UNIVERSITY OF BORÅS
SCHOOL OF ENGINEERING

Master Thesis Final Report

ME3+ Track 2

Prioritising Ecodesign Strategies for Product Sustainable Circularity Using AHP and LCA: a study case

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Master thesis

Subject Category: Technology

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Date:	29th of August, 2023
Keywords:	Product circularity; Life Cycle Assessment; Analytical Hierarchy Process (AHP); Circularity Indicator.

ABSTRACT

Addressing environmental burdens associated with the operation and infrastructure of the electrical transmission system products is imperative. Implementing Ecodesign practices in the early stages of product development and adopting circularity approaches throughout the product value chain is crucial to mitigate adverse impacts. However, transitioning from a traditional to a circular business model necessitates a well-defined strategic plan enabling organisations to assess their current situation and develop effective tactics. Nevertheless, trade-offs between circularity and sustainability must be carefully considered, as circular practices may not always align with the triple bottom line. Therefore, accurately prioritising circular strategies is essential for establishing a circular and sustainable product life cycle. This research evaluates business practices of Grid Solutions and proposes priority strategies, guidelines and KPIs to enhance product circularity. For this purpose, the Analytic Hierarchy Process (AHP), a Multi-Criteria Decision-Making (MCDM) methodology based on expert's judgment, is implemented. The prioritised strategies are analysed using an Importance vs Difficulty matrix to identify high-value and strategic actions. Simultaneously, product circularity indicators are evaluated and ranked based on the AHP outcomes. Subsequently, the most relevant indicator is assessed through Life Cycle Assessment (LCA) in the prioritised guidelines, through High Voltage (HV) equipment. Results highlight that minimising energy consumption is essential for improving product circularity, as LCA analysis confirms. The chosen circular indicator is tested by comparing an HV product version with lower energy losses to the product baseline, exhibiting a 51.45% increase in sustainable circularity and approximately 20% reduction in adverse environmental impacts. Additionally, prioritising efforts to minimise non-conformities, promote repairability, and enable upgrades are also of high relevance. Finally, the research provides recommendations for New Product Introduction (NPI) frameworks and sustainable reporting.

Keywords: Product circularity; Life Cycle Assessment; Analytical Hierarchy Process (AHP); Circularity Indicator.

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1 CONTEXTUALISATION

1.1 GE Grid Solutions

Part of General Electric Renewables, GE Grid Solutions focuses on bridging the gap between developing new sustainable technologies and solving the power system sector's challenges. Its site in Villeurbanne, France, is responsible for the R&D, production, and testing of High Voltage (HV) equipment for the electrical grid, such as transformers and circuit breakers. This master’s Thesis took place in the Ecodesign & Materials Centre of Excellence (EM CoE), certified by ISO 9001, 14001 and 18001, which organisation is shown in Figure 1.

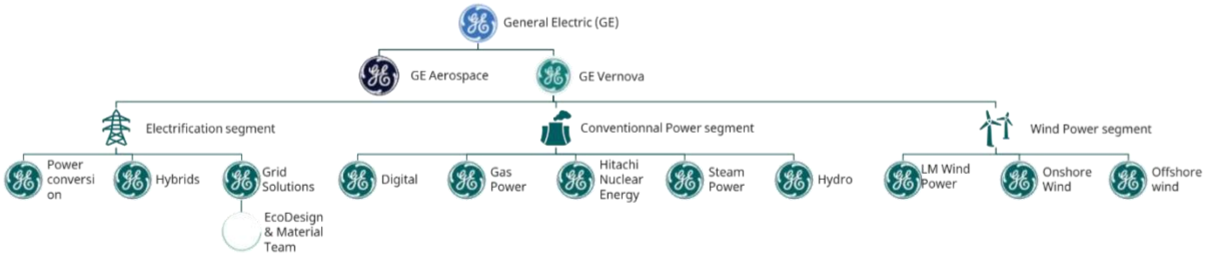

Figure 1: GE’s Organisation – focus on the EM CoE.

1.1.1 Materials and Ecodesign Centre of Excellence

EM CoE provides scientific-based studies and supports customers with material and design improvements alongside better environmental performance. Its main activities are listed below.

Table 1: EM CoE expertise.

Increasing Environmental Performance	**Analysing Corrosion & Metallic Materials**	**Supporting the Development of Insulation Materials**
1) Ecodesign a. Life Cycle Assessment (LCA) b. Regulation studies c. End-of-life manuals 2) Inspections and Homologations a. Materials characterisation b. Compatibility test c. Supplier and material homologation	1) Investigation a. Corroded and corrosive materials b. Moist heat cycling, salt fog tests c. Mechanical tests 2) Anti-corrosion a. Selection of anti-corrosion coating 3) Material selection a. Selection of the most suitable material class	1) Solid insulation a. Mechanical characterisation b. Ageing and lifetime studies 2) Liquid insulation a. Development of mineral and ester oils. b. Diagnostic techniques. c. Composite systems. 3) Gaseous insulation a. Development of better environmentally performing gas mixture. b. Gas analysis: new and aced SF$_6$ and g^3.

1.2 Developed Activities

The main developed activities during the internship were: (i) the thesis topic on selecting and evaluating circularity strategies using LCA and AHP methodology, (ii) the performance of an HV Equipment LCA, and (iii) participation in the publication of two scientific papers. Undertakings will be further presented in the sections below, where the (i) thesis topic will be further discussed and tested in (ii) the LCA of HV equipment.

2 INTRODUCTION AND JUSTIFICATIVE

The electrical transmission system is essential for transferring power from generation plants to load centres. This system is vital for powering the world and providing energy for industrial, commercial, and residential activities. However, as society strives for a sustainable future, addressing environmental burdens associated with this system's operation and infrastructure is necessary. In this regard, according to studies carried out by the EM CoE, three main challenges must be addressed: (i) the use of Sulphur Hexafluoride (SF_6), (ii) composites, chemical substances and critical raw materials used in manufacturing, and (iii) joule losses in the use phase.

SF_6 is widely implemented in electricity transmission and distribution systems due to its attributes that ensure a reliable grid. This technology has several benefits, including lower failure, reduced maintenance expenses, and safer and more stable operations over time (Nagarsheth and Singh, 2014; Xue et al., 2020). Additionally, SF_6 allows for better design and smaller equipment size, resulting in less land use. These advantages make it a highly preferred gas in the electrical sector, responsible for consuming 80% of the SF_6 produced worldwide (EPA, 2022).

Regulated by the Kyoto Protocol, this gas is 25200 times more effective at trapping infrared radiation than CO_2 over a 100-year period, having an atmospheric lifetime of 3200 years (IPCC, 2023). Thus, presenting substantial negative impacts if released into the atmosphere (Sovacool et al., 2021). SF_6 contributes up to 60% of a gas-insulated high-voltage equipment's CO_2 footprint, especially in the manufacturing and use phase (Treier et al., 2022). During the operation of this equipment, losses of SF_6 may occur due to malfunctioning or maintenance, with annual rate leakage from approximately < 0.1 to 0.5%, intensifying customers' Scope 1 GHG impact[1] due to increased fugitive emissions[2].

Moreover, many composite materials[3], possibly containing hazardous components, and Critical Raw Materials (CRM) are utilised in electrical grid equipment. The EU defines CRM as economically and strategically necessary materials with high supply risk and essential for products in areas such as renewable energy, digital, aerospace and defence technologies (European Commission, 2023). Aluminium, copper, and tungsten can be highlighted in the electric transmission and distribution sector. Regarding carbon footprint, aluminium is responsible for the biggest negative impact shares of most HV equipment manufacturing (Treier et al., 2022). In that regard, and considering the urge to limit climate change, grid operators have become more concerned about their environmental impact.

To help the industry decrease its negative effect on the environment, the EM CoE team developed an alternative fluorinated gas mixture for HV electrical transmission equipment called g[3]. Besides having fewer negative impacts on the environment than SF_6 (GWP[4] 99% lower), it provides several advantages, such as: allowing design with a reduced carbon footprint

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[1] Direct emissions from different sources owned or controlled by a company (GHG Protocol, 2019).

[2] Direct release of GHG compounds into the atmosphere (Horne, C., Medalla, R., Bacani, J).

[3] Combines two or more materials to create a final one that has better properties than each of the individual constituent materials (Hsissou et al., 2021).

[4] Global Warming Potential.

compared to other SF_6-free technologies and operating until -30ºC without gas liquefying risks. However, Life Cycle Assessment (LCA) studies carried out by GE show that SF_6-free GIS CO_2 emissions' most significant material impact occurs during the manufacturing phase and the most important LCA impacts take place in the equipment use phase due to energy and gas losses (Treier et al., 2022).

Therefore, potential measures to further mitigate adverse environmental impacts are possible. Treier et al. (2022) argue that these actions include but are not limited to the following priorities: (i) decreasing the carbon content of metals by changing its supply chain, (ii) reducing emissions from metal production and integrating recycled content into it, and (iii) replacing materials.

It is observable that measures to reduce the environmental burdens of electrical equipment are closely associated with (a) implementing Ecodesign[5] into the product's early stages of development and (b) through circularity approaches in the product value chain, transiting to circular equipment. However, significant changes such as transforming a traditional business model into a circular one demand an active strategic plan, enabling organisations to assess their current situation and develop and implement tactics. In addition, according to Saidani and Kim (2022), trade-offs between circularity and sustainability can occur as circular practices do not necessarily benefit the triple bottom line. Therefore, correctly prioritising and measuring the effectiveness of circular strategies (C-Strategies) to establish a sustainable product life cycle is essential for successfully increasing product sustainability.

Nonetheless, assessing the comprehensive impact of multiple existent circularity strategies on product operationalisation across various configurations continues to pose a significant challenge. This evaluation can be accomplished by prioritising strategies and analysing metrics and KPIs[6] to facilitate the measurement of their implementation and impacts toward product circularity. However, Shevchenko et al., (2022) mention that the debate on which metrics best measure circularity still needs to be clarified. As stated by Sassanelli et al., (2019), LCA is one of the most extensively used methodologies to assess products and processes' circular opportunities, identifying potential benefits or drawbacks of improving circularity.

Therefore, this study aims at prioritising C-Ecodesign strategies and guidelines for GE Grid Solutions to enhance its product sustainable circularity, evaluated through the Analytical Hierarchy Process (AHP), a Multi-Criteria Decision-Making (MCDM), and LCA. Additionally, circularity KPIs are assessed and presented by importance level to promote knowledgeable decision-making. A designated indicator is evaluated and tested through the LCA of one HV equipment, considering different circular scenarios. To finish, New Product Implementation (NPI) frameworks, indicators and processes for external reporting are suggested.

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[5] Integration of environmental aspects into product design and development to reducing adverse environmental impacts throughout a product's life cycle (ISO, 2020).

[6] Key Performance Indicators.

3 OBJECTIVE

To lead the electrical grid industry decarbonisation and satisfy costumer's needs, GE Grid Solutions is committed to implementing product stewardship and circularity goals into its product design, production process and supply chain. Therefore, this M.Sc. thesis aims to evaluate GE's business practices and propose priority strategies and metrics to enhance sustainable product circularity. The research provides insights and actionable recommendations to drive innovation and contribute to a more environmentally performant grid industry.

3.1 General Objectives

The overarching objective of this research is to comprehensively prioritise Circular Ecodesign (C-Ecodesign) strategies and guideline at product level and evaluate the priorities' effectiveness using Life Cycle Assessment (LCA) and circularity indicator as a tool. To achieve this objective, the Analytic Hierarchy Process (AHP), a well-established Multi-Criteria Decision-Making (MCDM) methodology, is employed considering Ecodesign expert's judgment. The ranked guidelines are further analysed in an Importance vs Difficulty matrix to select high-value and strategic actions.

In parallel, identified product circularity indicators are evaluated through the prioritised guidelines and ranked accordingly. Subsequently, the most relevant indicator is tested using LCA in strategic and high-value scenarios, specifically focusing on one of GE's High Voltage (HV) equipment. Finally, the best-case prioritised scenario to enhance products' sustainable circularity is scrutinised, and recommendations for New Product Introduction (NPI) frameworks and improvements in sustainable reporting are presented.

3.2 Specific Objectives

This thesis' specific goals are:

1. Perform a literature review on strategies and respective guideline for implementing product circular ecodesign and rank them using AHP methodology from a business perspective, considering the Sustainability Balanced Scorecard (SBSC).
2. Collect data on circularity indicators at the micro level (product level) from published sources and group them according to their respective measured circularity strategy, defined in point (1).
3. Develop a "circularity strategy ranking matrix" according to the prioritised strategies and guideline, which will serve as a comprehensive decision-making tool according to the Difficulty vs Importance of putting them into practice and monitoring.
4. Test strategic and high-value guideline through an HV equipment Life Cycle and selected indicators to analyse circularity opportunity scenarios and possible sustainability trade-offs.
5. Analyse the best-case scenarios for improving products' sustainable circularity.
6. Suggest New Product Introduction (NPI) and Company report improvement frameworks toward more sustainable and circular products.

4 LITERATURE REVIEW

For several decades, the prevailing economic model has been the take-make-use-dispose approach, which has led to a surge in natural resource consumption and hindered the optimisation of production processes. This model involves extracting finite natural reserves to create goods often underutilised and discarded as waste. A recent report by the The World Bank (2022) indicates that the materials mobilised from 2000 to 2015 were more significant than half of those extracted between 1900 and 2000. As illustrated in Figure 2, this alarming trend is projected to persist, causing significant environmental damage and irreversible harm.

Although Earth still possesses an abundance of materials, the scarcity and high supply risk of specific critical resources, such as aluminium, copper, and tungsten, have become apparent (European Commission, 2023). Moreover, the European Commission (2020b) highlights that more than 90% of biodiversity loss and water stress come from resource extraction and processing. In addition, these processes are responsible for half of the total GHG emissions. However, the most pressing concerns stem from the adverse environmental impacts of material extraction, processing, manufacturing, utilisation, and disposal (The World Bank, 2022). Raw material extraction and processing, being energy-intensive activities, can lead to ecosystem disruption and the pollution of water, air, and soil (OECD, 2023; Roche et al., 2023).

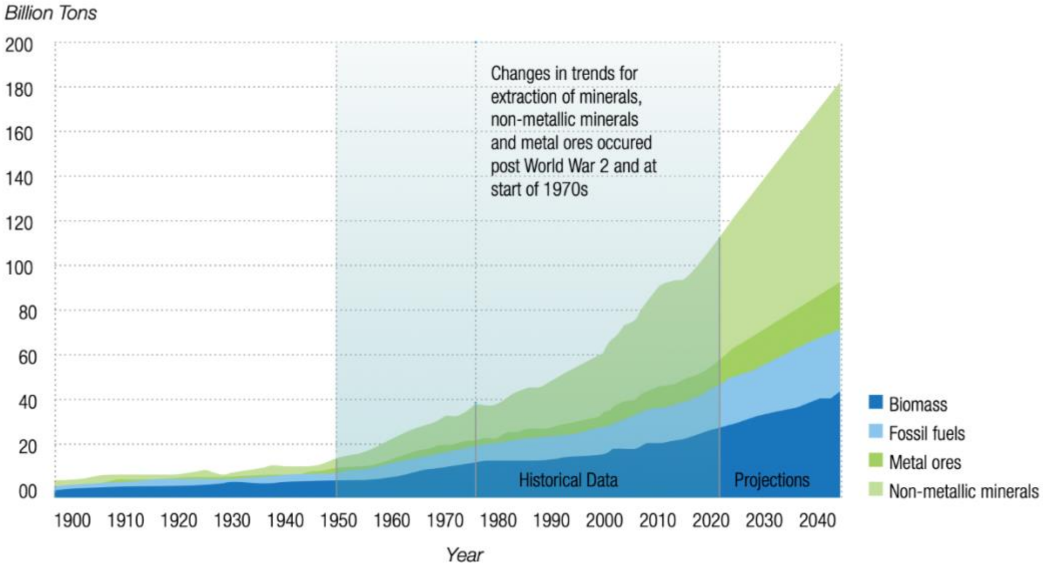


Figure 2: Historical and projected global material extraction by resource.
Source: The World Bank (2022) apud The European Commission (EC) Joint Research Centre (JRC) data.

4.1 Circular Economy (CE) Concept

In response to the escalating consumption of natural resources and the need for a fundamental reorganisation of production processes and global trade, the Circular Economy (CE) concept has emerged. Disrupting linear development arrangements, CE seeks to integrate economic and environmental interests to foster sustainable growth through a holistic approach (Fitch-Roy et al., 2020). Although the definition of CE has been subject to extensive scrutiny by experts, a need for more consensus on terminologies and definitions persists among scholars, policymakers, and practitioners (Homrich et al., 2018). To address this issue, Kirchherr et al.,

(2017) conducted a comprehensive review of 114 reports on the circular economy, suggesting a consolidated and unified definition, which is adopted in the present study, focusing on the micro level:

> “an economic system that replaces the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations” (Kirchherr et al., 2017).

The global consensus emphasises the importance of preserving the existing environmental balance to ensure fairness for future generations and to promote the well-being and dignity of humanity in the present time. Consequently, specific physical and environmental limitations are recognised, which must be adhered to to establish a sustainable CE (Desing et al., 2020).

Mantalovas and Di Mino (2020) argue that the CE can be viewed as a pathway to economic growth that aligns with the principles of sustainable development. This economic approach offers numerous benefits, extending beyond environmental advantages to economic advantages. By embracing CE principles, businesses can enhance their competitiveness, optimise energy and material usage, and unlock new revenue streams by repurposing or selling materials that would otherwise be discarded as waste. Additionally, the authors state that circular practices can mitigate environmental penalties and foster improved stakeholder relationships. By reducing material costs and projecting a positive corporate image, businesses can establish stronger connections with stakeholders.

The term “circular” in the context of the Circular Economy (CE) concept refers to the cyclical flow of nutrients, energy, and matter within a system. For instance, Morseletto (2023) defines CE as “an economic framework aimed at the conscious efficient use of products and resources through their reuse, reduction and recirculation, long-term value retention, and closing loops in production/consumption”. Moreover, in this model, economic activities shall maximise ecosystem functions and well-being (Murray et al., 2017).

At the core of the circular economy theory is the concept of cradle-to-cradle, which emphasises the continuous use of materials within the system through multiple cycles while ensuring the separation of biological and technical materials (Kirchherr et al., 2017). As illustrated by the Ellen Macarthur Foundation in Figure 3, this approach aims to achieve efficiency by enabling materials to be reused and recycled in a closed-loop system. Thus, it can be concluded that CE aims to increase resource efficiency by reducing waste and utilising renewable resources. This means minimising the use of limited natural resources such as energy, materials, and water while enhancing economic activity and avoiding extracting new raw materials. Furthermore, the goal is to maximise the value of materials while minimising any adverse environmental effects (Brändström and Saidani, 2022).

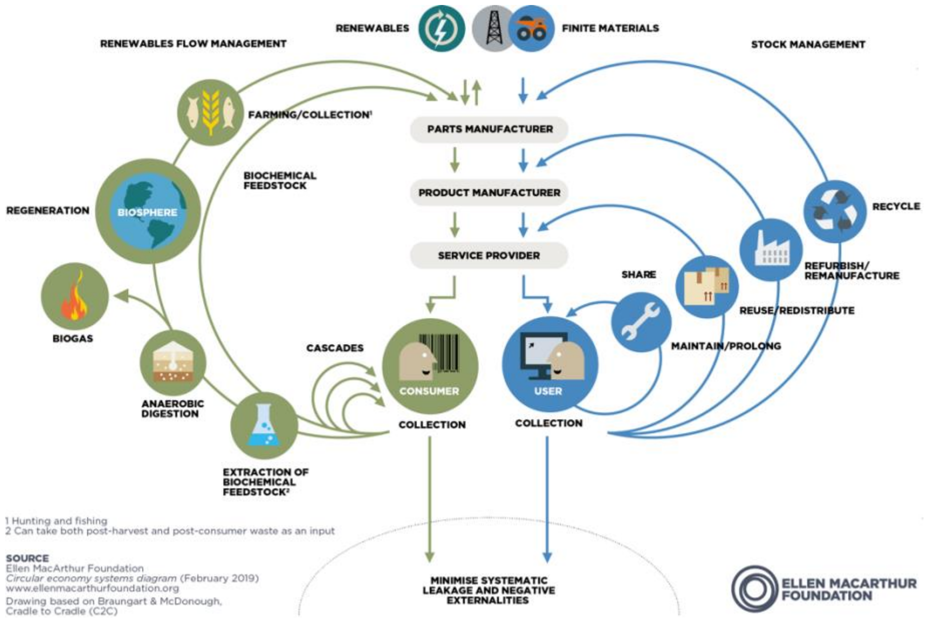


Figure 3: Circular Economy Butterfly diagram.
Source: EMF, 2019.

In the technical cycle (Figure 3 – right side), products and materials are circulated through, among others, reuse, refurbishment, and recycling. Meanwhile, nutrients return to the Earth to regenerate nature and ecosystems in the biological cycle (Figure 3 – left side). This division is critical to differentiate materials treatment. This study focuses on the technical micro-level product cycle, where various essential factors, such as the rising demand for raw materials, countries' interdependence, population growth, energy demand, and material scarcity, drive materials’ circularity.

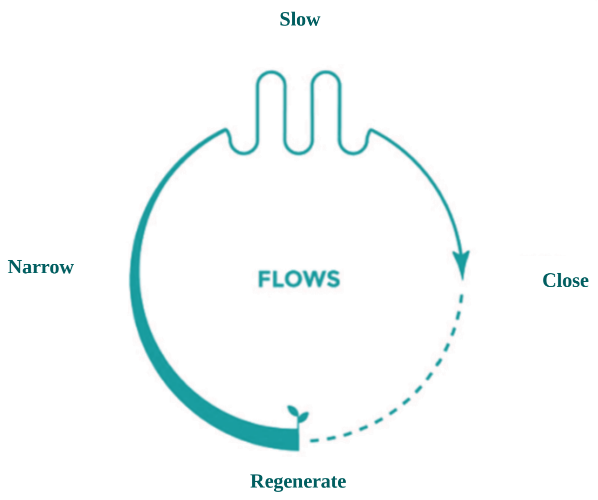
Several initiatives can be implemented across various business processes to improve products’ circular flow within a corporation. However, Watz and Hallstedt (2022) state that one area holding significant potential for improving the overall performance of a manufacturing company is the Product Development Process (PDP). A product's sustainability performance is primarily determined during the early stages of product development. Implementing proper requirements and considerations at PDP can prevent sustainability trade-offs.

To achieve better environmental performance and circularity within a production system, three vital interconnected practices should be emphasised (Kusumo et al., 2022): (i) pollution avoidance, (ii) reduction of hazardous material use, and (iii) Ecodesign. Among these practices, Ecodesign plays a crucial role as a precursor to achieving product circularity. In the Ecodesign stage, a product's relative sustainability is primarily defined, and the decisions made at this stage have implications for all subsequent stages of the product's life cycle (Van Doorsselaer, 2022).

4.2 Achieving Product Circularity through Ecodesign

Based on principles of Life Cycle Thinking, Ecodesign is defined by the international standard EN ISO 14006:2020 as including environmental considerations in a product’s design and development. It aims to balance ecological and economic requirements and ensures that environmental aspects are considered at all product lifecycle stages. The goal is to create circular products with minimal adverse environmental impacts. Ecodesign recognises that the potential for repair, upgrade, and remanufacturing of a product and improving material recyclability begins during the design phase. Consequently, incorporating Ecodesign guidelines and tools supports decision-making by designers throughout the PDP (Van Doorsselaer, 2022).

To effectively implement C-Ecodesign, businesses must focus on closing, slowing, and narrowing loops (Konietzko et al., 2020). Closing loops involve the reuse of products, components, and materials. For instance, within a manufacturing process system, the energy, waste, and heat generated in one step can be utilised in another stage of the same process (upcycling) or the production of another product (downcycling). Slowing loops refer to prolonging the use of products and components. Narrowing loops reduces the material and energy required throughout a product's lifecycle (Konietzko et al., 2020). These three core Ecodesign concepts for achieving circularity are illustrated in Figure 4.



Slowing/design for longer use: easy reparability, upgrading, disassembling.

Closing/using again: design for disassembly, recyclable, easy to identify

Narrowing/resource efficient: less weight, eco-efficiency, simpler bill of materials (BoM)

Figure 4: Narrow, slow, close, and regenerate material and energy flows.
Source: Based on Konietzko et al., (2020) and Weetman (2021).

While Ecodesign applications offer numerous advantages, manufacturing companies often encounter barriers when attempting to implement them (Rodrigues et al., 2017). Brambila-Macias and Sakao (2021) argue that companies must effectively transform their design practices to achieve Ecodesign goals. However, designing considering environmental issues is just one of the numerous requirements designers must comply with. For instance, the authors mention that factors such as reducing time to market, ensuring safety, managing costs, and maintaining quality also play significant roles.

As a result, organisations require guideline, as outlined in ISO 14006:2020, to develop and implement Ecodesign approaches that improve the environmental performance of their products. Pigosso et al., (2013) emphasise that this approach should be integrated into management processes and deliver tangible and lasting benefits. Achieving a certain level of Ecodesign maturity requires companies to follow a series of steps and continuously strive for improvement.

4.2.1 Ecodesign Maturity Level

Pigosso et al., (2013) developed and tested an Ecodesign maturity model to help companies implement sustainable practices through research. The proposed model is divided into three main elements:

i) Ecodesign practices: comprises activities aiming at integrating environmental issues into product development and its respective processes.

ii) Ecodesign maturity level: comprises the stages for incorporating environmental concerns into product development.

iii) Application method: continuous improvement to support Ecodesign implementation.

By assessing their maturity level in these three elements, companies can identify areas for improvement and develop a roadmap for advancing their Ecodesign practices. The model provides a structured approach for companies to enhance their sustainability performance by integrating Ecodesign principles.

On this basis, Ecodesign practices can be categorised into two main groups (Pigosso et al., 2013): (i) management practices and (ii) operational practices. Management practices focus on product development management and encompass strategies, policies, and decision-making processes that facilitate the integration of environmental considerations. Conversely, operational practices concern the technical aspects of product design, including design specifications and requirements.

Operational practices represent the primary responsibility of the EM CoE (Ecodesign & Materials Laboratory) and involve applying technical tools, techniques, and methodologies to incorporate environmental considerations into the product design process. By emphasising operational practices, the study aims to delve into the specific actions and approaches taken by the EM CoE to facilitate sustainable and environmentally conscious product design. This focus will enable a deeper understanding of the technical aspects and challenges associated with implementing Ecodesign principles in the context of EM CoE's responsibilities.

4.2.1.1 Ecodesign Strategies

In their review of operational practices, Pigosso et al., (2013) identified and grouped more than 480 design options into six strategies that address major environmental concerns during the Product Development Process (PDP). These strategies are as follows:

(1) Minimise energy consumption.
(2) Minimise material consumption.
(3) Extend the material life span.
(4) Optimise product lifetime.
(5) Select low-impact resources and processes.
(6) Facilitate disassembly.

It is essential to highlight that each strategy can comprise multiple guidelines. For instance, strategy (2) contemplates, among others, reducing material contained in a product, minimising waste, and avoiding/minimising packaging (Pigosso et al., 2013).

Stefanakis and Nikolaou (2022) mention that Ecodesign considers the totality of relevant effects of a product during its life cycle. However, it does not explicitly aim at circularity. Hence, the selection of operational strategies must consider the potential negative and positive environmental impact throughout the product's life cycle. In this regard, Geissdoerfer et al., (2017) concluded that three relationships between circularity and sustainability are possible: (a) CE being a condition for sustainability, (b) CE and sustainability in a mutually beneficial relationship and (c) a trade-off relationship. While circularity is one of the critical factors for achieving sustainable systems, the last relationship shall be carefully analysed by decision-makers.

4.2.2 Circularity and Sustainability Trade-offs

Integrating sustainability frameworks and adopting practices that promote material preservation within a circular economy can help companies reduce their negative environmental impacts. By implementing broader strategies that reduce waste and emissions, companies can make significant strides towards sustainability (Brändström and Saidani, 2022). However, it is vital to recognise that improving one aspect of a product's design or lifecycle may have unintended consequences or even lead to increased negative environmental impacts in other areas.

The implementation of operational practices is influenced by several factors, notably the product's characteristics in terms of its life cycle and impact. Additionally, customised design options according to the product under development may occur, which can be connected to Ecodesign methods and tools (Rodrigues et al., 2017). Hence, circularity should be perceived as a roadmap to achieve sustainability, where circularity-focused practices and synergies can contribute to implementing multiple sustainability goals (Schroeder et al., 2019).

To assess the tradeoffs and impacts of implementing circular strategies, conducting Life Cycle Assessment (LCA) studies is essential for evaluating products' environmental footprint and their overall sustainability. LCA provides a comprehensive evaluation of a product's environmental impacts throughout its entire lifecycle, allowing for informed decision-making and identifying areas where further improvements can be made (Brändström and Saidani, 2022). By integrating sustainability considerations, utilising circularity-targeted practices, and leveraging tools such as LCA, companies can make informed decisions and work towards achieving sustainability goals while minimising their product’s negative environmental impacts.

4.2.2.1 LCA as a Tool to Achieve Sustainably and Circular Ecodesign

The LCA methodology commonly assesses effects on the overall environmental sustainability of products, projects, and systems. LCA provides a systematic framework for quantitatively evaluating environmental impacts associated with the inputs and outputs of matter and energy (Larsen et al., 2022). By assessing resource inputs and outputs, waste generation, and emissions throughout a product or process life cycle, from raw material extraction to its end of life, LCA allows for evaluating resource efficiency in a product or system. Hence, the effectiveness of circular strategies can be assessed, and their influence on reducing negative environmental impacts can be estimated, helping companies to increase their environmental performance in an economically viable way.

LCA has been internationally standardised over time. For instance, EN ISO 14040 presents principles and frameworks for LCA, and EN ISO 14044 normalises requirements and guidelines. Hence, this methodology allows comparability between products and services when considering the proper system boundaries and dataset. Furthermore, it is a valuable tool for capturing trade-offs that may arise when implementing circularity in different life cycle stages. It allows for analysing the drawbacks and benefits associated with circularity strategies and supports decision-making in this area (Brändström and Saidani, 2022; Mantalovas and Di Mino, 2020).

4.3 Implementing Circular Product Strategies into Businesses

In section 4.2.2, it was discussed that setting circularity to increase could result in sustainability trade-offs. To navigate this challenge, companies must make informed managerial decisions that consider the unique characteristics of their products. This process involves utilising technical tools such as LCA and Ecodesign strategies while analysing several management criteria.

To enhance the understanding of organisational performance and facilitate decision-making, the Balanced Scorecard (BSC) is a valuable tool (Figure 5). The BSC provides a framework for assessing and managing performance across multiple dimensions, including financial, customer, internal process, and learning and growth perspectives. By adopting this instrument, companies can ensure that their decisions and actions align with their broader strategic objectives.

The BSC was developed to give managers control and insights into organisational performance. Besides incorporating financial metrics, it also contemplates performance indicators from three other perspectives: (1) customers, (2) business processes, and (3) learning and growth (Tawse and Tabesh, 2023). Nevertheless, Agarwal et al., (2022) state that this instrument overlooks sustainability aspects in performance evaluation. Hence, the authors propose a Sustainability Balanced Scorecard (SBSC), adding a social and environmental perspective to the BSC.

Thus, SBCS can be applied to assess the organisation's performance while considering its products' environmental and sustainability aspects. This holistic approach enables organisations to balance short-term financial goals with long-term sustainability objectives, fostering a more comprehensive and responsible approach to business management.

It is vital to set a reliable and measurable series of indicators to evaluate the effectiveness of circular actions and their progress. Thus, developing circularity metrics (C-metrics) for assessing product circularity performance is needed (Brändström and Saidani, 2022; Shevchenko et al., 2022). However, metrics are not standard, and indicators are still fragmented, thus, lacking investigation on what they aim to measure and their applicability. Hence, structured information is fundamental for supporting decision-making and improving circular business investments (Saidani et al., 2019).

Figure 5: Balanced Scorecard (BSC) example.
Source: Conway (n.d.)

In this sense, Rodrigues et al., (2017) argue that companies may lack the information, confidence, and capacity to move towards circular solutions due to:

a) a lack of indicators and targets,

b) awareness of alternative circular options and economic benefits, and

c) the existence of skills gaps in the workforce and lack of CE programmes at all levels of education (e.g. in design, engineering, and business schools).

According to the authors, to overcome these obstacles and move towards a more formalised and successful Ecodesign approach, companies must define and implement process-oriented indicators to track their performance and continuously improve towards higher maturity levels in Ecodesign. Additionally, multiple criteria analysis shall be carried out, considering a business's several perspectives to create substantial added value to the triple bottom line (Saidani et al., 2019).

4.4 Application of MCDM in Prioritizing Circular Strategies

Determining the best product C-Ecodesign strategies can be challenging, as it requires analysing multiple metrics through a complex Multi-Criteria Decision-Making (MCDM). MCDM, also known as Multi-Attribute Decision Making (MAD), is commonly used to weigh strategies and indicators due to its simplicity and ease of use (Alejandrino et al., 2021). However, after reviewing many cases, it has been found that the Analytic Hierarchy Process (AHP) is one of the most used MCDM methods in this area.

4.4.1 Analytical Hierarchy Process (AHP)

Initially developed by Saaty (1980), AHP is a mathematically based process combining multiple criteria and experts' opinions. Used to derive priorities based on a set of pairwise comparisons, this methodology is built on an individual’s ability to structure perceptions and ideas in a hierarchy comparison, judging the intensity and importance of one criterion over the other. Finally, AHP allows the synthesis of all judgements to obtain the overall priority of chosen elements (Forman and Peniwati, 1998). DeWaters and Powers (2013) state that this technique is a systematic approach that helps to organise and analyse numerous complex criteria. It enables the ranking of sustainability indicators and the creation of a weighting system based on chosen criteria.

In the book "Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World, " Saaty (1990) states that AHP is based on expert's paired comparison judgement. Hence, decision-makers' experience and judgement are the basis for prioritisation. In this method, a raking analysis is carried out through a hierarchical structure, where measuring intangibles is a crucial factor. This makes this methodology well-suited for a wide variety of decision-making areas. Additionally, AHP allows analysing the consistency of expert's judgements. As a result, a comprehensive decision-making tool is presented (Curiel-Esparza et al., 2016).

Table 2: Sustainability/Environmentally oriented case studies where AHP was utilised.

Author	Title	Source	Findings
Ibáñez-Forés et al., (2023)	Prioritising organizational circular economy strategies by applying the partial order set theory: Tool and case study.	Journal of Cleaner Production.	Through literature review it was concluded that the most common method for prioritizing CE strategies is MCDM such as AHP.
Amoushahi et al., (2022)	Localizing sustainable urban development (SUD): Application of an FDM-AHP approach for prioritizing urban sustainability indicators in Iran provinces	Sustainable Cities and Society	Selected indicators were prioritized using AHP based on two scenarios.
Ilham et al., (2022)	Analysing dimensions and indicators to design energy education framework in Malaysia using the analytic hierarchy process (AHP)	Energy Reports	AHP was used to evaluate frameworks criteria selection, alternative indicators and priorities.
Iaria and Susca, (2022)	Analytic Hierarchy Processes (AHP) evaluation of green roof- and green wall- based UHI mitigation strategies via ENVI-met simulations	Urban Climate	AHP was used to investigate UHI-mitigation potential of green roofs and green walls.
Berliana et al., (2020)	KPI Selection Using The AHP Method on SOE X	International Conference on Business and Engineering Management	Weighted KPIs using AHP method is conducted by selecting performance indicators based on five perspectives (Financial and Market, Customer Focus, Product and Process Effectiveness, W orkforce Focus and Leadership, Governance, and Social Responsibility).
Zhou et al., (2019)	Model development of sustainability assessment from a life cycle perspective: A case study on waste management systems in China.	Journal of Cleaner Production.	AHP was implemented to rank alternatives to achieve a sustainable municipal solid waste management system.
Solangi et al., (2019)	Evaluating the strategies for sustainable energy planning in Pakistan: An integrated SWOT-AHP and Fuzzy-TOPSIS approach	Journal of Cleaner Production	Integrated SWOT, AHP and Fuzzy TOPSIS approach proposed as planning framework. Prioritize strategies for the sustainable energy planning and development proposed.
Balsara et al., (2019)	An integrated approach using AHP and DEMATEL for evaluating climate change mitigation strategies of the Indian cement manufacturing industry	Environmental Pollution	Climate change mitigations strategies for the cement industry are identified and prioritized using a hybrid methodology of AHP and DEMATEL .
Zhang (2016)	Study on the Development Evaluation of Circular Economy in Tianjin City Based on AHP Method.	ICEME and EBM congress.	AHP was used to combine the actual CE development and build an evaluation index system to allow an evaluation on the future development of CE in Tianjin area (China).

According to Saaty's research conducted in 1987, AHP emphasises the importance of consistent and accurate data and the relationships between different criteria. AHP is helpful in decision-making and resource allocation planning. Additionally, the method allows for both deductive and inductive thinking, considering multiple factors without relying solely on syllogism[7]. Finally, numerical tradeoffs are done to conclude.

Widely implemented in research concerning sustainability, social, and environmental issues, AHP is preferred over other MCDM methods since it allows for breaking problems into hierarchical parts (Saaty, 1987). Table 2 presents studies where AHP was implemented in sustainability matters.

Three principles drive AHP implementation: decomposition, comparative judgement, and synthesis of priorities. The upcoming sections will demonstrate the AHP measurement method, as Saaty (1987) explained in his scientific article "The Analytic Hierarchy Process - What it is and How it is Used”.

4.4.1.1 1st Principle: Decomposition

A hierarchy shall be established to address a societal problem using AHP, starting from the overall objective down to criteria and subcriteria, which are further divisions of criteria. Finally, the alternatives from which the choices are to be made are presented in the last level. Saaty (1987) states that the hierarchy shall concisely present the situation to capture changes. A hierarchical example is shown in Figure 6.

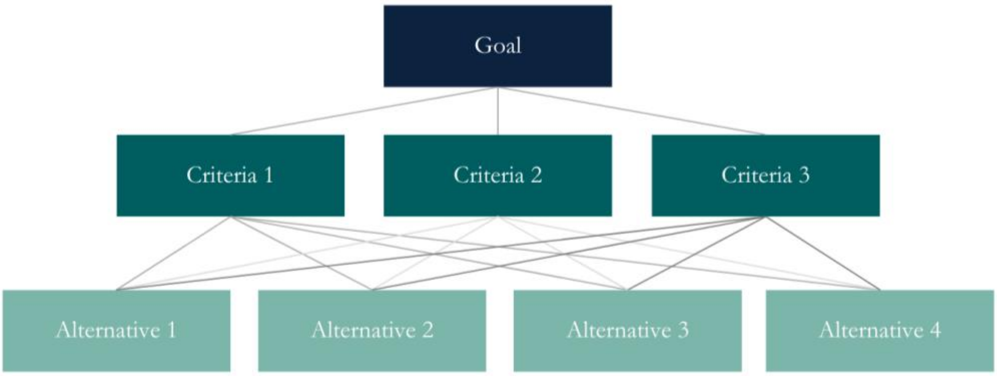


Figure 6: General AHP hierarchical model.

Thus, the problem analysis is decomposed into a hierarchy of criteria, which can be compared independently. Sub-criteria can be further added down after the criteria level. Once a logical order is constructed, decision-makers can assess alternatives through pairwise comparison.

4.4.1.2 2nd Principle: Comparative Judgment

Pairwise comparison is a vital step for successfully applying the AHP methodology. This evaluation is carried out either by concrete data or human judgement. Hence, through the human being intrinsic ability to structure his perceptions and ideas, judgements can be synthesised and

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Four logic processes in which two general statements lead to a more particular statement (Cambridge Dictionary, 2023).

a priority of elements obtained (Forman and Peniwati, 1998). In this step, the experts' groups judge the main criteria in pairs to establish priorities by their relative importance. A pairwise comparison matrix is then generated. Finally, the criteria level of importance is judged using a fundamental scale presented in Table 3.

If two activities contribute equally to the objective, the importance scale will be 1. This occurs when analysing a criterion over itself. In Equation (1), presented on next page, reciprocals are used if activity *i* was assigned one of the intensity numbers when compared to activity *j*. Hence, *j* would receive the reciprocal value when compared to *i*.

After comparing the main criteria, experts shall compare the alternatives belonging to each of the main criteria. Three or more pairwise comparisons for level 3 (Alternatives) shall be carried out in this regard. The last step is to weigh the results to get the alternatives' synthesised priorities.

Table 3: Saaty's scale of relative importance (Saaty, 2005).

Scale	**Intensity Importance**	**Reciprocal (1/a_{ij})** (Alternative i from j)
Extremely preferred	9	1/9
Between very strong and extremely	8	1/8
Very strongly preferred	7	1/7
Between strong and very strong	6	1/6
Strongly preferred	5	1/5
Between moderate and strong	4	1/4
Moderately preferred	3	1/3
Between equal and moderate	2	1/2
Equal Importance	1	1

4.4.1.3 3rd Principle: Synthesizing Priorities

AHP combines priorities for synthesising the alternatives' weights. First, a pairwise matrix a_{ij} comparison, as presented in Equation (1), shall be performed, where A is the pairwise comparison.

$$A = \{a_{ij}\} \text{ with } a_{ij} = {}^{1}/_{a_{ij}} \tag{1}$$

Secondly, a normalisation is carried out. For this, each value is divided by the total column sum value. In numerical terms, the standardised values as to the columns are given in Equation (2).

$$a_{ij}^{c\prime} = \frac{a_{ij}^{c}}{\sum_{1}^{J} a_{ij}^{c}} \tag{2}$$

Weights among criteria and attributes can then be calculated from the consolidated values. This is achieved by performing the arithmetic mean of the elements in their respective lines (Equation (3)).

$$p_i = \frac{\sum_{1}^{J} a_{ij}^{c}}{n} \tag{3}$$

This mathematical process is carried out for each alternative, from the perspective of each criterion. Hence, the weight value means ranking the alternatives from each criteria's perspective. To obtain the final weight analysis, the weighted average of each alternative's weight in terms of the multiple criteria are calculated according to Equation (4).

$$pg_j = \sum_{1}^{J} (p_i).(pa_{ij}) \tag{4}$$

where pa_{ij} is the weights' value.

Next, to transform the data into meaningful numbers, the following equations shall be implemented (Taherdoost, 2017):

$$Aw = \lambda_{max}\, w, \lambda_{max} > n \tag{5}$$

$$\lambda = \frac{\sum a_{ij} w_j - n}{w_1} \tag{6}$$

where,

w: normalised weight vector.
λ_{max}: maximum eigenvalue of matrix A.
n: matrix order.
a_{ij}: numerical value comparison between i and j.

To validate AHP pairwise matrix comparison, the Consistency Ratio (CR) is calculated by means of equation (7), where CI is the Consistency Index, given by equation (8).

$$CR = \frac{CI}{RI} \tag{7}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{8}$$

RI in equation (7) stands for Random Consistency Index. This value relates to the matrix dimension, being the CI expected from a matrix of this order (Donegan and Dodd, 1991). Several authors have computed this index through simulation experiments. Saaty (1996) carried out an experiment with 500 runs and obtained the results presented in Table 4. A consistency ratio lower than 0.10 means that the pairwise comparison is acceptable. Meanwhile, a value above 0.1 requires reconsidering the decision matrix for any rating inconsistency (Saaty, 1996).

Table 4: Random Consistency Index (RI).

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: Saaty (1987).

4.4.1.4 Aggregating Individual Judgements and Priorities

Forman and Peniwati (1998) stated that AHP is implemented in group situations, where group members either discuss to achieve a consensus or express their preferences individually. In this regard, individual judgement can be aggregated in different ways, where two methodologies stand out according to the authors: (1) Aggregating the Individual Judgements (AIJ) for each set of pairwise comparisons into an aggregate hierarchy or (2) Aggregating Individual`s Priorities (AIP) and synthesising the priorities.

According to the authors, three essential factors should be analysed for implementing one of those methodologies. First, whether the group of experts is assumed to be synergic or simply a collection of individuals. For instance, in an organisation, if individuals set aside their own preferences for the organisation's benefit, they work in harmony and become a collective entity. Therefore, the group becomes a 'new individual' and behaves as such. In this sense, inconsistencies in an individual's pairwise comparisons can be analysed, revised, or even excluded if an inconsistency is deemed high. Secondly, it is vital to consider if the individual is weighted equally or not. Finally, the mathematical procedure implemented shall be studied since the geometric and arithmetic mean are considered appropriate for ratio scales. In this regard, Forman and Peniwati (1998) justify that for AIJ, geometric mean shall be implemented, while both could be applied for AIP.

i) Aggregation of Individual's Judgements (AIJ)

Individual judgement matrices are aggregated to obtain a collective judgement matrix, as shown below (Dong et al., 2010).

$$A^{(c)} = (a_{ij}^{(c)})_{n\,x\,n} \tag{9}$$

where,

$$a_{ij}^{(c)} = \prod_{k=1}^{m} (a_{ij}^{(k)})^{\lambda_k} \tag{10}$$

Hence, the final priority collective vector from (9) is

$$w^{(c)} = (w_1^{(c)}, w_2^{(c)}, \dots, w_n^{(c)})^T \tag{11}$$

ii) Aggregation of Individual's Priorities (AIP)

This methodology derives the priority vector (12) from the individual judgement matrix $A^{(k)}$. Finally, a collective priority vector is obtained (13) (Dong et al., 2010).

$$w^{(k)} = (w_1^{(k)}, w_2^{(k)}, \dots, w_n^{(k)})^T \tag{12}$$

$$w^{(c)} = (w_1^{(c)}, w_2^{(c)}, \dots, w_n^{(c)})^T \tag{13}$$

where,

$$w_i^{(c)} = \frac{\prod_{k=1}^{m} (w_i^{(k)})^{\lambda_k}}{\sum_i^n = \prod_{k=1}^{m} (w_i^{(k)})^{\lambda_k}} \tag{14}$$

After analysing the expert's group and synthesising the results, priorities can be assessed, and knowledgeable decision-making can be made.

4.5 Corporate Sustainability Enhancement

By integrating circularity into Corporate Sustainability Processes, companies can adopt more holistic and comprehensive approaches to sustainability. This alignment can drive positive environmental and social impacts while improving operational efficiency and long-term resilience. Nevertheless, even if circularity matters are gaining significance in disclosure frameworks and taxonomies for sustainable finance and companies, initial evidence suggests that this topic needs to be more commonly integrated into corporate sustainability reports (Opferkuch et al., 2022).

Corporate reports result from sustainability accounting and strategic management processes (Lozano and Huisingh, 2011). The guideline provided by disclosure frameworks plays a crucial role in shaping a company's sustainability objectives and strategy (Baumgartner and Rauter, 2017). Sustainable Corporate Strategy encompasses a company's actions integrating social and environmental considerations into its business operations and engagement with stakeholders. It entails demonstrating a commitment to addressing social and environmental issues through responsible practices and fostering positive relationships with stakeholders (Van Marrewijk, 2003).

To achieve tools and process enhancement towards better and transparent sustainability communication and Product Development Processes, the implementation and improvement of specific instruments and procedures within an organisation are vital. These tools and processes support implementing a sustainable corporate strategy by providing frameworks, methodologies, and systems for measuring, managing, and improving environmental, social, and economic performance (Grainger-Brown and Malekpour, 2019).

Therefore, these strategies set the vision and direction for integrating sustainability into the company's operations, products, and services. It outlines the goals and targets related to environmental and social impacts and drives the overall sustainability agenda of the organisation. On the other hand, the tools and processes serve as practical means to operationalise and support the execution of the sustainable corporate strategy. They provide the necessary frameworks, methodologies, and guidelines to measure, monitor, and improve sustainability performance, enabling the company to effectively implement its strategy and achieve its sustainability objectives.

Hence, New Product Introduction (NPI) and Company Report improvement frameworks toward more sustainable and circular products shall be addressed. However, as previously mentioned, product circularity represents just one aspect of the broader CE framework. Companies must recognise that their actions should not be limited to this dimension alone. Instead, a more comprehensive approach is required, involving the formulation of long-term strategies and establishing targets that address various sizes of circularity.

5 METHODOLOGY

To reduce carbon emissions and enhance product circularity while avoiding sustainability trade-offs, the choice and assessment of operational tactics shall incorporate the potential environmental impact throughout a product's life cycle. However, these metrics and guidelines may not be precise and vary based on the company. Therefore, they should be according to different criteria, such as organisational needs, materiality, and perceptions.

To support GE Grid Solutions in leading the electrical grid industry decarbonisation, C-Ecodesign strategies and guideline, gathered from a literature review, were prioritised according to four business perspectives through AHP, based on experts' judgement. In parallel, a set of possible circularity indicators was ranked. According to their Difficulty vs Importance, the top-ranked guidelines were further tested using a selected C-Indicator and an HV equipment LCA performed by the author of this study. Finally, tools and process enhancement are proposed to support NPI and the company's external report.

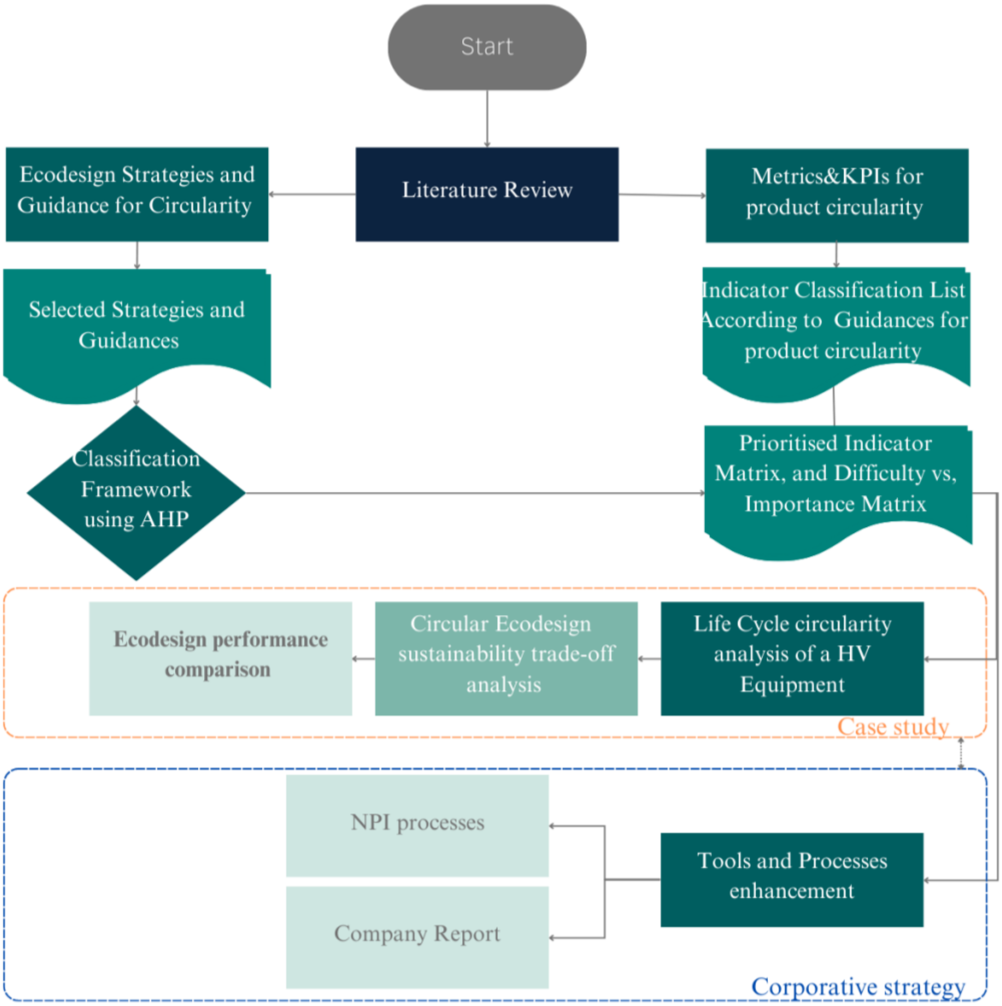

Figure 7: Methodology Flowchart.

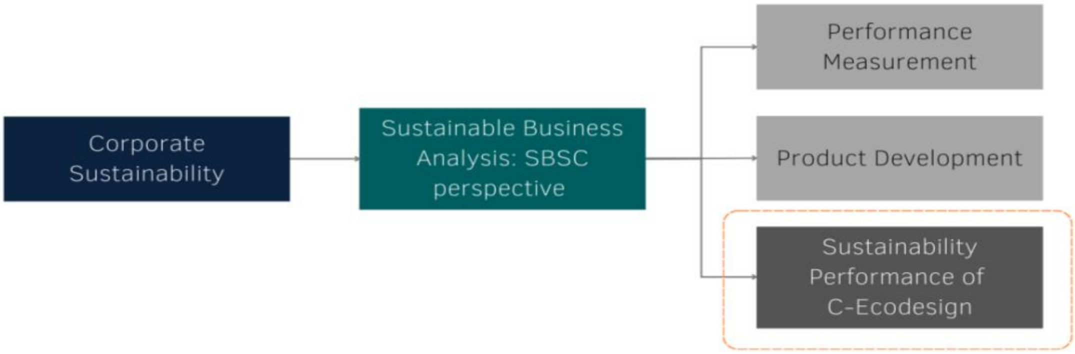

Figure 8: Research Scope.

The corporate sustainability business was considered in the micro-level circular economy (companies, consumers, and products). This study focuses specifically on answering what would be the prioritisation of sustainable C-Ecodesign strategies and guideline for GE business through the SBSC perspective using AHP methodology. Moreover, the study wants to answer possible effective indicators to measure their performance. In addition, the mapped indicator uses LCA as a tool to analyse the sustainability performance of the ranked C-Ecodesign strategies and guideline.

5.1 Ecodesign Strategies and Guideline

In an organisation, strategy refers to the priorities and purpose guiding efforts and how the company can achieve its goals. Usually, each strategy comes with a set of related guidelines that assist the organisation in working towards its objectives. Those two concepts are vital for effectively achieving circular products, considering the business perspective, and corroborating social and environmentally responsible management.

5.1.1 C-Ecodesign Strategies and Guideline Review

A literature review was carried out to set circular C-Ecodesign strategies and guideline. Keywords used in the research were: “circularity for Ecodesign”, “circularity strategies”, “circularity guidelines”, and “product circularity”. Next, a set of strategies and guidelines to transit to circular products was gathered by reading and analysing peer-reviewed published articles. To implement circularity into a product, six operational strategies represent significant environmental concerns during the development of a product, as presented in section 4.2.1.1 Ecodesign Strategies.

For this research, numbers (3) and (4) are considered in the same group called “Extend and Optimize Product Lifetime”. Each previously presented strategy comprises multiple guidelines to implement C-Ecodesign into a product successfully. Those guidelines were also gathered through a literature review, where the most relevant and informative studies were analysed and presented in Table 5.

Table 5: A literature review of C-Ecodesign guidelines.

Author	Title	Source	Findings
Riesener et al., (2023)	Design for Circularity – Identification of Fields of Action for Ecodesign for the Circular Economy	Procedia CIRP	Derived a framework with nine fields of action for the realization of circular economy by ecodesign.
Bovea and Pérez-Belis (2018)	Identifying design guidelines to meet the circular economy principles: A case study on electric and electronic equipment	Journal of Environmental Management	Design guidelines required for the circular product design identified from an extensive review.
Allione et al., (2012)	From ecodesign products guidelines to materials guidelines for a sustainable product. Qualitative and quantitative multicriteria environmental profile of a material	Energy	Developed a list of ecodesign guidelines to help the material selection.

5.1.2 Selection of Strategies and Guidelines

After performing a literature review, strategies and guideline toward product circularity were selected for the AHP hierarchy construction. Considering the Ecodesign perspective, the choice was made according to their relevance for product circularity. In addition, their alignment with ideas from multiple authors and relevance for GE Grid Solutions business was also considered. Finally, selected guidelines were grouped according to the chosen strategies.

5.1.3 Strategies and Guideline Prioritisation using AHP

The AHP methodology was implemented according to Saaty, (1987, 2005, 1990, 1980). Moreover, the studies presented in Table 2: Sustainability/Environmentally oriented case studies where AHP was utilised. were also consulted and are explained below.

5.1.3.1 1st Step: Decomposition

The main goal of this study is to prioritise sustainable C-Ecodesign strategies and present a set of meaningful KPIs for decision-makers' choices. Thus, for raking strategy priorities and analysing imperative approaches for the organisation, firstly, the problem was decomposed into a hierarchy of criteria, presented in Figure 9.

a) **1st Level** – Goal: To set Prioritization of Ecodesign strategies and guidelines.

b) **2nd Level** – SBSC perspective: Making managerial decisions is a challenge that involves multiple business perspectives and criteria. The Sustainable Balanced Scorecard, as presented in section 4.3, is the first level to be analysed to improve understanding of organisational performance and provide a realistic prioritisation from a business perspective. The learning and Growth perspective is not included.

c) **3rd Level** – Circularity Strategies: Each business perspective is broken down into six circularity strategies. This allows transversal prioritisation through multiple business perspectives.

d) **4th Level** – Guidelines: The strategies were further broken into their respective guideline to make the overall final goal achievement possible.

5.1.3.2 2nd Step: Comparative Judgement

For this study, ideally, four expert groups would have been chosen to effectively judge from (1) a financial perspective, (2) a customer perspective, (3) an internal processes perspective, and (4) an environmental perspective. Finally, results would have been synthesised through the Aggregation of Individual Judgements, as presented in section 4.4.1.4. However, due to internal limitations, the comparative analysis was made according to the Ecodesign team judgement, which members discussed to achieve a consensus. With a well-established knowledge of the global Grid Solutions business, the Ecodesign team analysed each level from four different mindsets (financial, customer, internal processes and environment).

The pairwise comparison was carried out through a dynamic Excel file, developed by the author. The file contains a dashboard presenting the hierarchy and steps for analysing 25 pairwise comparisons shown as steps to be followed in a particular order through buttons. The main menu includes instructions on how to fill the matrices to ensure the Consistency Index is respected per pairwise comparison, automatically generated according to the equations presented in section 4.4.1.3. The pairwise comparison priority vectors are also shown once a matrix is filled. The final weight for the hierarchy levels is automatically generated according to the group analysis.

5.2 Priority Indicator Matrix: Difficulty vs. Importance

The prioritised guidelines were assembled into a “Priority Indicator Matrix”. For this purpose, the importance of the circularity guideline, based on the expert's judgement obtained through the AHP analysis, is considered from low to high rank in the x-axis. On the y-axis, the level of difficulty for implementation is evaluated. The difficulty of implementation was set for each guideline through conducting a discussion with the Ecodesign team and expertise of the Ecodesign team coordinator.

An importance/difficulty matrix is a tool used for plotting tasks in a given project according to their Significance and Hardness of implementation. It represents a valuable decision-making instrument for determining when priorities should be executed and finding high-value strategies. The matrix model is given in Figure 9. An indicator ranked matrix was developed based on that.

Figure 9: Priority Indicator Matrix: Difficulty vs. Importance. Source: Luma institute (n.d). Importance/Difficulty Matrix A quad chart for plotting items by relative importance and difficulty

5.3 C-Metrics and KPIs

In parallel with the research carried out to gather and prioritise Ecodesign strategies and guidelines for product circularity, a study was conducted on measuring these Ecodesign actions performance.

5.3.1 C-Metrics and KPIs Review

A literature review was conducted to find the best-suited indicators to measure product circularity. Keywords used in the research were: “circularity indicator”, “Ecodesign indicator”, “circularity metrics”, and “circularity measure”. Considering the scope and boundaries of this research, 40 indicators were investigated from the articles presented in Table 6.

Table 6: A literature review of C-Ecodesign indicators.

Author	Title	Source	Findings
Jerome et al., (2022)	Mapping and testing circular economy product-level indicators: A critical review	Resources, Conservation and Recycling	Test indicators as tools for assessing progress towards the circular economy (CE).
Vinante et al., (2021)	Circular economy metrics: Literature review and company-level classification framework	Journal of Cleaner Production	The authors review existing CE metrics and organize them according to a new circular Value Chain framework.
De Pascale et al., (2021)	A systematic review for measuring circular economy: The 61 indicators	Journal of Cleaner Production	Surveys 61 indicators measuring the CE. The indicators are grouped according to three spatial dimensions -macro, micro and meso- and on the basis of the 3R Core CE principles.

5.3.2 Selection of KPIs

After performing a literature review, indicators for measuring product circularity were gathered and studied regarding their inputs and outputs. Subsequently, an analysis was further performed according to their specific C-Ecodesign considered guideline.

Thus, when a guideline was measured in a respective KPI, this would receive the guideline importance based on the conducted AHP. The values are then summed up to represent that indicator level of importance in measuring product circularity for GE's business. As a result, an indicator importance matrix is obtained.

5.4 Case Study

Life Cycle Assessment (LCA) is vital tool to assess the sustainability of a product. In this regard, the prioritised guideline, according to results from the AHP and from the Difficulty vs Importance matrix, were tested using LCA, allowing to assess sustainability trade-offs when implementing circular strategies.

5.4.1 LCA Circularity Analysis: High Voltage Equipment

A study case was conducted in High Voltage (HV) equipment. The studied product is designed to meet a variety of needs offered by GE Grid Solutions to its customers. In particular, itprovides system voltage control, operational flexibility, stability, and reliability. In addition, it does not contain SF_6, an impactful greenhouse gas. The equipment choice is due to the data available in an up-to-date study conducted from the beginning by the author of this report. Therefore, its Life Cycle specificities were already well-known.

Additionally, the equipment underwent a recent design change where its material mass was considerably reduced. Moreover, some material changes were also performed, allowing four design comparisons for this study. Thus, a comparative LCA between the versions was conducted in the first step, making assessing fundamental design changes' environmental impacts possible.

The analysis was performed with SimaPro LCA software version 9.4. The calculation method used is EF 3.0 (Environmental Footprint) as implemented on SimaPro. For secondary datasets, Ecoinvent 3.8 life cycle inventory database has been used.

5.4.2 Sustainability Analysis

Possible sustainability trade-offs were analysed using the software Simapro 9.4 with Ecoinvent 3.8 dataset. The method is EF 3.0, as implemented in SimaPro. For this, the following steps were conducted:

i. LCA performance of a High Voltage Equipment: Base Line.
ii. LCA performance of three new High Voltage Equipment designs.
iii. Testing Ecodesign strategic and high value guidelines (from the difficulty/importance matrix).
iv. LCA sustainability trade-offs analysis using a selected circularity indicator from the indicator importance matrix.

5.4.3 Ecodesign Performance Comparison

A sustainability performance comparison was carried out after testing the strategies and guideline from the difficulty vs importance matrix using a circularity indicator from the indicator importance matrix through LCA. For this purpose, five midpoint impact categories were selected to represent circularity impact categories: Climate change; Land use; Water Use; Resource use, fossil; Resource use, minerals and metals.

The selection of impact categories was based on the defined study goals; critical environmental issues and impacts associated with the system considering the entire product life cycle; GE's ecodesign team judgement; the significance of the environmental impacts and relevance to the study, considering factors such as magnitude, severity, extent, and persistence of the impacts.

5.5 Sustainable Corporative Strategy

The integration of Ecodesign for circular products into a sustainable corporate strategy helps companies align their operations with sustainability goals, promote resource efficiency, enhance customer value, foster innovation, and demonstrate responsible business practices. It is a strategic approach that combines environmental considerations with business objectives to drive sustainable growth and positive impact. Hence, tools and process enhancement were analysed for implementing C-Ecodesign into GE's sustainable corporative strategy.

5.5.1 Tools and Processes Enhancement

Tools and Processes Enhancement for corporate sustainability refers to implementing and improving instruments and procedures within an organisation to enhance its sustainability practices. These tools and processes help companies measure, manage, and improve their environmental, social, and economic performance. Thus, this step aims to review and analyse how to enhance corporate sustainability within GE regarding C-Ecodesign implementation in two strands: New Product Introduction (NPI) and Sustainability Report. NPI refers to developing and introducing new products or services into the market. By implementing tools and process enhancement within NPI and integrating circularity into the sustainability report, a company can actively promote and demonstrate commitment to circular products. This approach fosters sustainability and resource efficiency while aligning with broader corporate sustainability goals.

5.5.1.1 NPI

NPI is the process of establishing an action plan in order to take a product from concept to its final form. In this regard and aiming at implementing circular Ecodesign strategies into a product's early design stages, improving NPI is vital. Thus, recommendations are given for this purpose.

5.5.1.2 Company Report

One of the biggest challenges regarding Extra Financial Report is to gather and present meaningful indicators. These not only must be transparent and address material topics for a company's stakeholders but also show improvements the organisation is pursuing towards more sustainable businesses. In this regard, recommendations are given to show circularity through indicators.

6 RESULTS AND DISCUSSION

The analysis of C-Ecodesign strategies revealed several significant findings regarding priorities and perspectives. The standpoints considered in this study were the customer, environmental, financial, and internal processes perspectives. Additionally, the study examined various strategies and their respective guideline for promoting more circular products. Moreover, analysing possible indicators to measure product circularity and using LCA as a tool allowed it to expose various sustainability trade-offs that might happen while setting circularity to increase. The results are presented in the next sections.

6.1 C-Ecodesign Strategies and Guideline Prioritization Using AHP

This section presents results for the conducted AHP.

6.1.1 Decomposition

The set goal of this AHP analysis was to prioritise Ecodesign Circularity Strategies and Guideline. Based on the comprehensive literature review conducted, it becomes evident that formulating strategies and guideline for an organisation necessitates a holistic consideration of various dimensions encompassing the SBCS perspectives, meaning financial, customer, internal process, and environmental aspects from a business standpoint. The learning and growth perspective is not considered since it is of low importance at this stage. However, it is worth mentioning that this encompasses areas such as employee training and development, knowledge management, employee satisfaction, and organisational culture. Thus, it shall be addressed later on to ensure long-lasting circularity implementation into GE’s business. The proposed hierarchy to unveil the study goal is presented below. Appendix 1 presents the hierarchy diagram.

1st Level – Goal: Prioritisation of Ecodesign Circular Strategies and Guidelines.

2nd Level – SBSC: Financial, Customer, Inpernal Processes and Environmental perspectives

3rd and 4th Level – Circularity Strategies and Guidelines respectively. Definitions in Table 7.

Table 7: 3rd and 4th level definition.

3rd and 4th Level	Definition in this study
1.Select low impact resources and processes	Refers to the deliberate and conscious decision-making process of identifying and choosing resources and processes that have minimal negative effects on the environment, society, or any other relevant aspect.
a.Design with recyclables	Use recycled materials in the product. E.g. recycled aluminium.
b.Design with waste	Waste materials or byproducts are intentionally incorporated into the design process to create new products, systems, or solutions.
c.Use renewable energy in production	Use energy from renewable sources to manufacture a product.
2.Facilitate disassembly	Design approach that focuses on making products or systems easier to disassemble at the end of their lifecycle
a.Dismountable connections	Design and implementation of connections or joints that can be easily separated or disassembled making product pieces recoverable.
b.Une monomaterials	Use of a single material type in the design and construction of a product, eliminating the need for complex material separations at EoL stage.
c.Reduce disassembly time	Design features that prioritize ease of disassembly.
3.Extend lifespan and optimise product lifetime	Efforts and strategies aiming at increasing the longevity of a product and maximizing its useful life to prevent premature product failures, reduce the need for frequent replacements, and minimize waste generation.
a.Remanufacture	Process of restoring used or returned products to their original specifications.
b.Repair	Fixing or restoring a damaged, malfunctioning, or broken product or component to its original functionality.
c.Reuse	Utilizing a product, component, or material multiple times or in alternative ways, extending its useful life and preventing it from becoming waste
d.Refurbish	Renovating, restoring, or rejuvenating a product or item to improve its condition, appearance, or functionality.
e.Upgrade	Improving or enhancing a product, system, or component by adding new features, capabilities, or technologies.
4.Minimise Energy Consumption	Minimising energy consumed to produce a product and by a product at use.
5.Minimise Material Consumption	Narrow material consumption at design stage.
a.Minimise material weight	Reduce amount of material needed to produce a product.
b.Minimise non-conformities	Reduce the occurrence of deviations or discrepancies from established standards, specifications, or requirements within a product.
c.Minimise waste	Reduce waste generated during a product’s life cycle.
6.Rethink	Critically examining or reconsidering a particular design
a.Rethink Supply chain	Think on more environmentally performance supply chains.
b.Rethink the design	Reconsider the design to make more circular products.
c.Rethink Materials	Think on purposeful materials, less harmful for the environment and society.

Source: Riesener et al., (2023); Bovea and Pérez-Belis (2018); Allione et al., (2012).

6.1.2 Synthesised Priorities

After performing the pairwise comparison according to the defined hierarchy, the ranked C-Ecodesign strategies and guideline were analysed and are presented in Tables 8 and 9. See Appendix 2 for a detailed overall hierarchy chart.

Table 8: AHP priority results – 2nd Level.

2nd Level	**Financial**	**Customer**	**Internal Proc.**	**Environmental**
Criteria Vector	19.3%	55.0%	4.5%	21.3%

Table 9: AHP priority results – 3rd and 4th Levels.

3rd and 4th Level	**Financial**	**Customer**	**Internal Proc.**	**Environmental**	Final Weight
Select low impact resources and processes	**8%**	**12%**	**20%**	**11%**	**11%**
Design with recyclables	11%	11%	8%	10%	1%
Design with waste	63%	31%	55%	33%	4%
Use renewable energy in production	26%	58%	37%	57%	6%
Facilitate disassembly	**4%**	**4%**	**3%**	**3%**	**3%**
Dismountable connections	54%	63%	57%	28%	2%
Une monomaterials	16%	26%	36%	62%	1%
Reduce disassembly time	30%	11%	7%	10%	1%
Extend lifespan and optimise product lifetime	**21%**	**37%**	**10%**	**22%**	**29%**
Remanufacture	23%	4%	7%	8%	2%
Repair	10%	47%	50%	36%	12%
Reuse	4%	6%	4%	13%	2%
Refurbish	21%	13%	24%	7%	4%
Upgrade	41%	30%	16%	37%	10%
Minimise Energy Consumption	**23%**	**26%**	**22%**	**13%**	**22%**
Minimise Material Consumption	**40%**	**20%**	**41%**	**21%**	**25%**
Minimise material weight	18%	27%	33%	19%	6%
Minimise non-conformities	75%	67%	59%	8%	15%
Minimise waste	7%	6%	8%	72%	5%
Rethink	**3%**	**3%**	**4%**	**31%**	**9%**
Rethink Supply chain	56%	26%	24%	56%	4%
Rethink the design	9%	11%	14%	9%	1%
Rethink Materials	35%	63%	62%	35%	4%

6.1.3 2nd Level: SBSC Perspectives

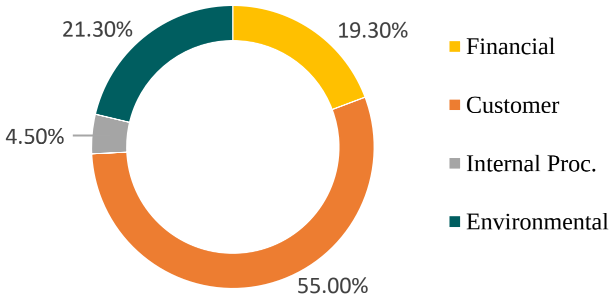

Figure 10: Hierarchical chart – AHP priority results from the different SBSC perspectives.

Results indicate that the customer perspective emerged as the most essential aspect, with a significant weightage of 55.0%. This implies that customers are the company's focal point, playing a crucial role in driving the adoption and success of C-Ecodesign strategies. The emphasis on the customer perspective suggests that the studied business should focus on creating products that align with consumer preferences and expectations as a first goal in the short term. Thus, the reviewed company can foster consumer satisfaction and loyalty by meeting customer demands toward sustainable and circular products while promoting a circular economy.

The environmental perspective ranked second in importance, accounting for 21.3% of the total weightage. This highlights the significance of considering the environmental impact of product design throughout its lifecycle, avoiding sustainability trade-offs, and reducing the environmental footprint of products.

The financial perspective held a weightage of 19.3% in the analysis. This indicates that economic considerations are essential for the business, having significant importance but not the only main priority for C-Ecodesign alongside sustainability enhancement. In this regard, the company must assess the cost-effectiveness and financial viability of adopting circular practices. While upfront investments may be required to implement specific circular strategies and guideline, the potential long-term benefits can contribute to improved financial performance.

Finally, the internal processes perspective, weighing 4.5%, indicates that the organisation should also optimise its internal operations and processes to support C-Ecodesing strategies, but this would be seen as the least focal point. By streamlining internal processes and promoting cross-functional collaboration, companies can enhance their ability to develop and produce circular products effectively. Based on internal observations at the studied company, implementing targets to enhance product circularity presents initial challenges due to the requirement for design and process modifications. However, it is essential to recognise that these changes must be approached as a comprehensive and concerted effort rather than a one-time endeavour.

6.1.4 3rd Level: Strategies

According to the four different perspectives, the prioritised C-Ecodesign strategies are shown in Figure 11. The overall final ranking considering the multiple perspectives weighting is presented in Figure 12.

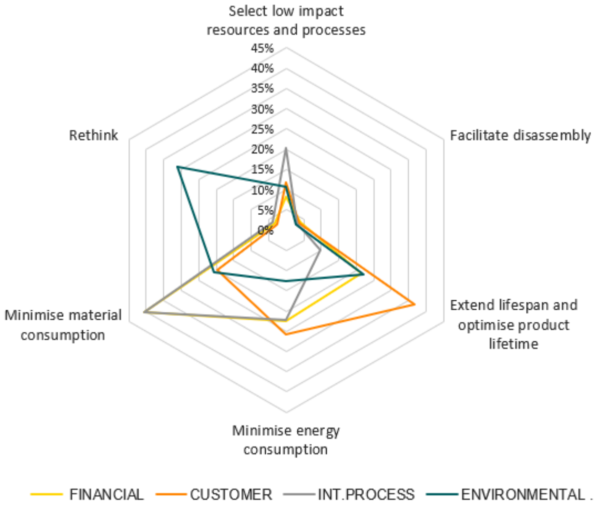

Figure 11: Prioritised C-Ecodesign strategies from different perspectives.

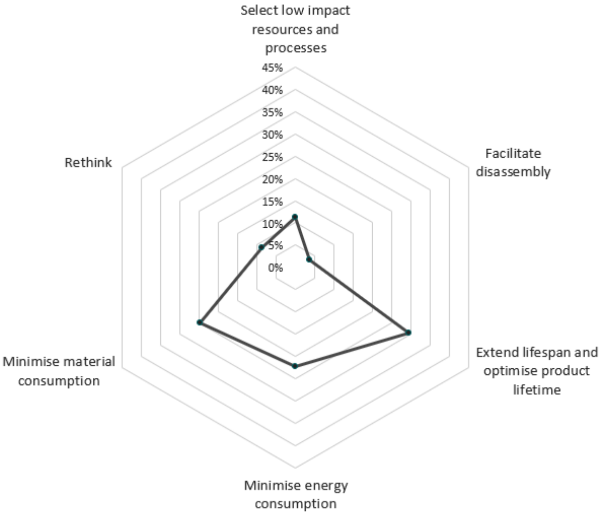

Figure 12: Overall final strategy prioritisation weighted according to the different perspectives.

The analysis bare that minimising material consumption emerged as the most relevant approach from the Financial and Internal Processes perspectives, counting 40% and 41%, respectively. Meanwhile, from the Environmental and Customer perspectives, rethinking (31%) and extending lifespan and optimise product lifetime (37%) were the most effective strategy, respectively.

The findings elucidate the primary measures with significant potential for promoting cost reduction and mitigating adverse environmental effects within distinct perspectives or sectors. Specifically, the financial perspective aims to minimise expenses and increase revenues, while the environmental perspective focuses on minimising detrimental ecological impacts. Conversely, the customer perspective seeks to enhance product durability, while the internal process perspective strives to facilitate the creation of products with simplified manufacturing processes.

After weighing the strategies (Figure 12), Extending and Optimising Product Lifetime emerged as the most relevant approach, accounting for 29%. This emphasises the importance of designing durable, repairable, and upgradable products. By focusing on extending the lifespan of products, clients can reduce waste and minimise the need for frequent replacements. Minimising Material Consumption is the second most relevant strategy, weighing 25%. This highlights the significance of using materials efficiently and designing products with minimal resource inputs, while potentially achieving cost savings.

Minimising Energy Consumption ranked third in relevance, accounting for 22% of the weightage. This finding underscores the importance of energy-efficient design and manufacturing processes. By incorporating energy-saving features and optimising production techniques, companies can contribute to reducing greenhouse gas emissions and conserving energy resources. Selecting low-impact resources and processes received a weightage of 11%, indicating its moderate relevance in C-Ecodesign strategies. This strategy emphasises the importance of using environmentally performant materials and processes throughout the product lifecycle. Companies can mitigate their ecological footprint and promote sustainability by prioritising low-impact resources and processes. By employing materials efficiently and designing products with energy-efficient features, companies can contribute to preserving natural resources and reducing waste and pollution.

Rethinking, with a weightage of 9%, suggests that companies should challenge conventional design approaches and explore innovative solutions. This strategy encourages companies to consider alternative materials, business models, and production methods that can enable more sustainable and circular product design. Facilitating disassembly was found to be the least relevant strategy, accounting for 3% of the weightage. It is imperative to acknowledge that while prioritising Rethink aligns with the environmental perspective, examining solely one viewpoint fails to capture the anticipated impact on the triple bottom line. Consequently, to prevent environmental burdens, promote product circularity, and maintain a healthy business, it is vital to consider the diverse perspectives contributing to long-term success. Nonetheless, even if Facilitating Disassembly, Rethinking, and Select Low-Impact Resources and Processes are ranked as lower priorities, they must be addressed over the medium to long term to continually enhance product circularity and ensure the sustainability of the business.

6.1.5 4th Level: Guideline

The prioritised C-Ecodesign guidelines are shown in Figure 13. The overall final ranking, considering the multiple perspectives weighting, is presented in Figure 14.

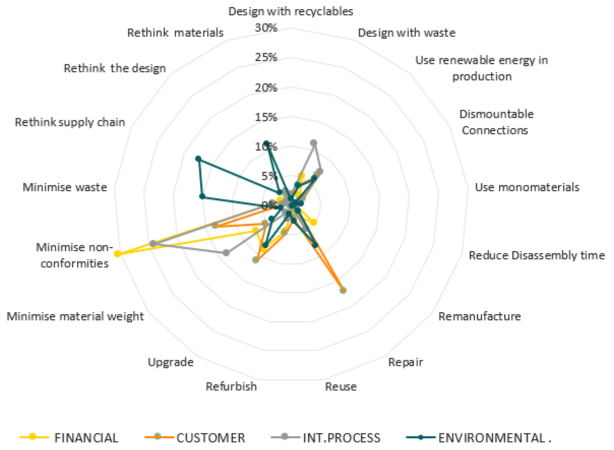

Figure 13: Prioritized C-Ecodesign guideline from different perspectives.

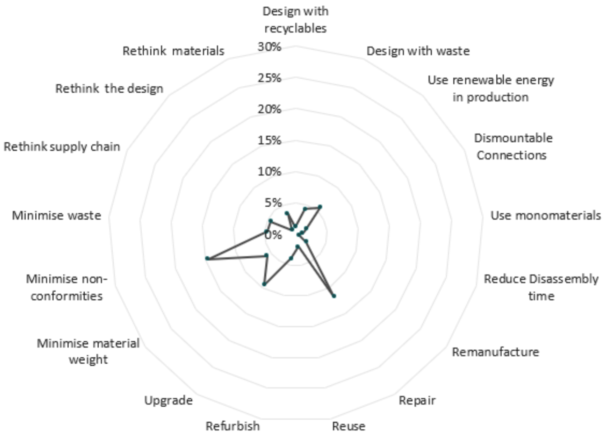

Figure 14 : Overall final guideline prioritisation weighted according to the different perspectives.

The analysis of C-Ecodesign guideline revealed several findings regarding specific recommendations for achieving circularity in product design. Figure 15 shows the weightage of each guideline according to its respective strategy.

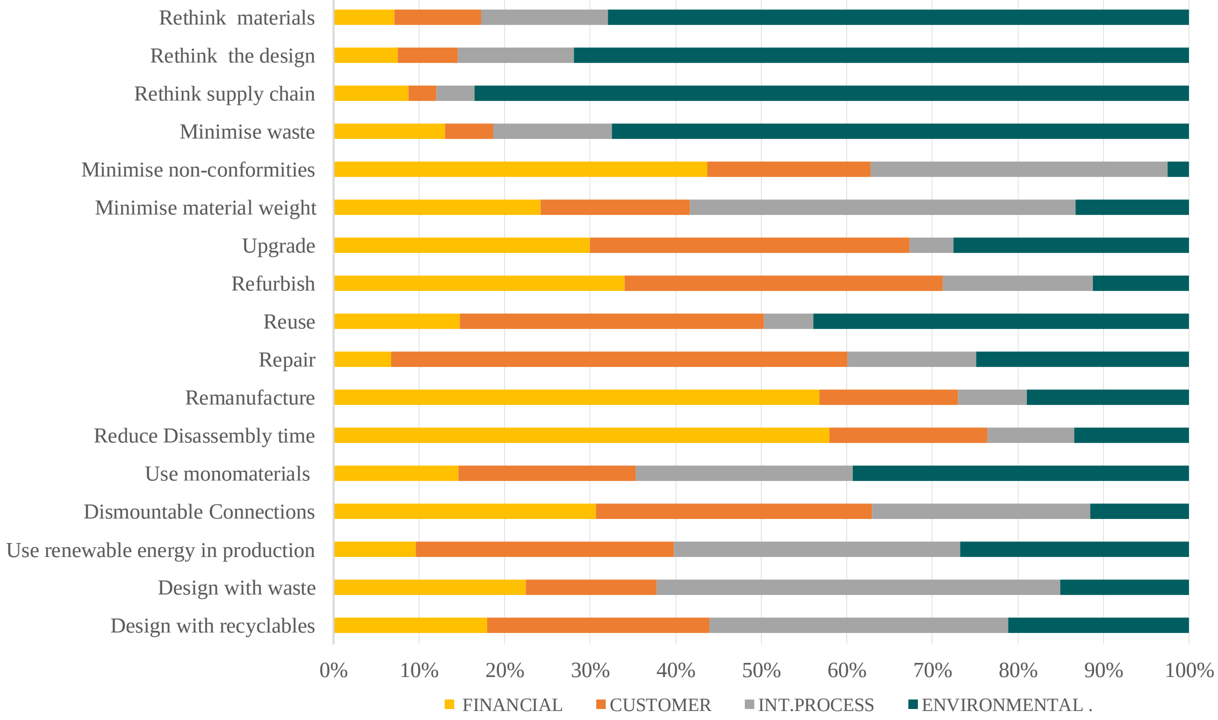

Figure 15: Guideline priorities share according to their respective perspectives.

The top five ranked guideline according to each analysed strategy is presented in Table 10.

Table 10: Top 5 guideline priorities according to their respective business perspective.

Perspective	Financial	Customer	Internal Proc.	Environmental
Top priority Guideline	1. Minimise NC 2. Upgrade 3. Minimise material weight 4. Design with waste 5. Remanufacture	1. Repair 2. Minimise NC 3. Upgrade 4. Use renewable energy in production 5. Minimise material weight	1. Minimise NC 2. Minimise material weight 3. Design with waste 4. Use renewable energy in production 5. Repair	1. Rethink supply chain 2. Minimise waste 3. Rethink Materials 4. Upgrade 5. Repair

From the financial perspective, the top five most relevant C-Guidelines would account for 56% of the efforts to make more circular products. Customer perspective was ranked the most important one. Thus, priority guideline from this viewpoint is likely vital regarding product circularity. The five most pertinent account for 54% of the overall perspective category.

The Internal Processes perspective was rated with the lowest weight. However, it is vital for implementing product circularity guidelines. Hence, its priorities should also be addressed to implement circularity changes successfully. Its five ranked priorities account for more than 60% most essential actions in this category. Finally, in order to decrease environmental burdens, this perspective is vital for implementing sustainable circular products. Nevertheless, since it is not the most critical viewpoint considering the business perspectives, weights varied compared to the overall priorities. However, it should be carefully considered to avoid sustainability trade-offs.

6.1.6 Overall result priorities

Based on the weightage assigned to each perspective, the following priorities emerged, emphasizing the significance and influence of different perspectives in business decision-making.

1. Minimise non-conformities (15%)
2. Repair (12%)
3. Upgrade (10%)
4. Use renewable energy in production (6%)
5. Minimise material weight (6%)

Minimising non-conformities is a crucial guideline strategy as it enables a business to optimise material usage and reduce resource wastage. Although it may not be the most compelling strategy from an environmental perspective, it gains increased importance from the financial and customer perspectives, which hold higher weights.

Two guideline stood out as the most important in extending and optimising product lifetime strategy. Repair emphasises the significance of designing products that are easily repairable, thereby extending their lifespan and reducing the need for premature replacements. Similarly, upgrade focuses on designing products that can be upgraded or updated with new features or functionalities, prolonging their useful life and minimising waste. These strategies hold relevance across all four studied perspectives.

In the Selecting Low Impact Resources category, the priority guideline is to use renewable energy in production, accounting for 6% of the weightage. This finding underscores the significance of incorporating sustainable energy sources into manufacturing processes. By adopting renewable energy, it is possible to reduce carbon footprint and contribute to environmentally performant production.

Rethink strategies identified two critical guideline approaches: Rethink Supply Chain and Rethink Material, both holding a weightage of 4%. This highlights the need for the organisation to critically evaluate and optimise its supply chain processes and material choices. Rethinking the supply chain enables the identification of opportunities for efficiency improvements and reducing environmental impacts. Similarly, rethinking material selection promotes the consideration of alternative materials with lower environmental footprints and increased recycled content.

Minimising material weight ranked second within the category of minimising material consumption, with a weightage of 6%. This strategy emphasises the importance of designing products with lightweight materials to reduce material usage and associated negative environmental impacts. Minimising waste, with a weightage of 5%, highlights the significance of waste reduction measures throughout the product lifecycle. Implementing waste minimisation strategies such as recycling and waste management systems allows companies to minimise their environmental impact.

Designing with waste ranked second in importance in selecting low-impact resources, accounting for 4%. This strategy suggests using waste materials or by-products as resources in the design and manufacturing processes, thereby minimising waste generation and promoting resource efficiency.

Facilitating disassembly's most crucial guideline strategy was the incorporation of dismountable connections, accounting for 2% of the weightage. This emphasises the need to design products with easily separable components to enable efficient disassembly during end-of-life processes. By facilitating disassembly, companies can promote the repair, reuse, and recycling of product parts, enhancing resource efficiency and waste reduction.

Overall, Minimising energy consumption emerged as a critical ecodesign strategy, holding a weightage of 22%. This underscores the importance of designing energy-efficient products and optimising manufacturing processes to reduce environmental impact and promote sustainability. No specific guideline was attributed to this strategy since it varies according to multiple factors, such as the product to be manufactured and the technology used. Thus, to reduce energy needs in product manufacturing, it is vital to analyse its value chain deeply.

6.2 Priority C-Guideline Matrix

Even though all circularity guidelines are essential in the overall product circularity, assess what the company should tackle first in a future action plan towards circular products is essential. Based on the ranked guideline importance, a priority matrix was created according to the guideline relevance vs its difficulty of implementation (Figure 17). This valuable tool allows knowledge decision-making crucial in prioritising elements within a business action plan.

This analysis facilitates a systematic approach to determining which aspects should be addressed first, ensuring that the most critical areas receive appropriate attention. Moreover, it emphasises the need for comprehensive measurement of essential factors yet lacking quantitative evaluation. In doing so, organisations can bridge the gap between subjective perceptions of importance and objective performance assessment, thereby enhancing the effectiveness of decision-making processes. Consequently, this tool offers a valuable framework for informed decision-making and strategic planning within the business context.

Importance is based on the AHP, a well-defined criteria approach making the importance assessment objective and data driven. For difficulty, it is relevant to mention that managers shall have a comprehensive knowledge of the business when defining it. Additionally, it is relevant to guide the difficulty level definition based on matters such as, but not limited to, financial, technical readiness, internal processes feasibility, supply. Thus, providing informed and reasonable assessment. Difficulty level was defined based on discussion with Ecodesign team. To make it more precise, a broad exercise can be carried out by a group of managers from different sectors of the company and quantitative data considered. Appendix 3 to 6 present the Difficulty vs importance matrix from the different business perspectives.

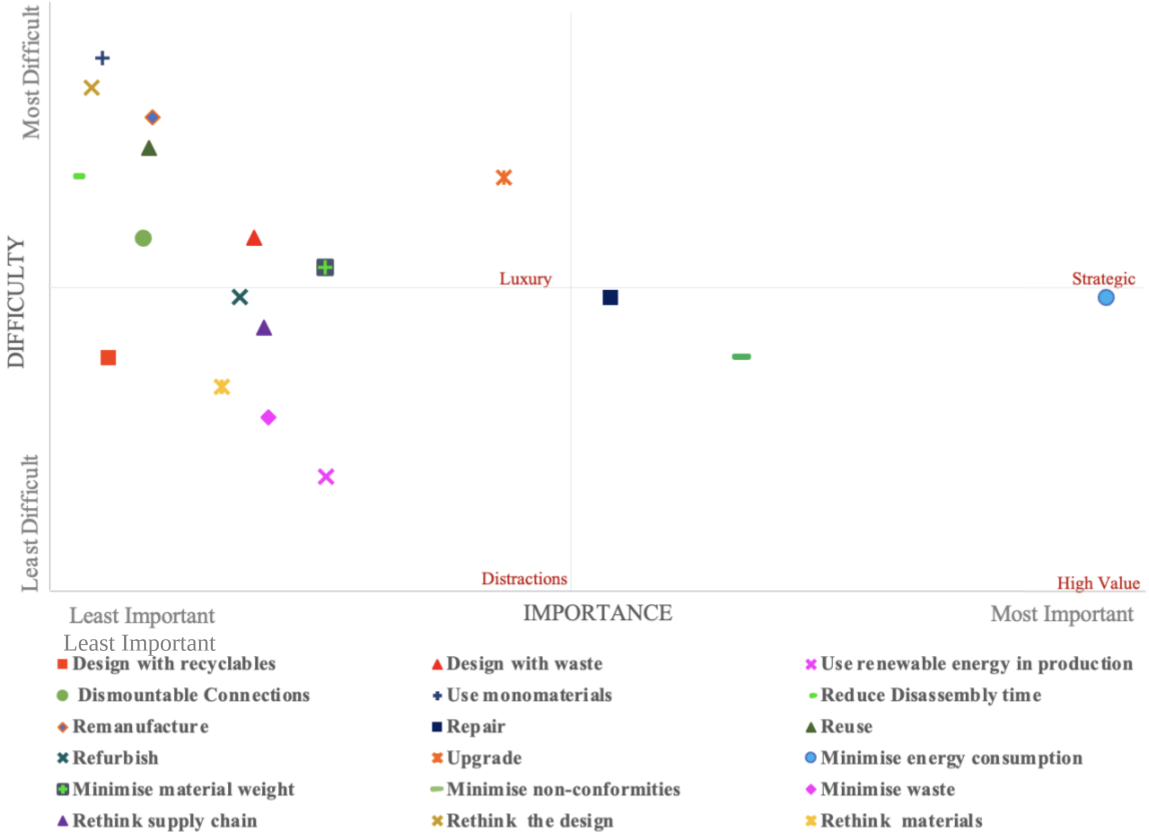

Figure 16: C-Guideline Importance vs. Difficulty.

According to the explained in section 5.2, three guidelines are of a High-Value now: (1) Minimise Energy Consumption, (2) Minimise non-Conformities, and (3) Repair.

The first priority is not divided into guidelines due to its several possible approaches, for which assessment is not the focus of this study. For instance, technological improvement can be made to reduce energy consumption in order to achieve more efficient equipment and process optimisation, not only during the assembly step (at GE’s site) but also within the supply chain through engaging with suppliers to promote energy-efficient solutions and sustainable practices throughout the supply chain. In addition, insulation and heat recovery can minimise heat losses.

Moreover, adopting energy-saving practices and implementing Energy Management Systems can be a tool. Thus, further breaking it into guideline highly depends on a product type and its production line.

The second-ranked action is Minimise non-Conformities. This guideline is essential for, among others, maintaining high product quality, reducing waste and costs, improving operational efficiency, and fostering continuous improvement. Non-Conformities in the HV equipment manufacturing sector can occur in various stages of the production process. For instance, it could arise from using substandard or defective materials and components; in the assembly process when assembly errors occur; during testing and inspection, resulting in defects, performance issues, or safety hazards. Depending on the equipment and extension of the non-conformity, the entire product can be discarded as waste, implying problematic environmental burdens, especially when a circularity approach is neglected in this waste treatment. Repair is also mapped as a strategic approach. Mainly related to customers' perspective, it allows longer use of the equipment and, consequently, slows the loop.

Closely defined as Strategic, upgrading HV equipment presents challenges, where some can be mentioned: technical complexity, high cost, safety concerns, system compatibility, and staying abreast of technological advancements. In addition, design changes such as making dismountable connectors and reducing disassembly time, can be required. Thus, since it relates to multiple other actions, it presents higher difficulties but should be addressed in the short to medium term.

Eight guidelines were defined as Luxury: Minimise material weight, design with waste, refurbish, remanufacture, reuse, use mono materials, reduce disassembly time and rethink design. Six were defined as Distractions: Use renewable energy in production, minimise waste, rethink the supply chain, rethink materials, dismountable connections, and design with recyclables. Multiple guidelines mapped in these two categories present a high potential of decreasing the negative environmental impacts of HV products. However, these were majority not considered the most important ones from the Customer perspective, which has a higher weight. In addition, it is important to note that implementing these guidelines may face challenges and considerations specific to HV products.

Firstly, these types of products often require robust and durable materials to ensure their reliability and safety. Minimising material weight, while beneficial for reducing environmental impacts, should not compromise the integrity and performance of the equipment, especially regarding energy losses in the use phase. Striking a balance between weight reduction and maintaining necessary strength and functionality can be challenging. Secondly, the design with waste and refurbishment principles may face limitations. This is because strict quality and safety standards must be met. Incorporating recycled or refurbished components may introduce risks and uncertainties regarding their performance and reliability, necessitating careful assessment and testing procedures.

Thirdly, remanufacturing and reusing HV products may require specialised expertise and facilities. The intricate nature of HV equipment, including complex electrical and mechanical components, may require sophisticated processes and expertise to ensure proper remanufacturing and reuse. The availability of such specialised facilities and the associated costs can pose challenges. Furthermore, while mono materials and dismountable connections can enhance recyclability, they may only sometimes be feasible or optimal for HV products. The specific requirements for insulation, electrical conductivity, and other performance characteristics in HV equipment may necessitate using multiple materials and more permanent connections.

Lastly, rethinking the supply chain and implementing renewable energy in production for HV products may encounter challenges related to the availability and scalability of renewable energy sources and complex global supply chains involving various stakeholders and locations. Overall, while the defined guidelines can potentially decrease the negative environmental impacts of HV products, their application must be carefully evaluated and tailored to HV equipment's unique characteristics and requirements, requiring more time to make it possible. Addressing these challenges can contribute to developing sustainable and environmentally performant HV solutions.

6.3 Priority Indicator Matrix

Appendix 7 presents the studied circularity indicators from the conducted literature review. An excel file and articles/ documents with indicators' explanation was provided to the company. Appendix 8 presents the assessment of guidelines measured by each indicator. A Priority indicator matrix containing quantitative indicators was developed (Table 11). In addition to the quantitative indicators presented, qualitative KPIs were assessed, but are not focused on in this study. However, these can capture a broader picture of circularity.

In addition to the quantitative indicators presented, qualitative KPIs were also assessed. For instance, the "Circular Economy Toolkit", "CE indicator Prototype", and the "Circularity Design Guidelines". These would receive 71%, 67% and 43% relevance from the overall perspective. Thus, even though they were not focused on this study, qualitative indicators shall be addressed since they allow to capture a broader picture of circularity opportunity in products.

From the table, it is possible to observe the different nuances of critical points from the financial, customer, internal processes and environmental perspectives. From an environmental perspective, indicator RIS has higher relevance, allowing insights on how recyclable a product is, how to reduce waste and rethink materials to increase its recyclability. Additionally, MCI is also significant. The first promotes an understanding of the fraction of mass collected for recycling at the product's end of life, providing knowledge on material types and dismountable connections. The LI indicator is considered significant for customers, despite being irrelevant from other perspectives. The VRE indicator represents the output sum of resources' volume weight. It considers the input value of energy, material and service. Thus, by decreasing the costs of used resources, VRE increases. The SCI has an increased relevance, however, even though it has the benefit of considering social aspects into it, the calculation is not precise.

No studied indicator covers 100% of the company needs. Therefore, to incorporate the circularity aspects, using more than one indicator is recommended.

Table 11: Priority Indicator Matrix.

	Indicator		F	C	IP	E	Overall
	Name	*Abbreviation*					
1	Disassembly Effort Index	DEI	3%	3%	2%	1%	2%
2	End of Life Index	EoL-I	9%	5%	4%	4%	6%
3	Recycling Indicator set	RIS	6%	5%	8%	29%	10%
4	Reuse Potential Indicator	RPI	5%	5%	5%	19%	8%
5	CE index	CEI	9%	6%	16%	20%	10%
6	Material Circularity Indicator	MCI	15%	14%	23%	35%	19%
7	Recyclability benefit rate	RBR	7%	11%	15%	33%	15%
8	Eco-cost Value Ratio	EVR	0%	0%	0%	0%	0%
9	Longevity Indicator	LI	8%	26%	9%	13%	19%
10	Material Reutilization Score	MRS	1%	1%	2%	1%	1%
11	Recycling Indices	RI	1%	1%	2%	1%	1%
12	CE Performance Indicator	CPI	0%	0%	0%	0%	0%
13	Product-level circularity Metric	PLCM	2%	4%	2%	4%	3%
14	Value-based Resource Efficiency Indicator	VRE	30%	31%	36%	17%	28%
15	End -of-Life Indices	EoLi	7%	5%	3%	6%	5%
16	Product Reuse Index	CRP	13%	26%	8%	14%	20%
17	Product Cycle potential	CPP	6%	3%	2%	3%	3%
18	Percent of reusable components	CPUM	3%	5%	2%	4%	4%
19	Percent of recyclable materials	CPRM	1%	1%	2%	1%	1%
20	Product Cycled Content Index	CCP	13%	27%	10%	15%	21%
21	Percent of used (remanufacture/repurpose) components in a product	CPUU	6%	4%	1%	4%	4%
22	Percent of recycled materials used in a product	CPRU	1%	1%	2%	1%	1%
23	Recycling Desirability Index	RDI	4%	5%	5%	6%	5%
24	Material Security Index	MSI	0%	0%	0%	0%	0%
25	Sustainable Circular Index	SCI	26%	28%	27%	29%	28%
26	Global resource Indicator	GRI	4%	4%	5%	29%	9%
27	Linear Flow Index for product families	LFI2	4%	3%	5%	16%	6%
28	Potential reuse index	PRI	1%	2%	0%	3%	2%
29	Potential Recycle index	PReI	6%	5%	8%	29%	10%
30	Effective Disassembly Time	EDT	3%	3%	2%	1%	2%
31	Ease of Disassembly Metric	EDM	4%	3%	3%	4%	3%
32	End-of-Use Product - Value Recovery	EOUPVR	0%	0%	0%	0%	0%
33	Remanufacturing with the aid of the PROduct PROfiles tool	RProProfile	42%	57%	47%	35%	49%
34	Circularity Calculator	CC	11%	8%	5%	4%	7%
35	CirculAbility (Enel)	CirculAbility	45%	63%	64%	53%	58%

F: Financial Perspective; C: Customer Perspective; IP: Internal Processes Perspective; E: Environemntal Perspective

The most relevant indicator from Table 11, which comprises most of the relevant guidelines from the four studied perspectives, is the CirculAbility Model© (Enel Group, 2018). This KPI was published by the Enel Group, which is part of Grid Solutions client portfolio corroborating to the defined priorities in the AHP (customer perspective). This KPI is a system for measuring the performance of products and processes. It incorporates the measurement of material and energy flows, being based on five pillars where each pillar presents a series of metrics:

1. Circular inputs: On the input side, material and energy flows are measured based on whether they originate from circular or non-circular sources.
2. New life cycles: On the output side, the measurement of material and energy flows depends on whether they are recycled or discarded as waste.
3. Sharing platforms: The measure of increased load factor when sharing a product is compared to the standard for that product.
4. Product as a service: Measures how much more demand there is for a product when it is offered as a service compared to its standard form.
5. Product life extension: Measures the product's shelf-life extension beyond its standard duration.

As a result, the model presents a Circularity Index (CI) based on the calculation of a Flow Circularity and Use Circularity, as presented in the equation below.

$$Ci = Cf + \frac{(1 - Cf)\ x\ (Cu - 1)}{2\ x\ Cu} \tag{15}$$

Where,

Cf: Circular flow, represents the circularity in flows of material and energy.

Cu: Circular Use, represents the circularity in the use approach.

$$Cu = \frac{L_{ex}}{L_{BAU}}\ x\ \frac{U_{sh}}{U_{BAU}}\ x\ \frac{U_{SAP}}{U_{BAU}} \tag{16}$$

Where:

L_{ex}: extended useful life (years) thanks to dedicated measures of design/ maintenance that can extend the useful life in a measurable and certified way.
L_{BAU}: standard useful life of the project/product (i.e. without dedicated measures).
U_{sh}: time of use of the asset (as % on total time) in case of sharing.
U_{BAU}: time of use of the asset (as % on total time) in Business as Usual case.
U_{SAP}: time of use of the asset (as % on total time) in case of ‘service as a product’.
U_{BAU}: time of use of the asset (as % on total time) in Business as Usual case.

$$Cf = \frac{\left(2 - (\frac{V}{T_i} + \frac{W}{T_o})\right)}{2} \tag{17}$$

This index considers the weight of not circular inputs on total inputs (V/T_i) and the weight of the waste that goes to final disposition (W/T_0).

where:

Ti: total inputs.
To: total outputs.
V: total input from not sustainable virgin material.
W: total output sent to disposal.

Model calculation in Appendix 9.

6.4 Testing the CirculAbility© KPI using LCA as a tool: an HV equipment study case

The selected indicator and the prioritised circular guideline in section 6.2 were tested through the LCA of one of GE's HV equipment in its four versions, conducted by the author of this study.

6.4.1 HV Product Characteristics

The performed study aimed to promote a comparative LCA of one Grid Solutions' HV equipment ancient and new design. The new design was studied in three versions, where materials were changed in quantity and quality. Therefore, four designs of the same equipment were analysed, quantifying environmental impacts across their entire life cycle, from cradle-to-grave[8]. The results are applied by the engineering team to weigh up possible environmental benefits and trade-offs of the new designs. The equipment composition is of confidential information since it is still not available in the market. Therefore, only percentage values are shared.

In this report design versions are called v1, v2, v3 and v4. v1 uses the highest material weight, while v4 uses the least (51.7% less than v1). Additionally, versions v3 and v4 had some material changes performed. However, as weight is set to decrease, energy losses in use phase tend to be higher, increasing environmental impacts at this stage. Some of the designs' characteristics are presented in Table 12 and from Figure 17 to 20.

Table 12: HV studied designs characteristics - mass and energy losses.

Equipment	Mass compared to v1	Energy losses compared to v1
v2	-44.62%	-2%
v3	-45.26%	-3%
v4	-51.67%	+24%

For the EoL scenario, demountable parts are landfilled. Dismantlable parts EoL are set according to the EN 50693 (EU, 2019).

Table 13: End of Life average treatment considered for dismountable parts.

Material	End of Life scenario
Aluminium	70% recycled, 30% municipal waste disposal
Steel	80% recycled, 20% municipal waste disposal
Copper	60% recycled, 40% municipal waste disposal
Polymers	60% incinerated with recovered energy, 50% landfilled
WEEE	75.66% recycled, 11.67% incinerated with recovered energy, 12.66% municipal waste disposal
Composites	50% incinerated with recovered energy, 50% landfilled
Inert Waste	100% landfilled

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[8] Considers the entire product life cycle, from raw material extraction to the product end of life.

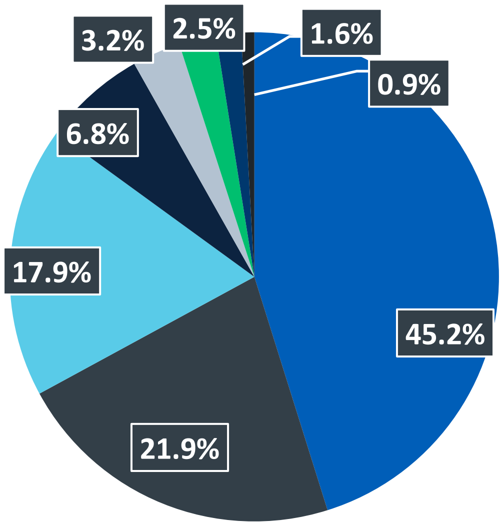

Figure 17: v1- Materials distribution by weight.

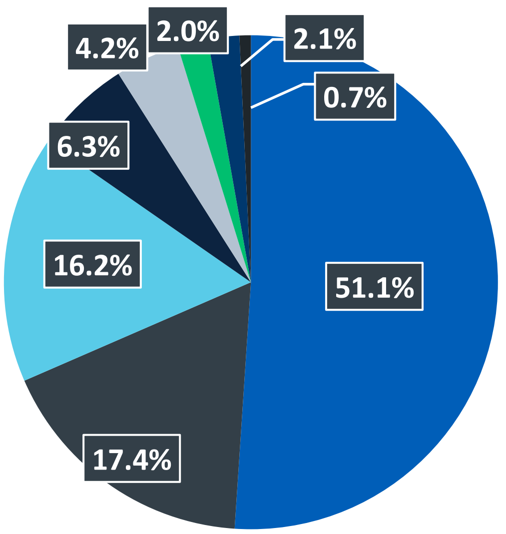

Figure 18: v2- Materials distribution by weight.

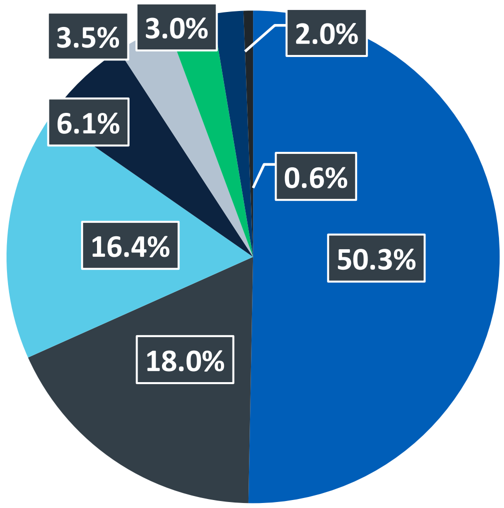

Figure 19: v3- Materials distribution by weight.

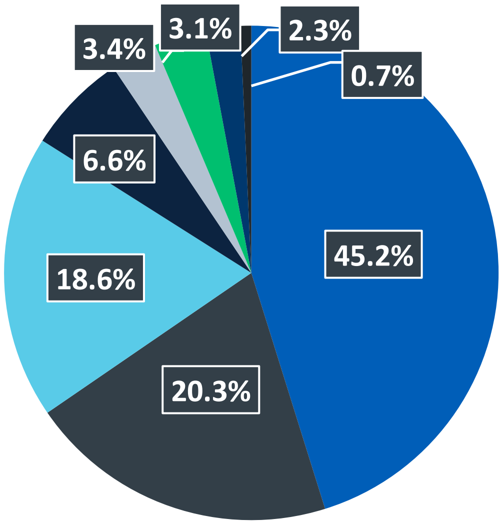

Figure 20: v4- Materials distribution by weight.

The LCA results show that highest impacts throughout the entire products life cycle are in the use phase. This is due to energy losses. Additionally, the second biggest impacts regard manufacturing, due to materials extraction and processing.

Comparing the four designs, v4 is the most impacting one. This is due to its increased energy losses. However, since it uses the least amount of materials, its manufacturing impacts are the lowest. v3 seems to present a more optimised design in terms of materials weight and losses.

6.4.2 Testing CirculAbility© indicator and Prioritised guidelines

From the developed graph in Figure 16: C-Guideline Importance vs. Difficulty. three actions were set as High Value: (1) Minimise energy consumption, (2) Minimise non-conformities, and (3) Repair. Upgrade is close to strategic. Thus, the circularity of these four guidelines are tested through LCA and the selected indicator. v1 was set as the baseline. The indicator value and the environmental impact indicator percentage are set as the increasing or decreasing value percentage according to design version 1.0.

For calculating the Circularity Index, material weight for the four designs were considered. Additionally, energy flows consider electricity lost at use phase, electricity needed at assembly phase and electricity used for equipment curing. Thus, the Circular Flow considers materials and energy inputs and outputs from the system.

HV equipments are not meant to be shared. They are installed and remain in a certain substation for usually 30 to 40 years. Considered indicators for calculating the Circular Use in Table 14.

Table 14: Circular Use – CirculAbility Indicator

Circular Use - Cu	Indicator	Value
Extended Useful life	Lex	40
Standard Useful Life	Lbau	30
Time of use of the asset in case of sharing	Ush	100%
Time of use of the asset in case of Business as usual	Ubau	100%
Time of use in case of product as service	Usap	100%
Time of use in case of business as usual	Ubau	100%

6.4.2.1 *Minimise Energy Consumption*

Minimise Energy Consumption is a guideline with multiple possible actions depending on the product characteristics, manufacturing process technology, inputs and outputs. Thus, the electricity consumption at the use phase was considered for testing. Additionally, electricity used for curing and assembly was considered. No recycled or reused material is set for the inputs. Output of dismountable pieces is set according to Table 13. Dismountable parts are set to be disposed.

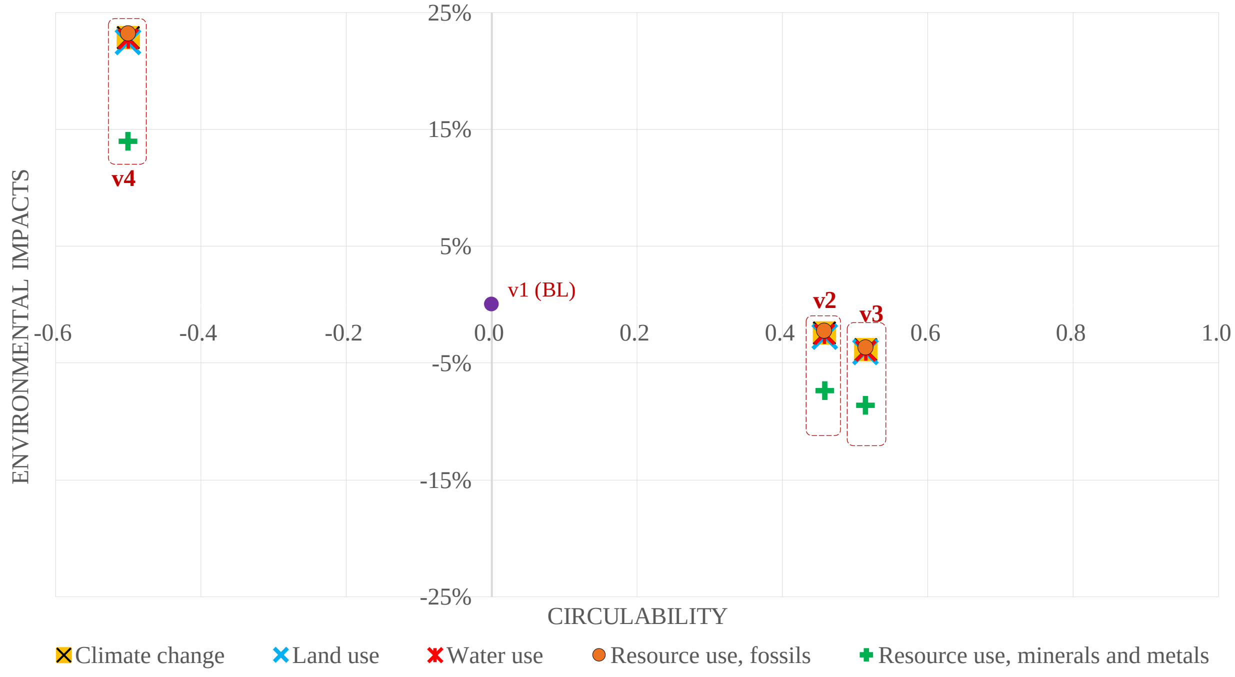

Figure 21: Minimise Energy Consumption Guideline Test using HV equipment LCA and CirculAbility© Indicator.

From the results presented in Fifure 21, even though v4 possess less material weight than the three other studied versions, it has decreased circularity. This is because of the increased energy flow due to higher energy losses at the use stage. Thus, more electricity shall be produced to compensate for these losses.

v3 seems to be an optimised design, where the CI increases by 51.45% if compared to version v1. Additionally, this version presents around 20% less environmental impacts compared to the set baseline, being resource use the most affected due to less materials used.

6.4.3 Minimise non-conformities

Set as one of the most relevant guideline for improving product circularity, non-conformities data is not available. This indicates that efforts shall be implemented to measure non-conformities. By this means, it would be possible to state the relevance of this priority with quantitative data from the business perspective.

6.4.4 Repair

The studied HV equipment is extremely low in maintenance during its useful life, where only painting is redone at specific points for visually maintaining the equipment in good condition. Additionally, no study on a relationship between this painting's maintenance and longer lifespan is available. Thus, this criterion is not tested. However, it is important to mention that this guideline is of high importance for GE’s product circularity and shall be extrapolated to other HV product circularity studies.

6.4.5 Upgrade

For testing environmental impacts and circularity indicators for upgrading from equipment v1 to v2, v3 and v4, a scenario where all accessories, foundation and support structure was set to be reused. The equipment core was set to be upgraded, and a new piece would be manufactured and transported until the client’s site since this equipment core is impossible to be dismountable. Thus, v1 was set as baseline, from cradle to crave, where the entire equipment would be produced but accessories, foundation and other structures would remain the same. Hence, not considering dismountable parts manufacturing but taking EoL of these parts into account (Figure 22).

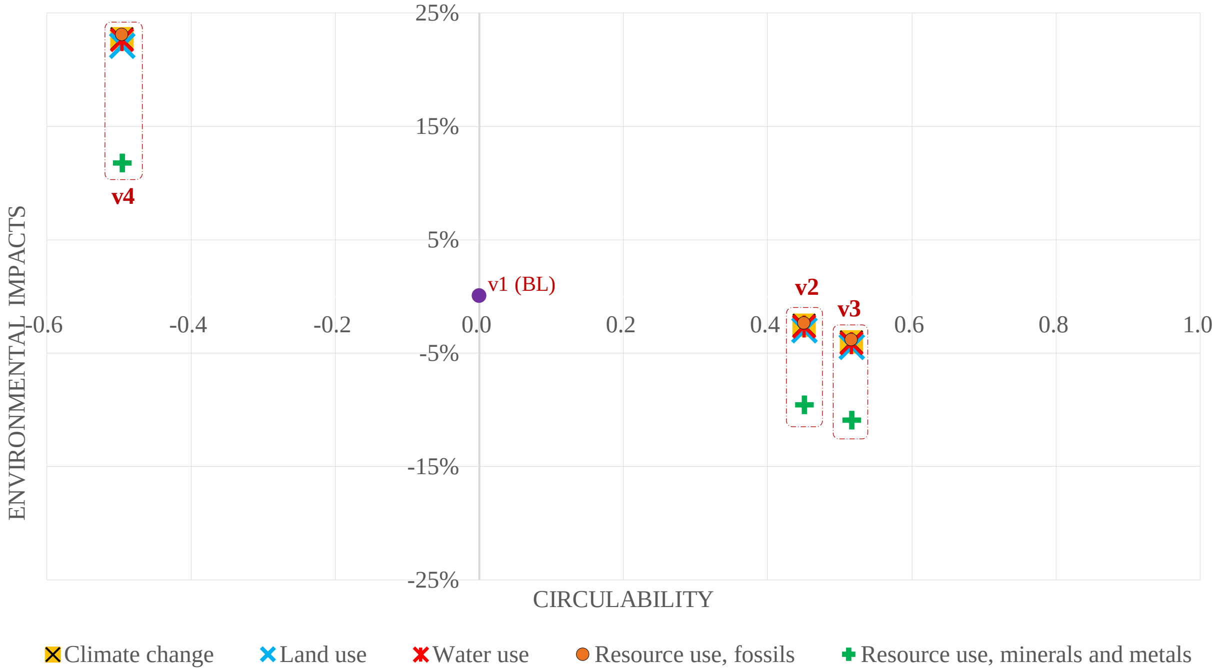

Figure 22: Upgrade Guideline Test using HC equipment LCA and CirculAbility (C) Indicator.

Since a significant amount of energy is lost at the use phase, the other circularity approaches do not present relevance for the Circularity Index, demonstrating the relevance of decreasing energy use in HV products. In this regard, a graph without use phase was made for comparative purposes (Figure 23). Nevertheless, all life cycle phases shall be considered when studying product circularity.

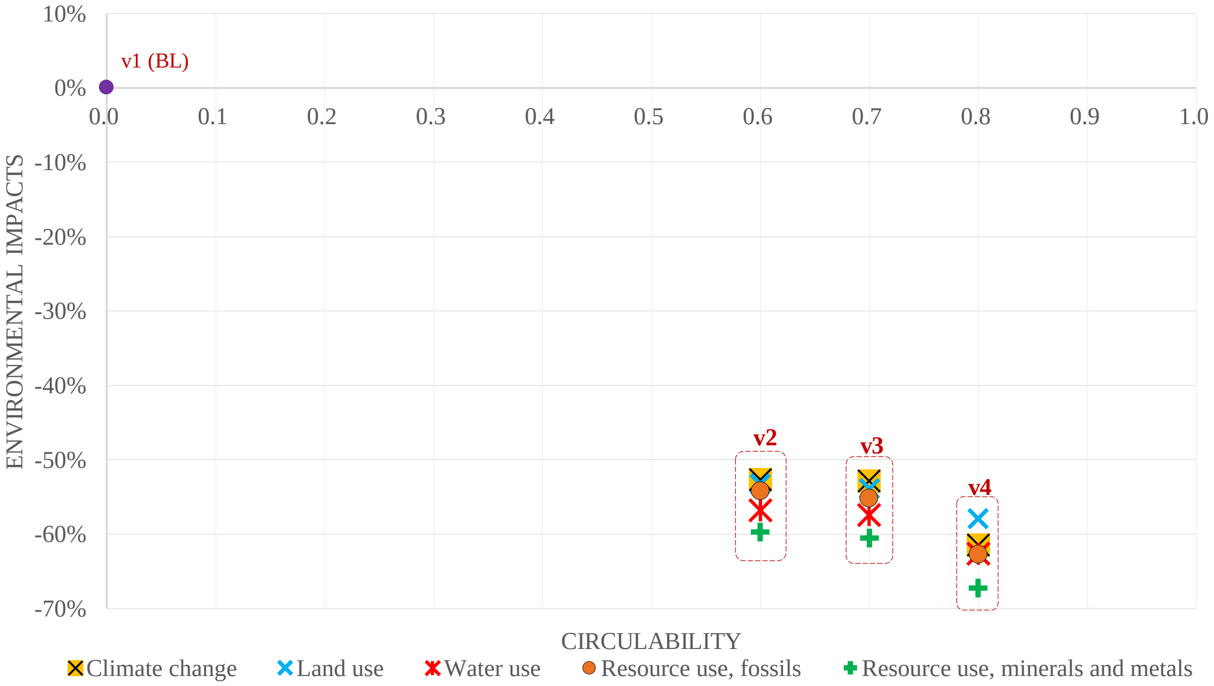

Figure 23: Upgrade Guideline Test using HC equipment LCA and CirculAbility (C) Indicator – without use phase.

The graph shows that the circularity index increases the most for v4, since no energy losses are being considered. This is because this version uses the least material weight. In this regard, it is possible to state the importance of narrowing materials and that energy losses indeed account for a critical share of environmental negative impacts and should be treated as a top priority.

6.5 Tools and processing enhancement

6.5.1 NPI Process

For achieving circular products, Ecodesign strategies shall be implemented in a product's early design stages. From the outputs of the present study, recommendation for NPI process are:

1. Gap Analysis: assess the current state of NPI processes within Grid Solutions. Identify gaps and opportunities for improvement regarding circularity integration and evaluate the company's Ecodesign maturity level.
2. Framework definition: for engineers and designers to work together with Ecodesign team. Make available Circular Design Guidelines for NPI targeting the prioritised strategies in this report and LCA equipment's performance. Additionally, implementing a tool for circularity calculation and analysis of the in development product.

Paula Pinheiro et al. (2018) state that some guideline, methods and tools are valuable for integrating product portfolios and Ecodesing (Figure 21). Proposals regard, among others, Ecodesign checklists to verify whether environmental parameters are being considered in the product development; integration with stakeholders; create a transversal working group, incorporating strategies and suggestions on making the process effective.

Figure 24: Framework for integration between product portfolio management and Ecodesign. Source: Paula Pinheiro et al. (2018)

6.5.2 Company Reporting

Extra financial reporting is vital for a business health, providing an insightful description of its impact across ESG realms. The following aspects can be mentioned in Grid Solutions reporting:

- Present LCA studies and Circularity Index of products, where presenting actions towards enhancing product sustainable circularity and transparently identifying areas for improving the equipment's environmental performance through a clear action plan can be valuable.
- Use carbon footprint tools, such as Product life cycle GHG accounting[9] to assess emissions associated with a product and actions towards reducing it.
- Present how the company engages with stakeholders, especially customer.

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[9] Product Life Cycle Accounting and Reporting Standard (2021).

7 CONCLUSION

This study aimed to propose and rank the best Ecodesign strategies and their respective guideline towards Grid Solutions' product circularity from a transversal business perspective, presenting the best suited indicator for measuring improvements and sustainability drawbacks. To achieve this goal, AHP method was used through an extensive literature review, where LCA is used as a tool for assessing circularity trade-offs together with the CirculAbility© Model.

While environmental factors are essential for driving sustainable circular products, the research highlighted the need to analyse strategies from a business perspective, considering the importance of customer satisfaction and financial standpoint especially. Although prioritising strategies is needed, knowing which action to tackle first is vital for developing an action plan successfully. In this regard, the Difficulty vs Importance matrix provide valuable insights, ensuring that high-value and strategic measures are addressed accordingly. However, lower-ranked actions should not be disregarded, as their implementation is key toward achieving product circularity entirely.

Energy consumption emerged as a crucial aspect for sustainable circularity. This corroborates the demonstrated through the LCA study case, where use phase has the biggest environmental impact shares, which has been the case for most LCAs conducted by the EM CoE team. In this regard, optimising design can be a key solution, as per demonstrated through v3 design.

For Upgrade guideline, a scenario where the equipment core is substituted was set. However, for other equipment, modelling would most probably differ. Since the studied equipment is low in maintenance, and the equipment core is undismountable, this guideline was not tested. Nevertheless, it is essential for increasing grid electrical products' lifespan and must be addressed for other products. Thus, focusing efforts on improving data collection for LCA, including non-conformities, which could not be tested, is key to ensure accurate and comprehensive analysis.

The conducted work provided insights and recommendations to enhance Grid Solutions' sustainable product circularity and ESG reporting, where the CirculAbility© was assessed as the most relevant indicator from the conducted literature review through an overall business perspective. It is worth mentioning that this model was developed by Enel, which is one of Grid Solutions' valuable clients. Therefore, corroborating with findings from the AHP where customers emerged as the most relevant business perspective.

However, while the Circularity Inex provides insights, it should not be the sole basis for defining a product's sustainability. Instead, it should be set in conjunction with LCA to comprehensively assess trade-off and ensure a more holistic evaluation of environmental impacts associated with a product's life cycle step.

8 RECOMMENDATION

Collaboration and knowledge-sharing among various teams becomes vital in driving circularity initiatives throughout the organisation. Thus, establishing an interdisciplinary and cross-functional working group is recommended. This group would lead a comprehensive discussion on practices and frameworks targeting an effective implementation of Ecodesign towards sustainable circularity and strengthen NPI process in a more dynamic way.

This collaborative approach would enable to identify synergies, solutions, and the integration of Ecodesign principles across different product lines, being also valuable for discussing the strategies' difficulty of implementation and making it more precise, targeting actions accordingly. It is recommended to implement High-Value and Strategic actions ins a phased manner through an action plan.

Additionally, is advised that the company measure, monitor and make available data on non-conformities. Depending on the extension of it, implement an action plan towards its treatment. Moreover, as per the comparative LCA conducted, develop Repair vs. Lifespan Increase study would enable to assess the data driven benefits of improving reparability and the extent of that. In this line, a mass increase vs. energy losses and lifespan curve would also allow to find an optimal point where less material weight is used, to have the most extended lifespan possible with the lowest energy losses at the use phase.

To demonstrate the commitment to sustainable circularity, the company can communicating the progress made in implementing with the CirculAbility Model©. Nevertheless, it should not be solely implemented in order to assess sustainability trade-offs as well. Furthermore, as a next step, identify key suppliers and engage them in discussions on circularity and sustainable sourcing can be valuable.

9 LIMITATIONS

Limitations of this study regard two main points: (1) the availability of experts from the transversal business perspectives to conduct the AHP analysis and (2) data availability.

Selecting an expert group holds immense importance in the AHP method, as it translates experts' judgments into meaningful mathematical values, being instrumental in the decision-making process.

Being a management tool, the difficulty vs importance matrix provides an overall idea of addressed strategies. In this study, importance was based on well-defined criteria from the AHP analysis, and difficulty from the EM CoE expertise. To provide more assertive assessment, a discussion can be performed with multiple managers from different departments and perspectives within GE. However, the matrix remains relevant as it can provide informed and reasonable assessments for the company.

Additionally, some guidelines set as top priorities could not be tested using LCA due to a lack of data. This regards especially non-conformities. Nevertheless, this also represents an outcome of the present study, which shows that efforts toward measuring and monitoring this data are needed.

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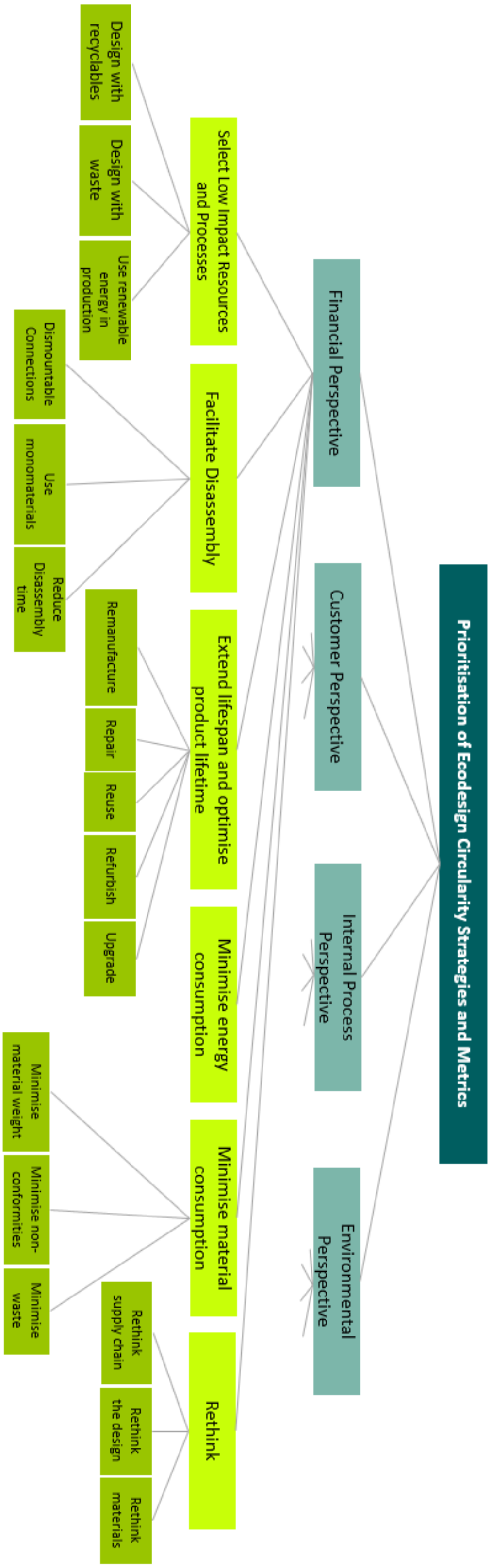
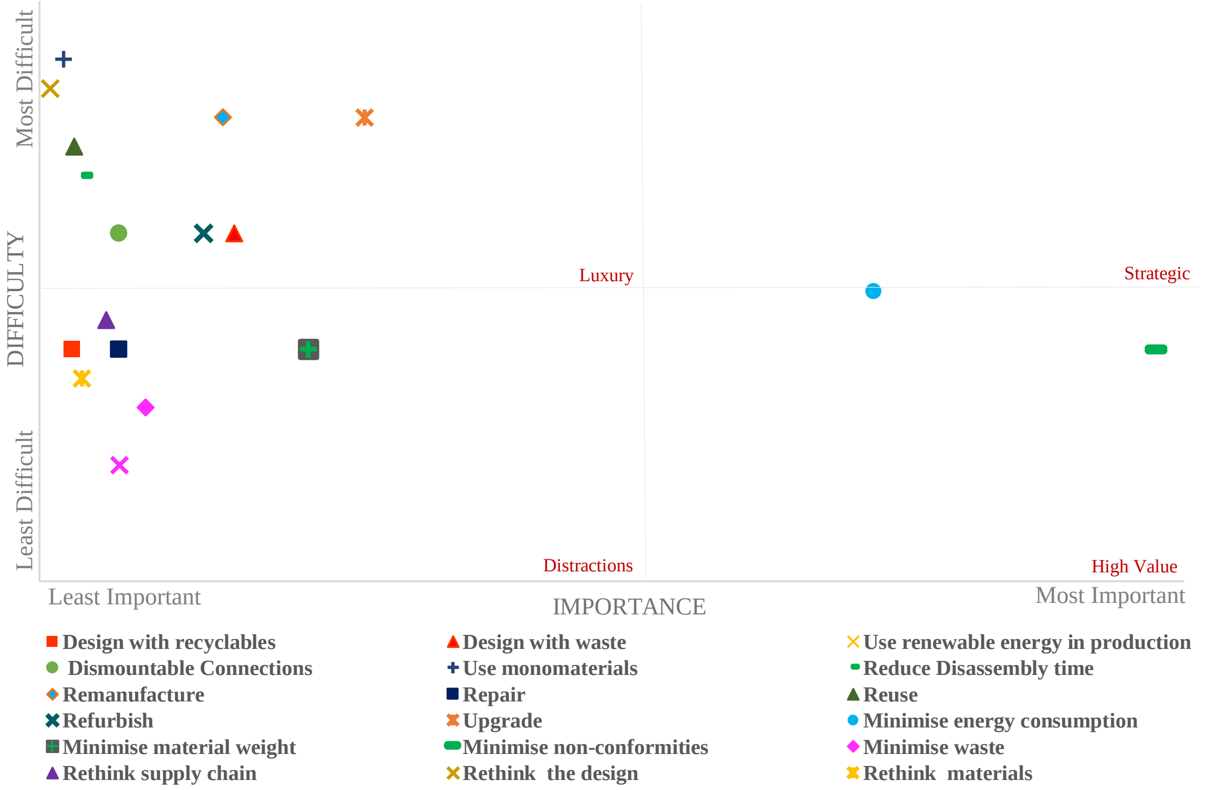
Appendix 1: AHP Hierarchy diagram

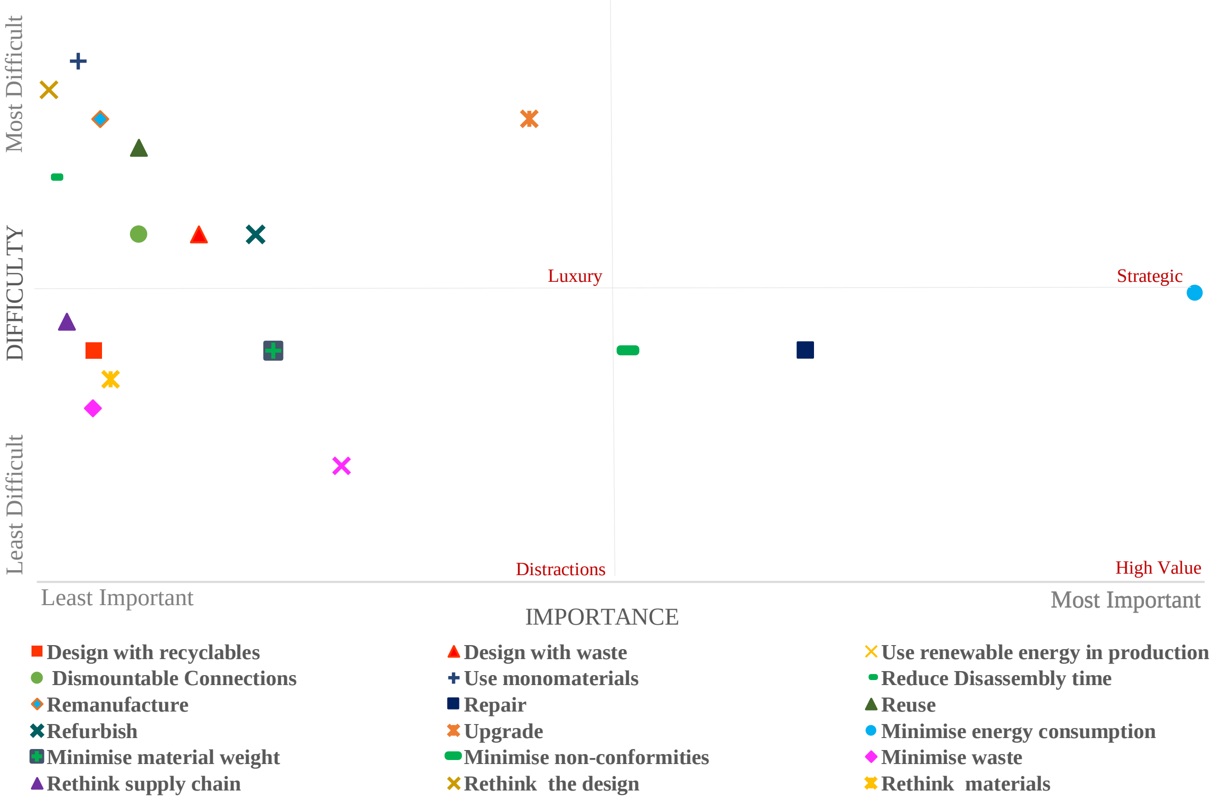


Appendix 2: Overall prioritisation, C-Ecodesign strategies and guideline

Appendix 3: Difficulty vs Importance Matrix - Financial Perspective



Appendix 4: Difficulty vs Importance Matrix - Customer Perspective



Appendix 5: Difficulty vs Importance Matrix - Environmental Perspective

Appendix 6: Difficulty vs Importance Matrix - Internal Processes Perspective

Appendix 7: Analysed Circularity Indicators

Indicator	Acronym	Definition	Type	Scale	Specification/limitation	Data/factor/information needed
Disassembly Effort Index	DEI	Total operating cost to disassemble a product. The score can be compared against the projected market value of the disassembled and subassemblies parts to get an economic measure. Applicable in manual disassembly cases.	Quantitative Qualitative	0-100	Considers: product handling; disassembly worker training and instructions, product disassembly and part and material handling. Collection is considered an unavoidable cost, hence, not considered. Does not give an exact cost. It rather produces a valid evaluation that can be used in disassembly decision making	factors considered: (i) time (ii) tools (iii) texture (iv) access (v) instruct (vi) hazard (vii) force requirements.
Circular Economy Toolkit	Ce toolkit	It uses product lifecycle steps to formulate questions and answer choices ranked from a “least ideal” to a “most ideal” circularity choice.	Qualitative	Low=1 ; Medium =2; High = 3	It is a non-points online test and provides qualitative results.	The questions relate to design, manufacturing and distribution (7); usage of the product (3); product maintenance and repair (6); product reuse and redistribution (3); refurbish and remanufacture (10). Two of them relate to product-as-a-service, and two to product recycling at EoL.
End of Life Index	EoL-I	Uses AHP. Indicator for assessing EoL performance of products. Provides a combination of values corresponding to the relative performance of the product within the accessible EoL choices during all the stages of design	Quantitative	0-10	The major sub indicators are constituted by disposal, disassembly and recovery. Further decompositions are developed for each of the sub indicators, until the simplest estimable measurements are obtained. Various sub-indicators are calculated using weights and indicator values from the EoL scale tables	Considers sub-indices for: - disposal (time, environmental impact and value of recycling the material) - disassembly (time) - recycling (value of material, time, energy recovered) - remanufacturing (value of remanufactured material, time)
Recycling Indicator set	RIS	Set of 4 indicators in accordance with WEEE directive: - weight recovery of target materials (consider recycling impurities) - Recovery of critical materials - Closure of materials cycles - Avoided environmental burdens	Quantitative	0-1	Outputs allow visualisation of trade-offs that need to resolve for improving the recovering efficiency	Calculated when the input and output structures of the WEEE recovering tasks are identified, including transparency, market price and output fraction efficiency.
Reuse Potential Indicator	RPI	Specify how “resource-like” versus how “waste-like” specific materials are on a continuum. The underlying idea of the reuse potential indicator is that what creates a reuse opportunity for a waste material is the knowledge of where and how to use it	Quantitative	0-1	Rely on technological development, is dynamic and not an inherent property of waste. The reuse potential increases as technological options increase, enabling more material recovery. This indicates that the concept of reuse potential is inherently time dependent. Also dependent on the geographical location.	Present numbers are valid for the emissions in the EU28 for 2015 as these emissions have been used in calculating the weights of each individual pollutant. *Presents the amount of material that can be reused through available technologies against its marginal revenue earned by selling processed materials minus disposal costs at capacity
CE index	CEI	Key Recycling Info sheet for data collection (data from materials used in the design and gross value added). Relationship between the value of the material realised by the recycler to the intrinsic material value entering the recycling process.	Quantitative	Economic value	Supports the use of new technologies, jobs and rection of externalities.	Material value recycled from EoL products/material value needed for (re)producing EoL products

Material Circularity Indicator	MCI	Instrument for European companies to evaluate performance and circularity of their products and BM. It allows firms to recognize added and circular value of their products, materials and components, and attenuate hazards derived from price volatility and supply	Quantitative	0-1	Primarily addressed to product design, but it can also be utilized in house reporting or for procurement and investment choices. Considers material flows.	Comprises multiple sub indicator. For instance: fraction of recycled sources, fraction of reused sources, Fraction of biological material, mass of finished product, fraction of mass collected for recycling at EoL, mass going to energy recovery, lifetime, among others.
Recyclability benefit rate	RBR	Ratio between the potential environmental savings attained from recovering the product and the environmental exploitation deriving from the use of virgin resource in the production and subsequently, through their disposal.	Quantitative	Functional unit	Quantify the environmental impact in terms of resource consumption using the Cumulative Exergy Extraction from the Natural Environment method. Does not consider the potential substitution of different materials occurring in open-loop recycling.	Data obtained through the LCA of a product. Ratio of the potential environmental savings that can be achieved from recycling the product over the environmental burdens of virgin production.
Eco-cost Value Ratio	EVR	Applied to evaluate weakness environmental linked to business models and to offer a new model on which giving useful information based on costs, eco-costs and market value.	Quantitative	Economic value	Eco-cost is a virtual cost	Eco-cost/value
CE Indicator prototype	CEIP	Assess product performance in the framework of CE.	Qualitative	least ideal; most ideal	15 questions. Available upon demand	-
Synthetic Economic Environmental Inidcator	SEEI	Uses Global Cost method and is presented as a monetary measurement to sustain investment decisions. The Global Cost method reflects initial investment and amount of annual and disposal costs. Environmental impacts are also considered.	Quantitative	Economic value	Considers environmental indicators at the end of life (level of disassembly, recycled materials quantity, waste production quantity), embodied energy, and embodied carbon and its costs	Indicators from LCA and LCC
Logevity Inidicator	LI	Assessment of the average life of product and material utilisation. Value oriented approcha (non-monetary)	Quantitative	time unit	Needs secondary data. Primary data would be difficult to find	Time spent in each life cycle step. How many additional months are gained due to return, refurbishment, reuse. Track the recycled lifetime contribution as a result of product being recycled
Material Reutilization Score	MRS	Design approach combining various aspects: safe materials, continuous recovery and reuse of materials, clean water, renewable energy and social equity	Quantitative& Qualitative	from bronze >=35 to platinum 100	Does not consider the disassembly or if the material will be easily dismantled	% recycled or rapidly renewable product content % of product recyclable or biodegradable
Recycling Indices	RI	Could no download the article		0-100%		Calculation not clearly stated. Calculate with a software which considers the elements in a product
CE Performance Indicator	CPI	It is obtained from the relationship between the actual obtained environmental benefit and the ideal one, considering its quality. These environmental advantages regard the natural resources consumption and be assessed through LCA.	Quantitative	Functional unit	To define the most appropriate waste treatment alternative, four possible waste treatment options are considered: I) closed-loop recycling; II) semi closed-loop recycling; III) open-loop recycling and IV) incineration (assuming that option I is the best and option IV is the least desirable).	Actual benefit (of currently applied waste treatment option) divided by the ideal benefit according to quality
Product-level circularity Metric	PLCM	Relationship between the re-circulated economic value and the total product value. It converges on circularity product structure in terms of raw and recycled materials and the necessary actions to recycle materials.	Quantitative	0-1	Combined product parts equation available	Economic value of recirculated parts and economic value of all parts

Value-based Resource Efficiency Indicator	VRE	Estimates resource efficiency and circularity. It considers aspects that regard product and service values, i.e. the prices of exploited resources	Quantitative	Economic value	Considers the input value of energy, material qnd services. Thus, by decreasing costs to used resources, the VRE increases	It is the output valu / sum of volume weight of resources.
End -of-Life Indices		Help defining the best EoL regarding sustainability of each scenario, evaluating revenues and costs of each strategy.	Quantitative	Economic value	Three indicators regarding recycling, remanufacture and reuse are used	Needs complex inputs for all product assemblies regarding recovery index, dismountable connections etc.
Product Reuse Index	CRP	Metric designed to help supply chain managers compare single-use products with reusables whose lifespan can be extended with maintenance, reuse, repair, etc.	Quantitative	%	Needs an understanding and data on reuse repair etc strategies.	CRP =(1-1/n.of potential cycles)×100,
Product Cycle potential	CPP	Designed to help supply chain managers assess the potential of a product without knowing future material flows. Defined as the ratio of the mass (or economic value) of materials or components within a product that are potentially reusable and the total product mass (or economic value)	Quantitative	%	Sub indicator of the CRP	CPP =MPUM + MPRM + MPCMMTP×100 PUM is the mass (or economic value) of components that could be remanufactured or repurposed for future products, MPRM is the mass (or economic value) of materials that could be recycled, MPCM is the mass (or economic value) of materials that could be composted, and MTP is the total mass (or economic value) of the product
Percent of reusable compoents	CPUM	Ratio of the mass (or economic value) of components within a product that are potentially reusable and the total product mass (or economic value)	Quantitative	%	Sub indicator of the CRP	CPUM =MPUM/MTP×100
Percent of recyclable materials	*CPRM*	Ratio of the mass (or economic value) of materials within a product that are potentially recyclable and the total product mass (or economic value).	Quantitative	%	Sub indicator of the CRP	CPRM =MPRM/MTP×100
Product Cycled Content Index	CCP	It is a backward-looking metric designed to help supply chain managers assess the content used in a product that came from post-consumer, EOL sources	Quantitative	%	Sub indicator of the CRP	CCP = (MPUU + MPRU)/MTP×100 MPUU is the mass (or economic value) of components from post-consumer remanufactured or repurposed sources, MPRU is the mass (or economic value) from post-consumer recycled (PCR), and MTP is the total mass (or economic value) of the product
Percent of used components in a product	CPUU	Ratio of the mass (or economic value) of post-consumer components within a product and the total product mass (or economic value).	Quantitative	%	Sub indicator of the CRP	CPUU =MPUU/MTP×100
Percent of recycled materials used in a product	CPRU	Ratio of the mass (or economic value) of PCR materials within a product and the total product mass (or economic value)	Quantitative	%	Sub indicator of the CRP	
Recycling Desirability Index	RDI	New approach to prioritising product recycling. consider material scarcity, and availability and security of technology, for modelling a method able to capture the desirability of product recycling	Quantitative	0-2.5		products simplicity, material security index of constituent materials and the maturity of technologies for reclaiming the materials

Sustainable Circular Index	SCI	This index represents an important benchmarking tool for manufacturing companies to assess their sustainable and circular behavior and represents a guideline for managers	Quantitative	0-1		-Input in the production process from virgin, recycled and reused components - Utility during the use phase - Efficiency of recycling - Rate of non-hazardous waste - rate of hazados waste - Amount of water -Amount of energy
Global resource Indicator	GRI	Incorporates various aspects of resource appraisal to enhance resource characteristics. Various attributes related to accessibility, involving both geopolitical availability and recyclability of resources, constitute the multi-criteria indicator to complement the resources deficiency	Quantitative	0-10		
Linear Flow Index for product families	LFI2	Measures the proportion of material flowing linearly, that is, from virgin materials and up to unrecoverable waste.	Quantitative	Structure of product families	complexity of this calculation depends on the number of components or modules and the number of different manufacturing materials	Vj is defined as the mass of virgin feedstock used to manufacture a j product variant. Wj is the mass of unrecoverable waste associated with a j product variant manufacturing, Mj is the total mass of the product variant, Wfj is the mass of unrecoverable waste generated when producing recycled feedstock for the j product variant, and WCj is the mass of unrecoverable waste generated in the process of recycling parts for the j product variant.
Potential reuse index	PRI	Measurement of the degree of potential reuse of components between different product variants within the product family	Quantitative	0-1	A potential considering the expected ideal reuse of components. The user is responsible for the reuse, not products and components.	mass of reusable components, number f times the component is reused in the prodct family and the total mass of the product family]
Potential Recycle index	PReI	Measurement of the degree of potential recycling of components within the product family	Quantitative	0-1	material flow balance is not 100% conservative in the product lifecycle due to the recycling process efficiency, which involves an unrecoverable waste fraction that is generated.	Mi is the mass of the i component, Fi is the fraction of recyclable mass of the i component, Ei is the efficiency of the recycling process for the same component, Mt is the total mass of the product family, and n is the number of modules or components involved in the product family
Circularity Design Guidelines	CDG	Methodology to examine how a product's design matches the recommendations from CE point of view and determines which attributes should improve product integration with circular economy models.	Qualitative	High; Medium; Low		
Combination matrix	CM	Combines both longevity and circularity methods. Two-dimensional indicator combining: 1. Circularity can be described as the sum of three contributions: "initial use"; "refurbishment" and "recycling". 2. Longevity is expressed as: the initial lifetime of the product; recycled lifetime and refurbished lifetime contributions.	Qualitative	Low-High	Qualitative data. Only mentions refurbish. Hence, not very comprehensive	Expressed in the number of times a resource is used in a product system.

Effective Disassemby Time	EDT	Methodology for assessing the effective disassembly process for industrial products	Quantitative	Minimum Corrective Factor: 0.91	Data on types of connectors, liaison type, and standard disassembly time are needed	Needs sub indicators such as standard disassembly time, it is based observation/classification/elaboration of data from real de-manufacturing activities.
Ease of Diassembly Metric	EDM	Calclates the disassembly time based on the Maynard operation sequence technique (MOST)	Quantitative	Time for disassembly	Gives ideas on changing design	1. Disassembly sequence of components 2. disassembly sequence of connectors components 3. number of connectors 4. number od product manipulations 5. Identifiabiliy 6. Tool type
PROduct PROfiles tool	RProProfile	Tool to assist designers in the development of durable products		External and internal criteria	It helps clarify the objectives and requirements for the end of life of the product.	
Circularity Calculator	CC	Online tool to help measure circularity		%.	Free version available. However, the most complete one shall be bought	Presents parts in remanufacturing, refurbishment, recycling cycles
CirculAbility (Enel)	CirculAbility	Circularity indicator defined through inputs and outputs of a system. Data regarding material and energy flow needed. Electricity is converted in mass terms in order to create a single indicator for measuring circularity.		0-1	Considers recycled used and waste output sent to recycling or other. Can give insights on design with waste	Measured in terms of circular flow and use. Requires data on energy and material cycles. Details in Appendix

Appendix 8: Indicator Analysis According to the Respective Guideline Measured

	Indicator		**Select Low Impact Resources and Processes**			**Facilitate Disassembly**			**Extend lifespan and optimise product lifetime**					**Minimise energy consumption**	**Minimise Material consumption**			**Rethink**		
	Name	*Abbreviation*	*Design with recyclables*	*Design with waste*	*Use renewable energy in production*	*Dismountable Connections*	*Use monomaterials*	*Reduce disassembly time*	*Remanufacture*	*Repair*	*Reuse*	*Refurbish*	*Upgrade*	*Minimise energy consumption*	*Minimise material weight*	*Minimise non-conformities*	*Minimise waste*	*Rethink supply chain*	*Rethink design*	*Rethink materials*
1	Disassembly Effort Index	DEI				•		•												
2	Circular Economy Toolkit	Ce toolkit	•			•	•	•	•	•	•	•	•	•	•		•		•	•
3	End of Life Index	EoL-I	•			•		•	•											
4	Recycling Indicator set	RIS	•				•										•			•
5	Reuse Potential Indicator	RPI	•								•						•			
6	CE index	CEI	•	•													•			
7	Material Circularity Indicator	MCI	•			•					•				•		•			•
8	Recyclability benefit rate	RBR	•		•												•			•
9	Eco-cost Value Ratio	EVR																		
10	CE Indicator prototype	CEIP	•	•	•		•			•	•			•	•		•	•		•
11	Synthetic Economic Environmental Inidcator	SEEI																		
12	Logevity Inidicator	LI	•							•	•	•								
13	Material Reutilization Score	MRS	•																	
14	CE Performance Indicator	CPI																		
15	Product-level circularity Metric	PLCM	•								•									
16	Value-based Resource Efficiency Indicator	VRE												•	•					
17	End -of-Life Indices	0	•						•		•									
18	Product Reuse Index	CRP							•	•	•	•								
19	Product Cycle potential	CPP	•						•											
20	Percent of reusable compoents	CPUM				•					•									
21	Percent of recyclable materials	CPRM	•																	
22	Product Cycled Content Index	CCP	•						•	•	•	•								
23	Percent of used (remanufacture/repurpose) components in a product	CPUU							•		•									
24	Percent of recycled materials used in a product	CPRU	•																	
25	Recycling Desirability Index	RDI	•			•	•												•	

26	Material Security Index	MSI																	
27	Sustainable Circular Index	SCI	•											•		•			
28	Global resource Indicator	GRI	•														•		•
29	Linear Flow Index for product families	LFI2	•													•			
30	Potential reuse index	PRI									•								
31	Potential Recycle index	PReI	•				•									•			•
32	Circularity Design Guidelines	CDG	•			•	•	•		•	•		•		•	•		•	•
33	Combination matrix	CM	•									•							
34	Effective Disassemby Time	EDT				•		•											
35	Ease of Diassembly Metric	EDM				•		•										•	
36	Remanufacturing with the aid of the PROduct PROfiles tool	RProProfile	•			•	•		•	•	•			•	•			•	
37	Circularity Calculator	CC	•						•			•							
38	CirculAbility (enel)	CirculAbility	•	•	•					•	•			•	•	•			

Appendix 9: CirculAbility Model© by Enel

CirculAbility Model ©

Methodological approach

Summary

1. Overview

Circular Economy represents a huge opportunity in terms of innovation, competiveness and environmental sustainability. As it covers many different fields of applications, one of the main challenges has always been the definition and the implementation of effective KPIs in order to measure, compare and improve circularity in projects and products. The definition of circular KPI is so difficult to be approached both for the fact that it is a relatively new topic and for the wide range of topics make it difficult.

Enel is developing many initiatives in the field of Circular Economy and, with the aim of further improving its activities, developed its own approach on KPIs. The aim of the approach is to define a final KPI that can be considered as a proxy of all the circularity parameters of the product or of the project.

Main challenges consist in the fact that:

- Physical indicators (e.g. renewable input) and use indicators (e.g. load factor') have to be compared
- Within physical indicators, it is necessary to compare both material flows and energy flows

The most straightforward solution would be to define different indexes, one for each homogeneous category, but such an approach would make the approach ineffective as an overall indication would be missing. For this reason, we preferred to define a final single index, based on some assumptions:

- Inclusion of some empirical formulas, i.e. not related to physical considerations but useful to achieve the target of a single indicator
- Taking into account of energy through their conversion into the material (i.e. in kg) used to produce such an amount of energy
- Use indicators that are pure numbers, through the use of ratios

The model considers an overall circularity index, Circular Index (C_i), so defined:

$$Ci = Cf + \frac{(1 - Cf) \times (Cu - 1)}{2 \times Cu}$$

The rationale of this formula is the following:

- The first addendum Circular Flow (C_f) consider the contribution in terms of circular inputs and outputs of material and energy
- The second addendum considers (1 - C_f) therefore the 'not circular contribution' from energy and material inputs/outputs and multiplies it for a component that considers a 'use factor' to consider what was the load factor of this 'not circular' contribution. The use factor is defines as:

$$\frac{(Cu - 1)}{2 \times Cu}$$

It is an empirical formula that let to take into consideration the use factor but with a weight within the range [0; 0,5] where:

C_f, Circular Flow: represents the circularity in the flows of materials and of energy

C_u, Circular Use: represents the circularity in the use approach

2. Circular Use

This indicator considers the solutions adopted to increase the load factor of an asset. The environmental benefit is related to the fact that if the same asset is used for example from two users, the amount of assets required is halved and therefore the consumption of material and of energy. This indicator is defined starting from three sub indicators:

$$\boldsymbol{Cu} = \frac{\boldsymbol{L}_{\mathrm{ex}}}{\boldsymbol{L}_{\mathrm{BAU}}} \times \frac{\mathrm{U}_{\mathrm{sh}}}{\mathrm{U}_{\mathrm{BAU}}} \times \frac{\boldsymbol{U}_{\mathrm{SAP}}}{\boldsymbol{U}_{\mathrm{BAU}}}$$

Where:

- L_{ex}: extended useful life (years) thanks to dedicated measures in terms of design/maintenance that can extend the useful life in a measurable and 'certified' way
- L_{BAU}: standard useful life of the project/product (i.e. without dedicated measures)
- U_{sh}: time of use of the asset (as % on total time) in case of sharing
- U_{BAU}: time of use of the asset (as % on total time) in Business as Usual case
- U_{SAP}: time of use of the asset (as % on total time) in case of 'service as a product'
- U_{BAU}: time of use of the asset (as % on total time) in Business as Usual case

All the above benefits have to be clearly defined and measured, i.e. generic benefits cannot be taken into account but only dedicated and specific ones.

2.1 Life extension

Consider the extension of the useful life of a product or project thanks to solutions such as modular design, predictive O&M, etc. These solutions have to be innovative and not be standard market solutions

2.2 Sharing

Through sharing it is possible to highly increase the load factor. With sharing we mean the sharing of an asset among two or more customers in a 'client to client' relationship.

2.3 Product as a service

The benefit related to the product as a service is because the Company does not sell a product to the client but just the service (i.e. the use); in this way it is possible to have one asset used from many client allowing an increase of the load factor.

3. Circular Flow

This indicator measures the circularity in the use of resources, with the aim of considering the effort to reduce not sustainable inputs and waste. The used formula is the following:

$$Cf = +\frac{\left(2-\left(\frac{V}{Ti}+\frac{W}{To}\right)\right)}{2}$$

This index considers the weight of not sustainable inputs on total inputs (V/T_i) and the weight of the waste that goes to final disposition (W/T_0); where:

- *T_i: total inputs*
- *T_o: total outputs*
- *V: total input from not sustainable virgin material*
- *W: total output sent to disposal*

That are so computed

$$Ti = RC_i^n + RU_i + RES + V$$

where:

- *$RC^n{}_i$: total net input from recycle*
- *RU_i: total input from reuse*
- *RES: total input from renewable and from input reduction (efficiency)*
- *V: total input from not renewable virgin material*

$$To = RC_o^n + RU_o + O + W$$

where:

- *$RC^n{}_o$: total net output sent to recycle*
- *RU_o: total output sent to reuse*
- *O: output included in the final product*
- *W: total waste to disposal*

W is computed as

$$W = WRC_i + WRC_o + W_o$$

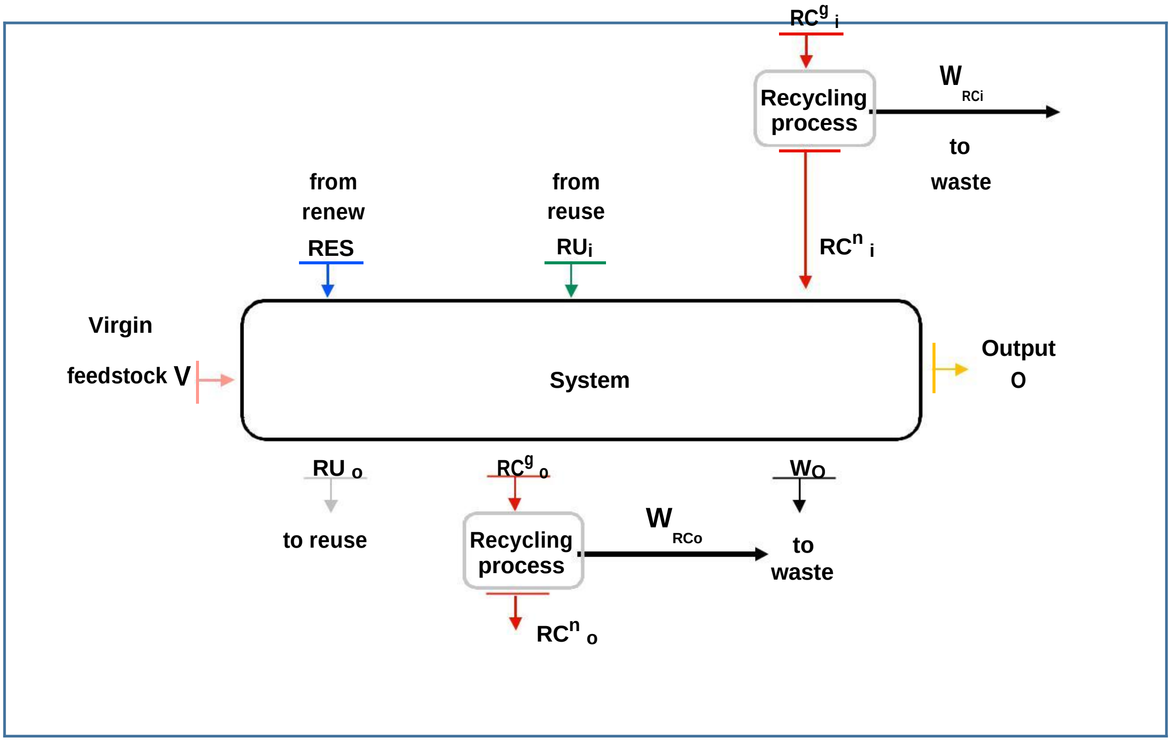
- *WRC_i: waste produced in the recycle phase before an input*
- *WRC_o: waste produced in the recycle phase after an output*
- *W_o: waste produced in the main process of our system*

Any of the variables considered in 'Circular use' is made up of two components, one related to materials and on to energy

The overall analysis that provides 'Circular Flow' indicators is therefore realized starting from four components:

- Materials inputs
- Energy inputs
- Materials outputs
- Energy outputs

The following figure provide an overall representation of the flows:



3.1 Material inputs

Considered indicators are the following:

3.1.1. Renewable materials (RES):

Represents the sum of the amount of renewable materials used. It's calculated by multiplying the total weight of each single used material for the related source percentage from renewables.

3.1.2. Input materials from reuse (RU i):

Represents the inputs from reuse (materials weight) that are calculated by multiplying the total weight of each single used material for the related source percentage from reused materials.

3.1.3. Input materials from recycle (RC i):

This indicator represents the amount of material from recycle. At first it is considered the amount of 'gross' material from recycle (RC^g_i) that is the output of a process before the process we are considering; then the net value is computed as difference between RC^g_i and WRCi (that is the waste produced during this recycle process). The result of this difference represents the amount of material that enters as an input into our process. This value is computed as:

$$RC_i^g = \frac{RC_i^n}{eff_i^{rc}} = \frac{RC_i^g - WRC_i}{eff_i^{rc}}$$

$$WRC_i = \frac{RC_i^n \times (1 - eff_i^{rc})}{eff_i^{rc}}$$

- Eff^{rc}*i*: represents the recycling efficiency of the process before our.

It's calculated by multiplying the total weight of each single used material for the related source percentage from recycled materials.

3.1.4. Virgin material (V):

It is the amount of virgin and not renewable material that is used as input; it's computed multiplying each material by the related percentage from virgin materials.

3.2 Materials output

This section considers the contribution of each component. The indicators considered are:

- $RC^n{}_o$: process output to recycle (does not include the waste in recycle phase)
- *WRCo*: amount of waste produced from the recycle process, computed as

$$WRCo = \frac{RC_o^n \times (1 - eff_o^{rc})}{eff_o^{rc}}$$

Where $eff^{rc}{}_o$ is the efficiency in the recycle phase of the output of our process

- *RU o*: amount of material sent to reuse
- *O (kg)*: amount of material included in the final product
- *Wo (kg)*: amount of waste from the main process

3.3 Energy Input

In order to have a homogeneous computing of energy and material, the defined approach is that of representing the amount of energy in terms of the amount of materials used to generate such energy according to the used sources.

In this respect, it is necessary to define the following conversion criteria

3.3.1 Conversion factor for electrical energy

From the data of the Italian Transmission Operator (Terna) 2016 we have:

Generation Italy 2016

Virgin source	**GWh generated**	**% vs total**
Coal	32.149	10,23%
CCGT	122.876	39,10%
Other thermal	15.305	4,87%
renewables	106.849	34,00%
Import	37.083	11,80%
Total (GWh)	314.261	

We make a few assumptions:

- We consider zero the amount of used material to generate renewable energy.
- The input material calorific value (pci) that generated the "import" energy has been computed as the pci weighted average of the other energy sources.
  We define the electric conversion factor for energy (fc_e) as the ratio between the total amount of required fuel (kg) for power generation and the total amount of MWhe fed into the grid.

It is possible to calculate the related necessity/consumption of material (in kg) by multiplying this factor by the amount of used energy, for example by a product.

$fc_e = 118{,}51\ kg/MWh_e$

3.3.2 Thermal energy conversion factor

For what concerns the thermal energy, we use the same calculation but considering MWht instead of MWhe. The result is:

$fc_t = 66{,}72\ kg/MWh_t$

3.3.3 Inputs

Defined the conversion factors, we name the energy amount as ‘material amount’ considering the conversion factor above defined. A number of possible supply options have been identified for the main sources.

3.3.3.1 Input from renewables (RES_ Ener):

Total amount of equivalent material (computed through the conversion factor) related to the renewables input

3.3.3.2 Reuse

Total amount of equivalent material related to reuse energy inputs (RU i_ Ener)

3.3.3.3 Recycle

Total amount of equivalent material related to recycle energy inputs (RC i_ Ener)

3.3.3.4 Virgin material

Total amount of inputs (V_ Ener) from not renewable materials, computed as sum of thermal inputs

3.3.4 Energy production

The five indicators above mentioned are computed starting from the following sourcing options:

3.3.4.1 From Grid

For the energy from the grid, the conversion is computed according to the chosen generation mix and the fc_e factor as defined below. We can assume for a MWhe:

○ 118,51 kg of fossil energy (that flows into V_Ener)

3.3.4.2 Auto producers

We assume that the autoproduction of electrical energy that can be classified in four cases:

- **Recycle**

  Input from recycle, RC^e_i

  To compute the input from recycle we consider the amount of energy before the recycle process and this value is multiplied by the electrical conversion factor (fc_e)

$$RC_i^e = \frac{ee_{riciclo} \times \text{fce}}{eff_i^{rc}\ ee}$$

  Where:

eff^{rc}_i : efficiency of the recycle process
$ee_{recycle}$: electrical energy from recycle
fce: electrical conversion factor

Waste from recycle, WRCi
It is computed from the amount of energy used for the production:

$$WRCi_{ee} = \frac{ee_{riciclo} \times (1 - \%rinnovabilità) \times (1 - eff_i^{rc}\ ee)}{eff_i^{rc}\ ee}$$

- **Reuse[2]**
  For reuse, it is assumed that the whole amount of energy from reuse in input is converted into electric energy

$$ee_{riuso} \times \text{fce}$$

ee_{riuso}: electrical energy from reuse
fce: electrical conversion factor

- **Renewables (biomass excluded)**

  To compute the amount related to renewable, the produced electrical energy is multiplied by the electrical conversion factor fc_e and by the percentage of renewable

$$RES_{ener} = ee_{res} \times fce \times \%rinnovabilità$$

In the case that some sources are not considered completely renewable, an amount of thermal is computed and added to the thermal amount hereafter

- **Solid fuel (thermal and biomass)**
  For this indicator we need to compute the amount of virgin material related to generation; we had to multiplies the generated electrical energy by the fc_e factor

3.3.4.3 Auto production of thermal energy

- **Recycle:**
  input from recycle, RC^t_i
  To compute the input from recycle we consider the amount of energy before the recycle process and this value is multiplied by the thermal conversion factor (fc_t)

$$RC_i^t = \frac{et_{riciclo} \times \text{fct}}{eff_i^{rc}\ et}$$

W[1]here:

eff^{rc}_i et: efficiency of the recycle process of thermal energy

$et_{recycle}$: thermal energy from recycle

fct: thermal conversion factor

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[2] With reuse we mean the direct use of an amount of energy coming from another process, whereas with Recycle we mean that before using the energy, this is somehow processed and some wastes are generated.

Waste from recycle, $WRCi_{et}$

It is computed both for the electrical and for the thermal part from the amount of energy used to produce it:

$$WRCi_{et} = \frac{et_{riciclo} \times (1 - \%rinnovabilit\grave{a}) \times (1 - eff_i^{rc}\ et)}{eff_i^{rc}\ et}$$

- **Reuse**

  It multiplies the amount of thermal energy sent to reuse by the thermal conversion factor fc_t

$$et_{riciclo} \times \mathrm{fct}$$

- **From renewable**

  To compute the amount of renewable energy related to the production from renewable sources the electrical energy produced is multiplied by the electrical energy factor fc_e and by the related percentage of renewable energy

$$et_{res} \times fct \times \%rinnovabilit\grave{a}$$

  In the case that some sources are not considered completely renewable, an amount of thermal is computed and added to the thermal amount hereafter

- **Thermal**

  We assume available the total amount of used fuel so that we can directly insert the kg of burnt fossil fuel.

3.3.4.4 Energy consumption during product lifetime

Since product production until the end of its life, we can have different situations about electrical needs:

- Products that don’t need energy anymore (ex. static object)
- Products that need electricity to work
- Products that need fuel to generate energy for working (ex. a vehicle)

In the first case, no further details are needed.
In the second case, the calculation is the same used for energy inputs in the process analysis.
In the third case, we suppose to be able to compute the weight of needed fossil fuel to run. This weight (kg) will be added to the amount of total material computed in input.
Both in the second and third case it could be necessary to transform the generated energy into another type of energy (ex. mechanical), thanks to an engine. In this case, it’s important to understand that not all the generated energy can be used and an adequate engine efficiency must be estimated to arrive at the real available energy and estimate the one lost (ex. by heat). Energy lost by conversion should be added to the process output waste.

3.4 Energy output

For what concerns wastes, these three king of wastes are considered:

- Wastes to recycle
- Wastes to reuse
- Thermal wastes not recovered

The considered final indicators are:

3.4.1 Output sent to recycle (RC o_ Ener):

Output to recycle, RCo

It referes to the amount of process waste that is recycled and used as input in an afterward process.
It is computed from the amount of waste heat produced in the recycle phase both for electricity production and for thermal production, computed as:

$$\begin{aligned} RCo &= RCO_{el} + RCO_{t} \\ RCO_{el} &= ee \times fce \\ RCO_{t} &= et \times fct \end{aligned}$$

Waste from recycle, WRCo

It considers the waste produced in the recycle phase. It is computed considering the waste produced during recycle, both for what concern electrical energy production and for what concern thermal energy production

$$\frac{RCo\ el \times (1 - eff_{o}^{rc}\ ee)}{eff_{o}^{rc}\ ee} + \frac{RCo\ et \times (1 - eff_{o}^{rc}\ et)}{eff_{o}^{rc}\ et}$$

3.4.2 Output sent to reuse (RUo):

It considers the amount of waste energy that is sent to reuse and used as input for an afterwards process. It is computed from the amount of heat sent to reuse both in the electrical autoproduction and in the thermal autoproduction, computed as:

$$\begin{aligned} RUo &= RUo\ el + RUo\ t \\ RUo\ el &= ee \times fce \\ RUo\ et &= et \times fct \end{aligned}$$

3.4.3 Waste directly sent to disposal (Wo_ Ener):

It considers the waste that is directly disposed, i.e. not recovered and directly dispersed in the air. They are computed as:

$$Wo_{ener} = ee \times fce + et \times fct$$

3.4.4 Output (O)

It considers the sum of the energy output for which the processi s designed. Is an indcator to be considered if the process considered is that of a power plant or of a thermal plant. The values to be inserted are directly those of electrical energy and thermal energy produced, that are then converted through the conversion factors:

$$\begin{aligned} O\_Ener &= O\ ee + O\ et \\ O\ el &= ee \times fce \\ O\ et &= et \times fct \end{aligned}$$