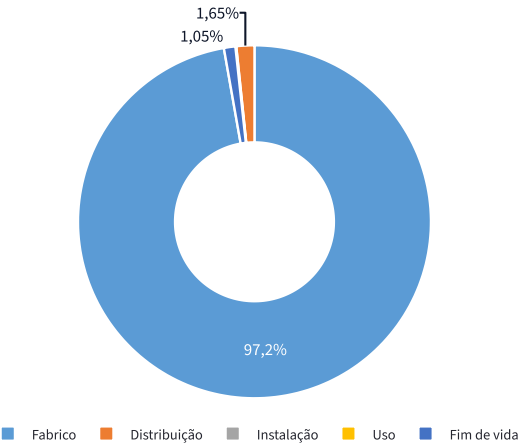
Pegada Carbónica do Ciclo de Vida (Projeto a 50 Anos)



Pegada Carbónica (tCO₂e) por Fase (Projeto a 50 Anos)



Distribuição da Pegada Carbónica por Fase (Projeto a 50 Anos)



Análise Gráfica

Navegue pelos separadores abaixo para analisar o desempenho circular, explorar as emissões do projeto e simular cenários de extensão de vida útil.

Circularidade (MCI) Emissões GEE (Projeto Global) Pegada Carbónica (Infraestrutura) **Matriz de Eco-Eficiência**

Integração de Resultados

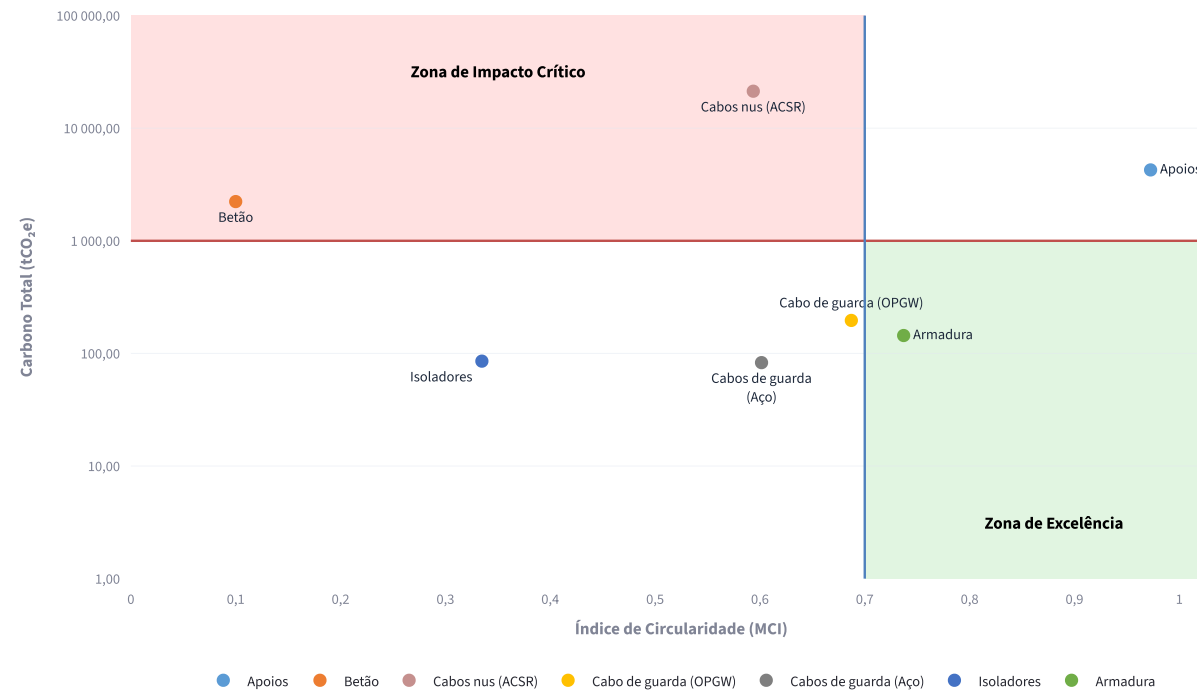
Matriz de Eco-Eficiência: Linha 150kV (MAT)

Eixo X (Circularidade):

☒ MCI Mássico ☐ MCI Exergético

Simulador: Fator de Extensão de Vida Útil (EVU)

1.00



Appendix D Material Inventories

This appendix reports the complete material inventories of the two case studies, referenced in Sections 5.2.1 and 5.3.1.

Table D.1: Material inventory, Viana do Castelo - Vila Fria LMAT line.

Stream	Quantity	L_{ref} (yr)	Repl.	Eff. mass (t)	Share (%)
Steel towers	1 204 t	63	0	1 204	20.7
Concrete	2 974 t	65	0	2 974	51.1
Reinforcement	62.7 t	70	0	62.7	1.1
ACSR conductors	330 km	40	1	1 505	25.9
OPGW ground wire	27.6 km	40	1	38.1	0.7
Steel guard wire	27.6 km	40	1	10.7	0.2
Insulator chains	672 units	20	2	27.4	0.5
Total				5 821	100

L_{ref} : reference service life from the EPD. Repl.: in-service replacements over the horizon. Effective mass: $m_i^{\text{eff}} = m_i \times \lceil L_{\text{proj}}/L_{\text{ref}} \rceil$, with $L_{\text{proj}} = 50$ yr.

Table D.2: Ponte de Lima substation material inventory by category.

Category	Quantity	L_{ref} (yr)	Repl.	Eff. mass (t)	Share (%)
Concrete	16 500 t	63	0	16 500	88.7
Steel towers	460 t	63	0	460	2.5
Autotransformer	1 unit	35	1	690	3.7
Circuit breakers	18 units	20	2	405	2.2
Disconnectors	15 units	20	2	195	1.0
Insulators	4 464 units	20	2	182	1.0
Current transformers	18 units	35	1	48	0.3
Auxiliary transformers	3 units	35	1	3	< 0.1
Capacitive voltage trans.	3 units	35	1	4	< 0.1
Protection cabinets	56 units	20	2	44	0.2
Cables and wiring	various	30–40	1	51	0.3
Other equipment	various	10–40	1–4	10	0.1
Total				18 592	100

L_{ref} : reference service life from the EPD. Repl.: in-service replacements over the horizon. Effective mass: $m_i^{\text{eff}} = m_i \times \lceil L_{\text{proj}}/L_{\text{ref}} \rceil$, with $L_{\text{proj}} = 42$ yr. The surge arresters, the station battery, and the telecontrol units are included under *Other equipment*. The surge arresters are listed individually in Tables 5.6 and 5.7.

Appendix E Material Flow Diagrams

This appendix presents the material flow diagrams of the two case studies, referenced in Sections 5.2.3 and 5.3.3. They contrast the input and output flows under current procurement with those achievable under best-practice conditions, visualising the reduction in virgin input and un-recoverable waste.

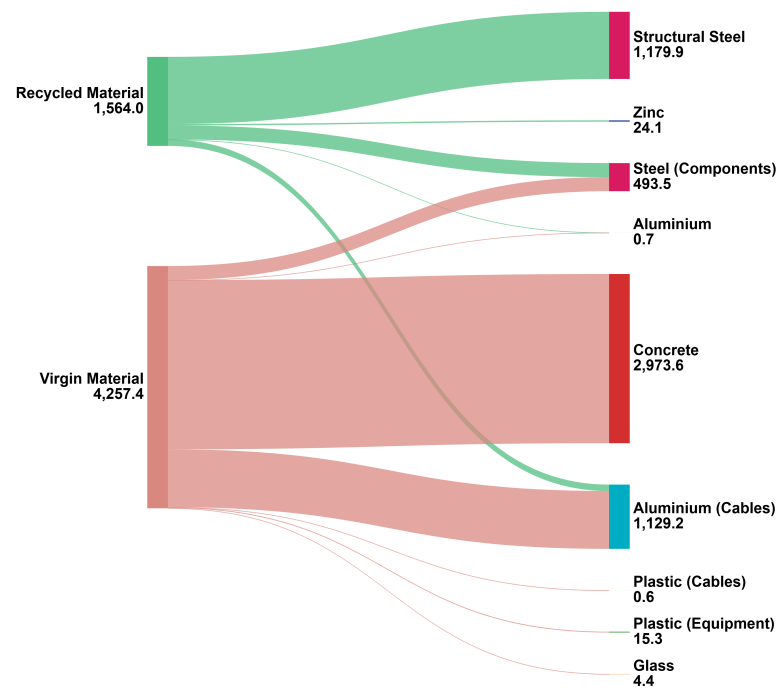


Figure E.1: Viana do Castelo - Vila Fria LMAT input flows, current procurement.

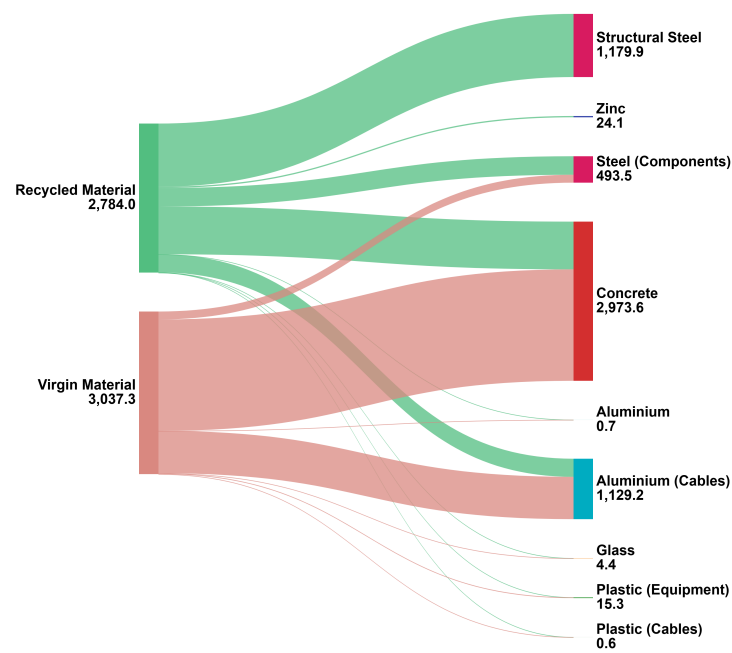


Figure E.2: Viana do Castelo - Vila Fria LMAT input flows, best practice.

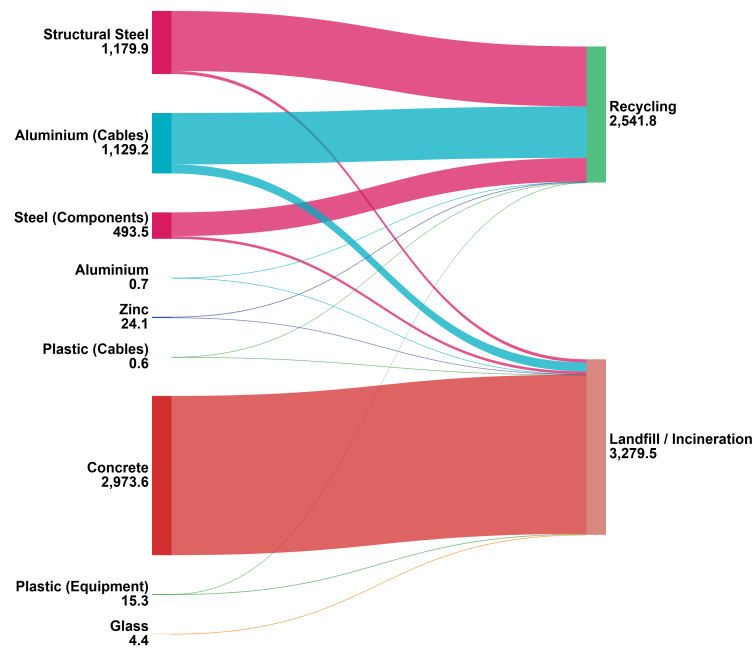


Figure E.3: Viana do Castelo - Vila Fria LMAT output flows, current procurement.

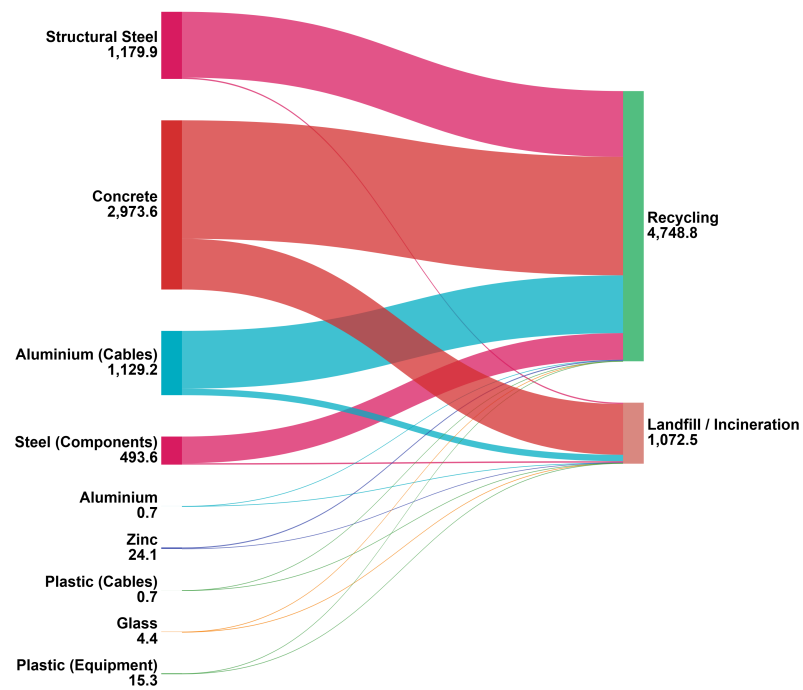


Figure E.4: Viana do Castelo - Vila Fria LMAT output flows, best practice.

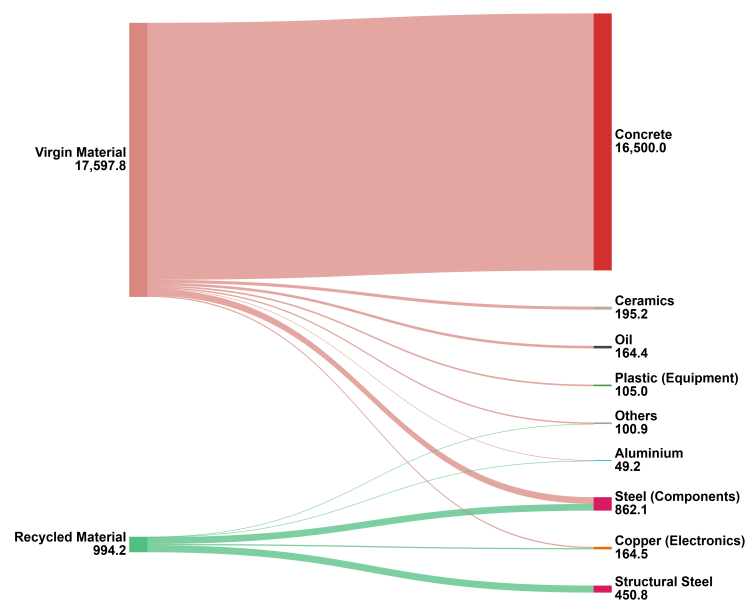


Figure E.5: Substation input flows, current procurement.

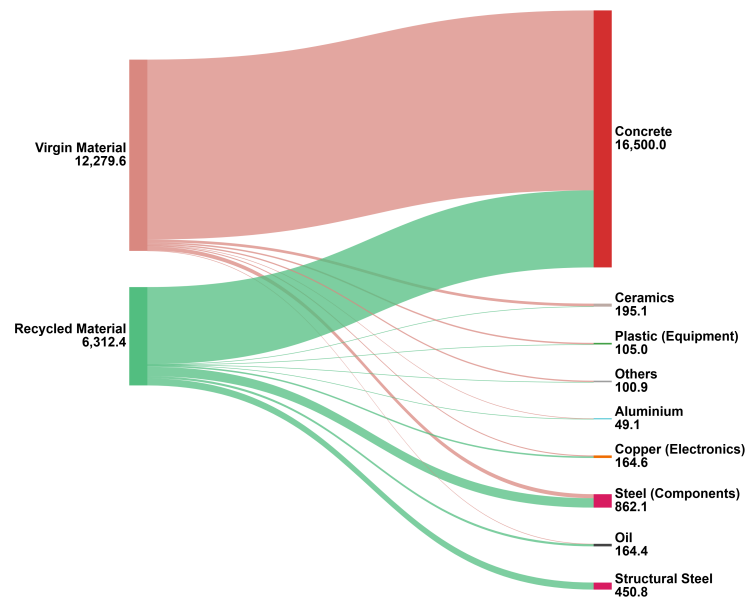


Figure E.6: Ponte de Lima Substation input flows, best practice.

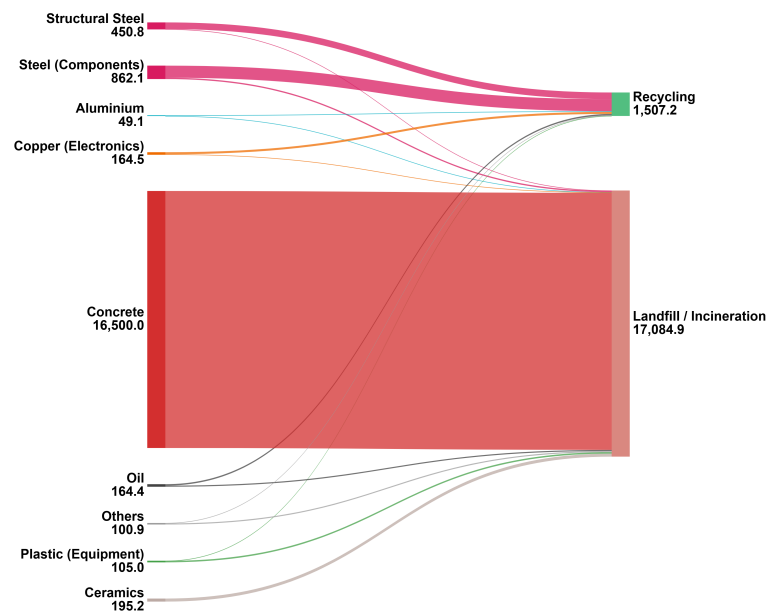


Figure E.7: Ponte de Lima Substation output flows, current procurement.

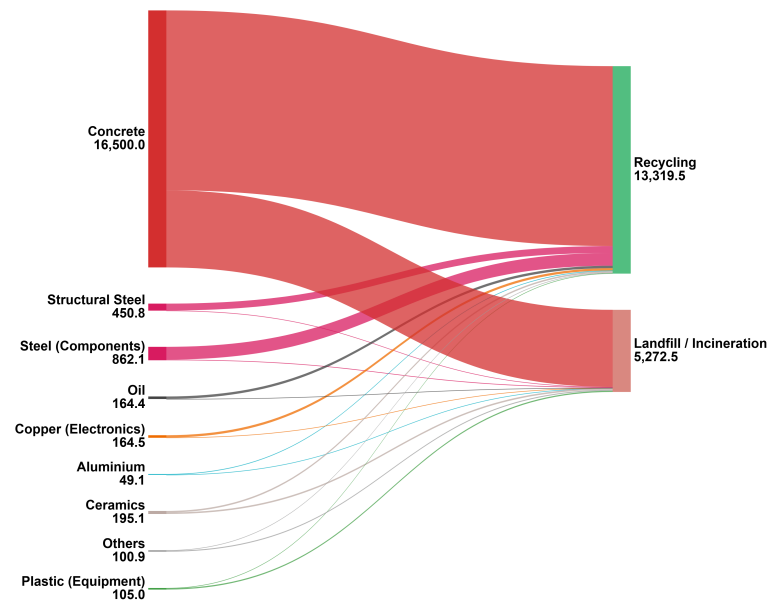


Figure E.8: Ponte de Lima Substation output flows, best practice.

Appendix F Sensitivity Analysis: Supporting Results

This appendix collects the supporting results of the variance-based sensitivity analysis of Section 5.6. It reports the first-order and total-effect Sobol indices, the amplitude-normalised ranking with the Spearman cross-check, the concrete interaction surfaces, and the Monte Carlo uncertainty bands of the two case studies.

Global Sensitivity Analysis (Sobol): LMAT Viana - Vila Fria 150kV

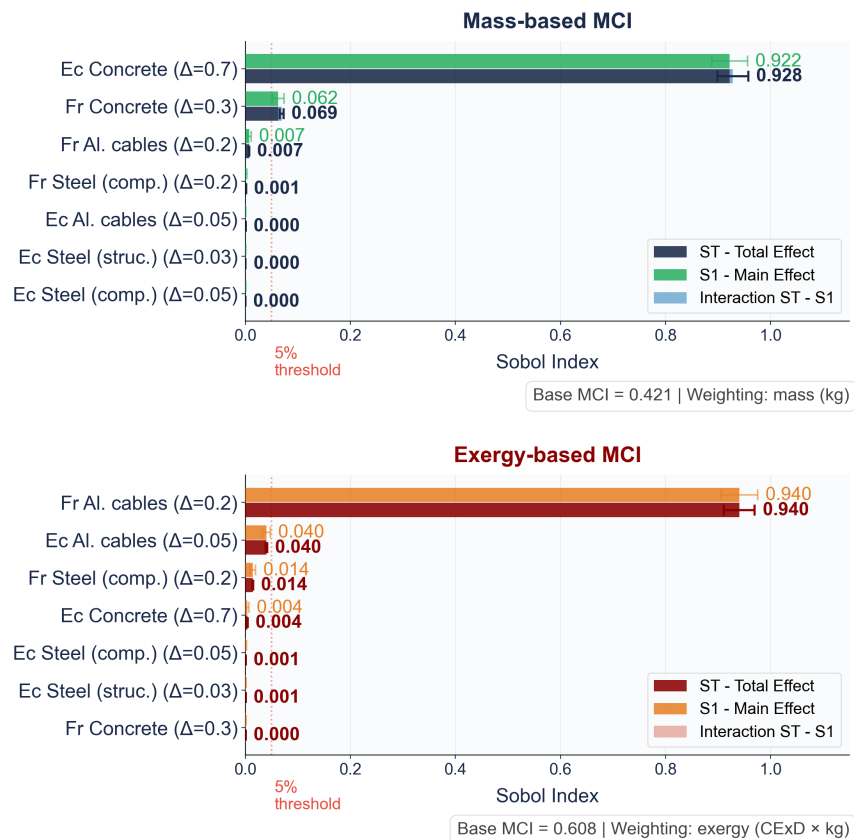


Figure F.1: Sobol indices, Viana do Castelo - Vila Fria LMAT line.

Global Sensitivity Analysis (Sobol): Ponte de Lima Substation

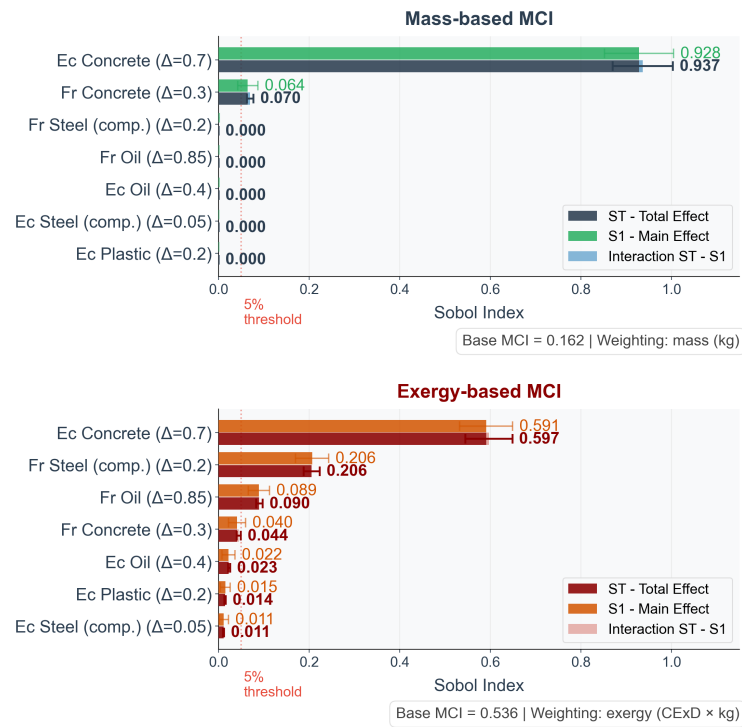


Figure F.2: Sobol indices, Ponte de Lima substation.

Amplitude-Normalised Sensitivity (ISAN): LMAT Viana - Vila Fria 150kV

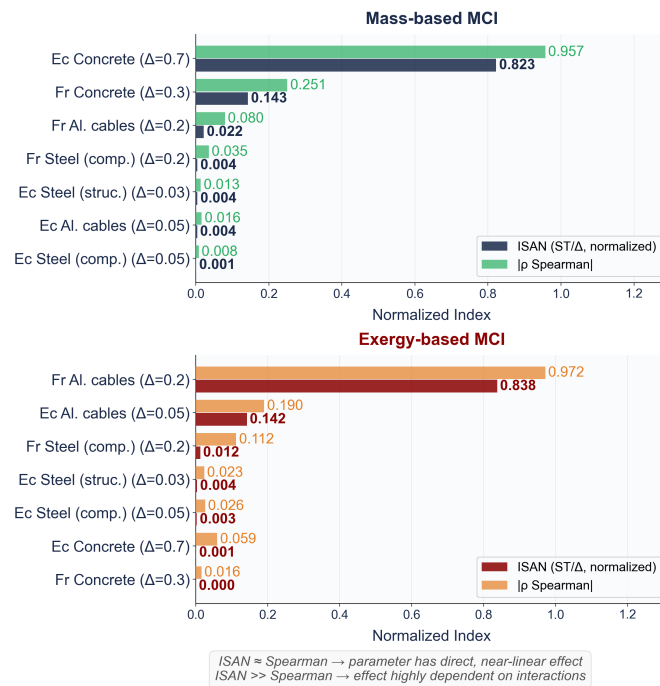


Figure F.3: ISAN ranking and Spearman correlation, Viana do Castelo - Vila Fria LMAT line.

Amplitude-Normalised Sensitivity (ISAN): Ponte de Lima Substation

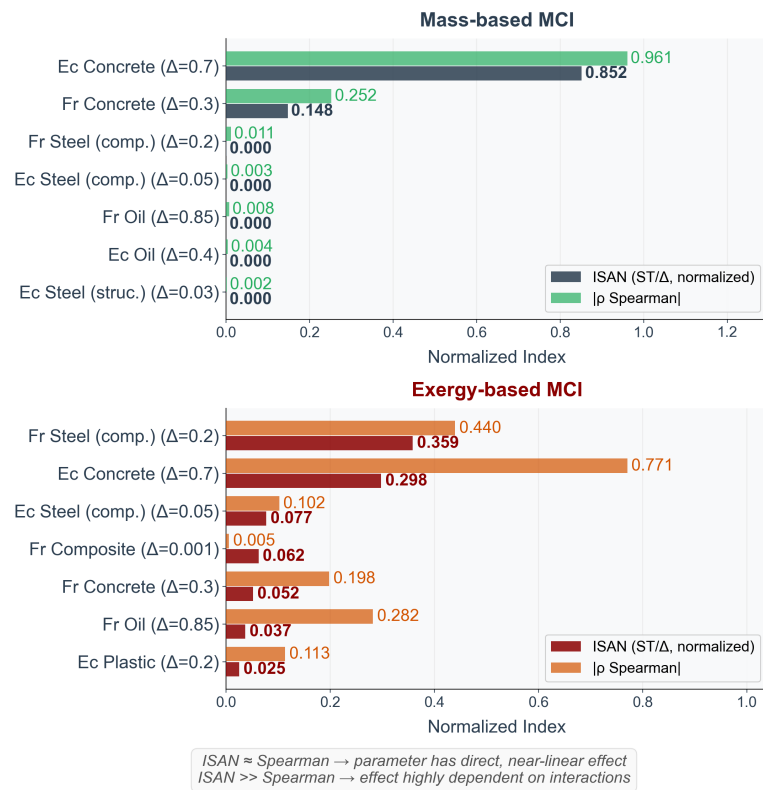
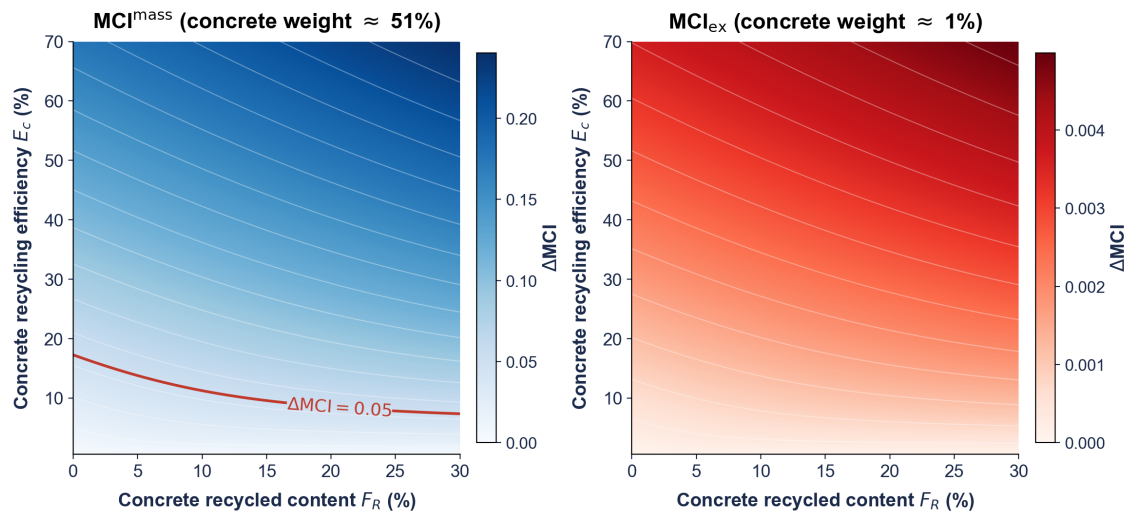


Figure F.4: ISAN ranking and Spearman correlation, Ponte de Lima substation.

Concrete F_R and E_c Interaction Surface: LMAT Viana-Vila Fria 150 kVFigure F.5: Concrete F_R and E_c interaction, Viana do Castelo - Vila Fria LMAT line.

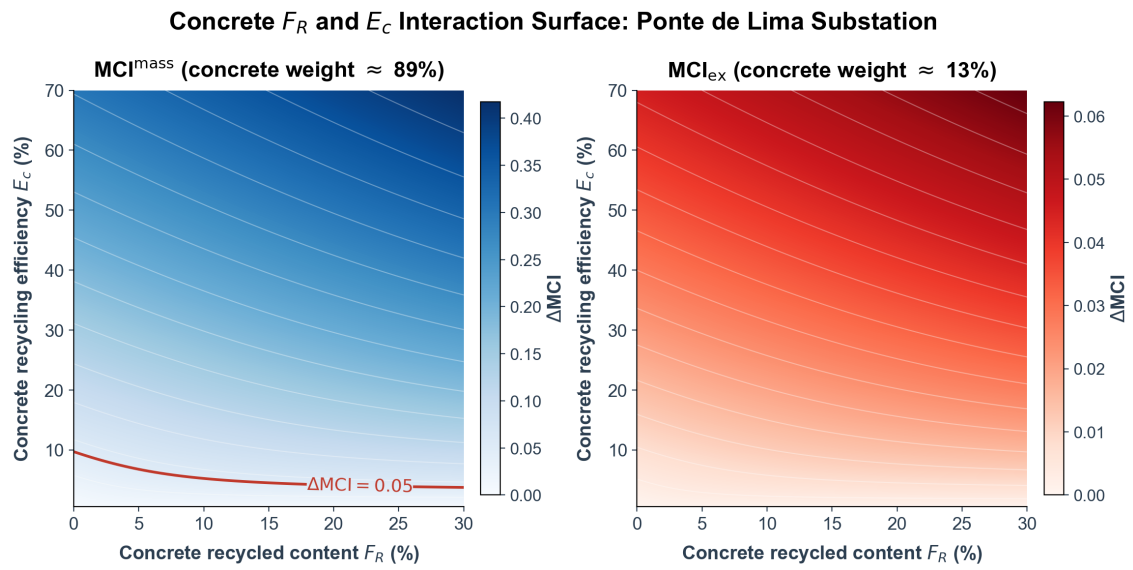
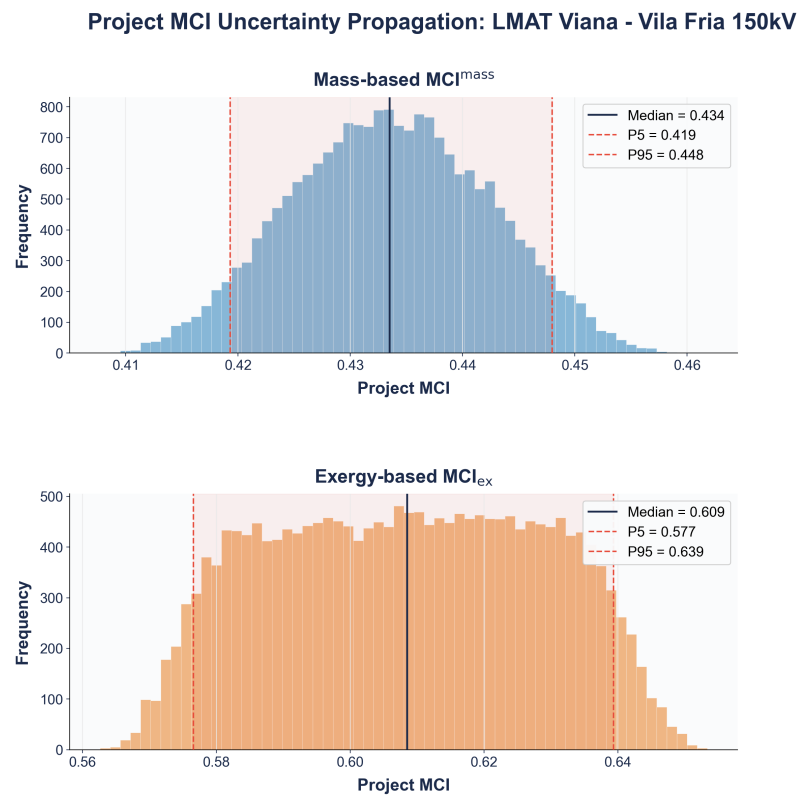
Figure F.6: Concrete F_R and E_C interaction, Ponte de Lima substation.

Figure F.7: Monte Carlo uncertainty band, Viana do Castelo - Vila Fria LMAT line.

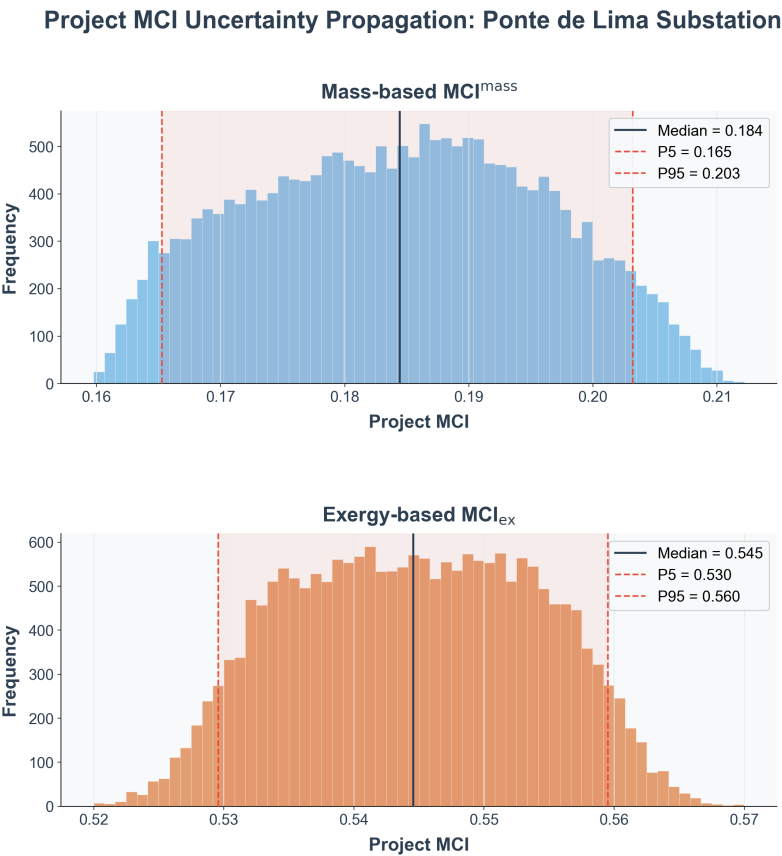


Figure F.8: Monte Carlo uncertainty band, Ponte de Lima substation.