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Integrating biodiversity concerns in sustainability strategy

A case study at Schneider Electric

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Abstract

Climate change and biodiversity loss present critical challenges for humanity, yet biodiversity often remains overlooked in corporate sustainability strategies. This study, conducted within Schneider Electric's environmental team, aims to address this gap by comparing the carbon intensity and biodiversity impacts of new production processes for aluminum and steel against conventional methods. Utilizing the ReCiPe Life Cycle Impact Assessment (LCIA) model, the research quantifies biodiversity impacts and normalizes them relative to unabated technologies to evaluate their environmental relevance. The analysis reveals that while carbon intensity and biodiversity impacts are correlated, focusing solely on carbon emissions does not provide a comprehensive understanding of a technology's overall environmental footprint. Some low-carbon technologies may inadvertently lead to negative biodiversity outcomes, emphasizing the need for a holistic approach to sustainability. The study also identifies promising technologies, such as green hydrogen and electrification, which have the potential to reduce both carbon emissions and biodiversity impacts. The findings underscore the necessity for comprehensive strategies that prioritize both carbon reduction and biodiversity conservation in industrial decision-making processes. This approach is essential for fostering resilience against environmental changes and ensuring the long-term sustainability of natural ecosystems.

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Nomenclature

BF	Blast Furnace
BFA	Biodiversity Footprint Assessment
BOF	Blast Oxygen Furnace
CCS	Carbon Capture Storage
$CCUS$	Carbon Capture Usage and Storage
CFC_{11}	Tichlorofluoromethane
CH_4	Methane
CO_2	Carbon Dioxide
$DALY$	Disability-adjusted life years
DRI	Direct Reduction of Iron ore
GBS	Global Biodiversity Score [CDC Biodiversité, 2020]
GHG	Green House Gases
$IPCC$	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
$LCIA$	Life Cycle Impact Assessment
MVR	Mechanical Vapour Recompression
NO_2	Nitrogen Dioxide
SE	Schneider Electric

1 Introduction

The Special Report on Global Warming of 1.5°C warns that a temperature rise of 1.5°C will cause major disruptions to human life, including more frequent and severe climatic events [Masson-Delmotte et al., 2022]. As a result, the urgent reduction of carbon emissions has become crucial. This urgency is underscored by the fact that human activities have already caused approximately 1.0°C of global warming above pre-industrial levels. Projections indicate that this could reach 1.5°C between 2030 and 2052 if current emission rates persist [Hondula et al., 2015]. In response, the 2015 Paris Agreement marked a pivotal moment for industries by establishing a 2°C limit on global warming above pre-industrial levels [United Nations Framework for Climate Change, 2015]. This agreement has led to significant policy shifts in committed countries, resulting in changes to industrial practices and emphasizing the need for sustainability strategies[Upreti, 2023].

However, sustainability strategies remain carbon-centered and put aside other environmental problems. But the urgency extends beyond just carbon reduction [Intergovernmental Panel on Climate Change, 2022]. To effectively tackle the climate challenge, policies must address both carbon reduction and biodiversity, given the strong interconnections between these issues. Despite this, many companies continue to prioritize climate change alone, although a few have started incorporating biodiversity concerns into their business operations. This approach overlooks the essential role biodiversity plays in sustaining ecosystem services, such as food production, water purification, and climate regulation. By integrating biodiversity considerations into sustainability plans, companies and governments can enhance resilience to environmental changes [Mrema, 2021].

Climate change and biodiversity loss are deeply interconnected challenges that demand urgent, coordinated action from companies. As global temperatures rise, ecosystems are disrupted, leading to habitat destruction and species extinction at unprecedented rates [Pecl et al., 2017]. Between 1970 and 2014, nearly 60% of the global populations of mammals, birds, fish, reptiles, and amphibians disappeared [World Wide Fund, 2018]. Alongside wildlife decline, crucial biological functions, such as the environment's ability to absorb greenhouse gas emissions, are also being compromised due to ecosystem destruction caused by human activity [Duffy et al., 2022]. Without natural barriers against global warming, living conditions will become increasingly difficult [Weiskopf et al., 2024]. For example, deforestation not only destroys habitats but also reduces carbon sequestration capacity, exacerbating climate change [Gatti et al., 2021]. The ocean, home to vast biodiversity, absorbs about 30% of human-produced carbon dioxide, but as marine ecosystems degrade due to warming and acidification, this crucial carbon sink is threatened [Bindoff et al., 2019].

Finally, biodiversity is also crucial for businesses prosperity. The economic implications are also staggering, with the World Economic Forum estimating that over half of the world's GDP – $44 trillion in economic value – is moderately or highly dependent on nature and its services [World Economic Forum, 2020]. Addressing these interlinked crises requires integrated strategies that simultaneously tackle emissions reduction and biodiversity conservation, recognizing that the health of our planet's ecosystems is inextricably linked to the stability of our climate.

Using a case study of Schneider Electric's (SE) procurement strategy for aluminium and steel production, the project underscores the importance of integrating biodiversity considerations into a firm's sustainability strategy, especially in light of the significant threats posed by climate change and biodiversity loss. Utilizing the ReCiPe Life Cycle Impact Assessment (LCIA) model, the research quantifies the environmental impacts of various production technologies, revealing that a narrow focus on carbon intensity can obscure the broader ecological consequences of industrial practices. The findings indicate that while some low-carbon technologies may reduce carbon emissions, they can inadvertently harm biodiversity, highlighting the need for a holistic approach to sustainability. The study ultimately aims to highlight the complexity of sustainability by examining Schneider Electric and similar organizations, focusing on the challenge of balancing carbon reduction with biodiversity conservation. This approach is crucial for ensuring long-term ecological and economic resilience.

1.1 Aim and objectives

This project was conducted within Schneider Electric's environmental team, which is strongly committed to eco-design, particularly through the integration of low environmental impact materials in its product designs. These structural and organizational changes require a systematic evaluation of various alternatives, including the use of recycled materials, bio-sourced materials, low-carbon manufacturing processes, and industrial ecology practices.

The company is rethinking its sustainable procurement strategy to better align with its eco-design goals. To support the development of this new strategy, a Marginal Abatement Cost Curve (MACC) study was conducted to explore alternative production technologies for specific commodities, such as steel, copper, aluminium, and thermoplastics. This study evaluated the cost, carbon reduction potential, and production volumes of various technologies, providing Schneider Electric with recommendations on the most viable options for achieving both carbon reduction and cost efficiency. However, the MACC study is focused solely on carbon reduction even if biodiversity impacts are crucial during establishment of such strategy.

In this context, this Master's thesis compares traditional and alternative production processes from Schneider Electric's MACC project. The comparison is conducted using a range of indicators, beginning with carbon intensity, followed by impacts on freshwater and terrestrial ecosystems, and concluding with effects on human health. The thesis aims to demonstrate that carbon-centered analyses must be complemented by a broader, cross-disciplinary approach to effectively address the wider challenges of sustainability.

1.2 Research questions

This study addresses the following research questions:

- Is there impact trade off between carbon and biodiversity?
- How can the biodiversity impacts of emerging production technologies be measured?
- Are the recommendations from the MACC project still valid when considering biodiversity concerns?

2 Background

This chapter provides essential background information necessary for understanding the Master's thesis. Since the project is conducted at Schneider Electric, the first section introduces the company and its core activities. Following this introduction, the scope of the project is defined, and the aluminum and steel production processes used in this study are presented. This overview also offers initial insights into the various environmental impacts associated with both materials. Next, a review of the MPP's studies is provided to explain the key recommendations and technologies they highlight. Finally, the environmental impact assessment is detailed, covering each stage from inventory analysis to impact evaluation, as the thesis involves a comprehensive Life Cycle Impact Assessment.

2.1 Schneider Electric introduction

Schneider Electric is a global leader in energy management and automation solutions, offering a comprehensive range of products and services that includes electrical distribution, industrial automation, power management, and smart grid technologies. The company's extensive portfolio features products such as circuit breakers, transformers, switchgear, energy monitoring systems, and industrial control software.

In the production of these products, Schneider Electric utilizes materials like aluminum, steel, and thermoplastics, chosen for their durability, strength, and conductivity. However, the use of these materials also results in significant carbon emissions during the manufacturing process. Recognizing this challenge, Schneider Electric is deeply committed to sustainability and strives to minimize the carbon footprint associated with its material sourcing.

To achieve this goal, the company has implemented a program focused on sourcing materials with lower environmental impacts and incorporating eco-design principles. This program involves the continuous evaluation of alternative production processes, allowing Schneider Electric to refine its procurement strategy and reduce the environmental impact of its operations. A notable example of this effort is the MACC project conducted in 2024, which assessed various alternatives to optimize sustainability procurement.

2.2 Scope of the project

While Schneider Electric's MACC project focuses on steel, copper, aluminium, and thermoplastics as the primary contributors to the company's carbon footprint [Schneider Electric, 2022], this study narrows its scope to examine only aluminium and steel due to time constraints. These two materials are particularly significant, accounting for 25% of the company's purchased materials [Schneider Electric, 2024].

Moreover, due to confidentiality concerns, the results from the MACC study cannot be publicly disclosed. Consequently, the findings from SE's project have been substituted with data from public sources. For both aluminium and steel, the data is sourced from Mission Possible Partnership (MPP) [Missions Possible Partnership, 2023a,b]. MPP is a global initiative that brings together industry leaders, policymakers, and stakeholders to accelerate the transition to a low-carbon economy by promoting decarbonization in hard-to-abate sectors like steel and aluminium [Missions Possible Partnership, 2023a].

The MPP's studies were initially used in the SE project, making it logical to continue utilizing them. These studies provide valuable insights into decarbonization strategies for both sectors and assess the carbon intensity of alternative technologies.

2.3 Introduction to aluminium and steel production processes

Aluminium and steel represent a significant volume in SE's purchased materials which make them crucial in SE's environmental impacts. The production of such metals involves various production processes, each with its unique characteristics. Factors such as energy demand, mineral types, and the use of fossil fuels or electricity as energy source vary depending on the metal being produced. These differences play a crucial role in shaping the environmental and economic impacts of the production processes. These issues are discussed in the next section starting with the classic production process and followed by the alternatives presented in the MPP's studies.

2.3.1 Aluminium Classic Production Process

The aluminium production process begins with mining bauxite, which can have significant environmental impacts. Open-pit and underground mining disrupt ecosystems and threaten biodiversity. Studies have documented these effects, such as habitat loss and soil degradation [Norgate and Haque, 2010].

The extracted bauxite is then processed at high temperatures to produce aluminium hydroxide. This stage is energy-intensive and generates substantial carbon emissions. According to the International Aluminium Institute, the production of aluminium hydroxide and alumina is responsible for $2.6tCO_2/tAluminium$ in 2022 [International Aluminium Institute, 2022].

Then the aluminium hydroxide is converted into alumina through the calcination phase, requiring high energy input. This process contributes approximately to $1tCO_2/tAluminium$ per ton of alumina produced in 2022 [International Aluminium Institute, 2022].

The smelting process, which uses the Hall-Héroult method [Mandin et al., 2009], is particularly electricity-intensive and is a major contributor to the overall carbon footprint of aluminium production. This stage only releases up to $11.4tCO_2/tAluminium$ in 2022 [International Aluminium Institute, 2022].

Finally, during casting, scrap aluminium is often added to enhance efficiency. Although recycling reduces the need for raw materials, it still involves energy use and emissions. To illustrate the whole classic production process for aluminium Figure 1 summarizes it.

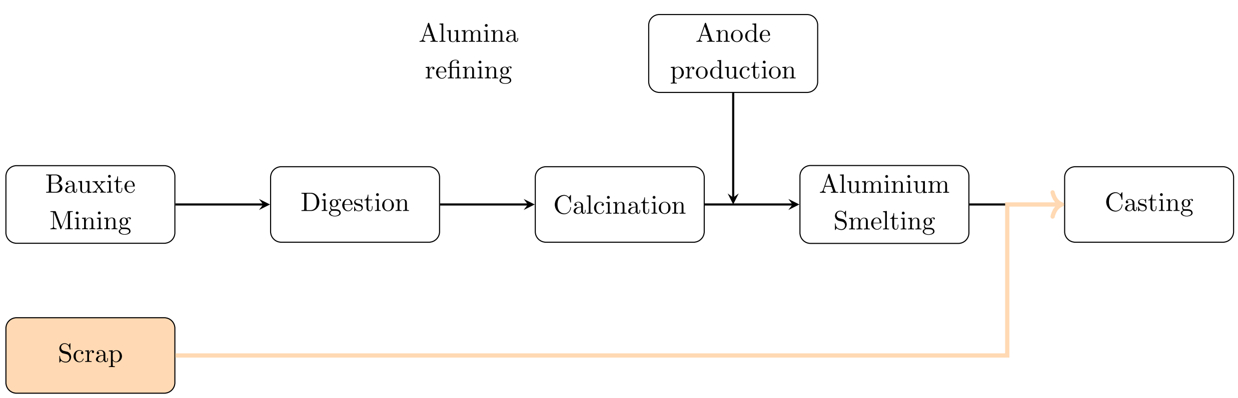

Figure 1: Production process of Aluminium

2.3.2 Alternative Production Processes for Aluminium

The overall objective of the project is to compare classic production process with alternatives. The Mission Possible Partnership (MPP) report on aluminium decarbonization explores various strategies for reducing carbon emissions within the aluminium industry [Missions Possible Partnership, 2023a]. Table 1 summarizes the different technologies with their associated carbon emissions from Missions Possible Partnership [2023a]'s stuy.

One of the central themes of the report is the electrification of aluminium production, particularly through the use of renewable energy sources. The MPP argues that shifting to renewable electricity for aluminium smelting can dramatically reduce the industry's carbon footprint [Missions Possible Partnership, 2023a]. This perspective is supported by the International Energy Agency (IEA) which emphasizes the critical role of renewable electricity in achieving significant emissions reductions in aluminium production by displacing the reliance on fossil fuels [International Energy Agency, 2021].

However, electrification of production seem insufficient to completely reduce carbon emissions. That is why, the MPP report underscores the adoption of green hydrogen as a crucial strategy to lower carbon footprint of the industry. Green hydrogen means that the hydrogen has been produced through water electrolysis and used renewable energies. By replacing fossil fuels with green hydrogen in the aluminium smelting process, the report suggests that significant reductions in CO_2 emissions can be achieved [Missions Possible Partnership, 2023a]. Furthermore, Fan and Friedmann [2021] support this idea and highlight green hydrogen's potential to decarbonize industries. Hassan et al. [2024] recognize the challenges related to cost and scalability but underline the long-term benefits of integrating green hydrogen into industrial processes. Additionally, according to Staffell et al. [2019], green hydrogen could play a pivotal role in achieving deep decarbonization across various hard-to-abate sectors, including aluminium.

Among the energy efficiency solutions, Mechanical Vapor Recompression (MVR) technology stands out as particularly promising. This innovative process involves compressing low-pressure vapor to increase its temperature and pressure. The high-temperature vapor is then condensed, releasing latent heat, which is subsequently used to warm incoming low-pressure vapor. This cyclical process significantly enhances energy recovery, leading to substantial improvements in both energy efficiency and cost-effectiveness of industrial operations [Missions Possible Partnership, 2023a].

Moreover, the study emphasizes Carbon Capture and Storage (CCS) as a key solution. This technology is explored specifically in the smelting process, where it is applied alongside the conventional carbon anode technology to capture the carbon dioxide generated during the electrolytic reduction of alumina.

Last but not least, the MPP report highlights the importance of increasing recycling and the adoption of circular economy principles as key strategies for reducing emissions in the aluminium industry [Missions Possible Partnership, 2023a]. By boosting recycling rates, the need for primary aluminium production, which is highly energy-intensive, can be reduced. This approach not only lowers emissions but also decreases the demand for raw materials, contributing to overall sustainability. Research supports this perspective, showing that increased recycling can significantly reduce the carbon intensity of aluminium production and help the industry meet global climate targets [World Steel Association, 2020b].

Production type	Process stage	Technology	Carbon intensity ($kgCO_2/t$ of steel)
Primary production		Classic	1.6×10^4
Secondary production		Classic	5.0×10^2
Primary production	Digestion	Classic	1.8×10^3
		Mechanical Vapour Recompression (MVR)	3.0×10^1
		Green hydrogen (H_2)	0.0
		Electric boilers	0.0
Primary production	Calcination	Classic	8.0×10^2
		Green H_2	0.0
Primary production	Smelting	Classic Carbon Anodes	1.3×10^4
		Carbon Capture and Storage	9.6×10^3

Table 1: List of technologies and carbon intensity for aluminium production Missions Possible Partnership [2023a]

2.3.3 Classic Steel Production Processes

Steel production encompasses a variety of sophisticated processes designed to transform raw materials into high-quality steel. The traditional Blast Furnace-Basic Oxygen Furnace (BF-BOF) method remains a cornerstone of the industry around 73% of the production in 2024 [?]. This technology is considered as the classic technology here. This process initiates with the smelting of raw materials in a blast furnace to produce pig iron, which is subsequently converted into steel using a basic oxygen furnace. While efficient, the BF-BOF method is not without environmental concerns. In 2022, it generated approximately $2.3 tCO_2/tSteel$ [World Steel, 2022]. Moreover, this process demands substantial water usage for cooling and cleaning, potentially leading to significant water pollution and thermal discharge issues [Geerdes et al., 2015].

In response to environmental and efficiency considerations, alternative methods have gained prominence. The Direct Reduced Iron-Electric Arc Furnace (DRI-EAF) process offers a notable alternative. This method utilizes direct reduced iron, derived from iron ore, as a feedstock for an electric arc furnace to produce steel. This approach serves as an effective substitute for traditional iron ore in steelmaking and can reduce CO_2 emissions by up to 70% compared to the BF-BOF route when powered by renewable electricity [Vogl et al., 2018]. However, it requires high-grade iron ore, which may lead to increased mining activities and associated environmental impacts [Cavaliere, 2019b].

Another variation is the Direct Reduced Iron-Basic Oxygen Furnace (DRI-BOF) process. While similar in its use of direct reduced iron, this method diverges by introducing the DRI into a basic oxygen furnace for steel production, rather than an electric arc furnace. This hybrid approach can potentially combine the lower emissions of DRI production with the high productivity of the BOF process, but still faces challenges in terms of energy efficiency and scalability [Hasanbeigi et al., 2021].

The selection of a particular steel production method is influenced by a complex interplay of factors including cost-effectiveness, raw material availability, and environmental impact considerations. Each method presents its own set of environmental challenges, from greenhouse gas emissions to water and air pollution, and resource depletion [Renzulli et al., 2016a]. As the industry moves towards more sustainable practices, technologies such as carbon capture and storage (CCS) and hydrogen-based reduction are being explored to further mitigate environmental impacts [Fischedick et al., 2014].

Figure 2 provides a comprehensive summary of these diverse production routes. It's important to note that while both Blast Furnace (BF) and DRI processes typically use iron ore as their primary input, when scrap metal is utilized as a raw material, the initial iron-making step is bypassed, leading to a more streamlined and potentially more sustainable production process [Cullen et al., 2012].

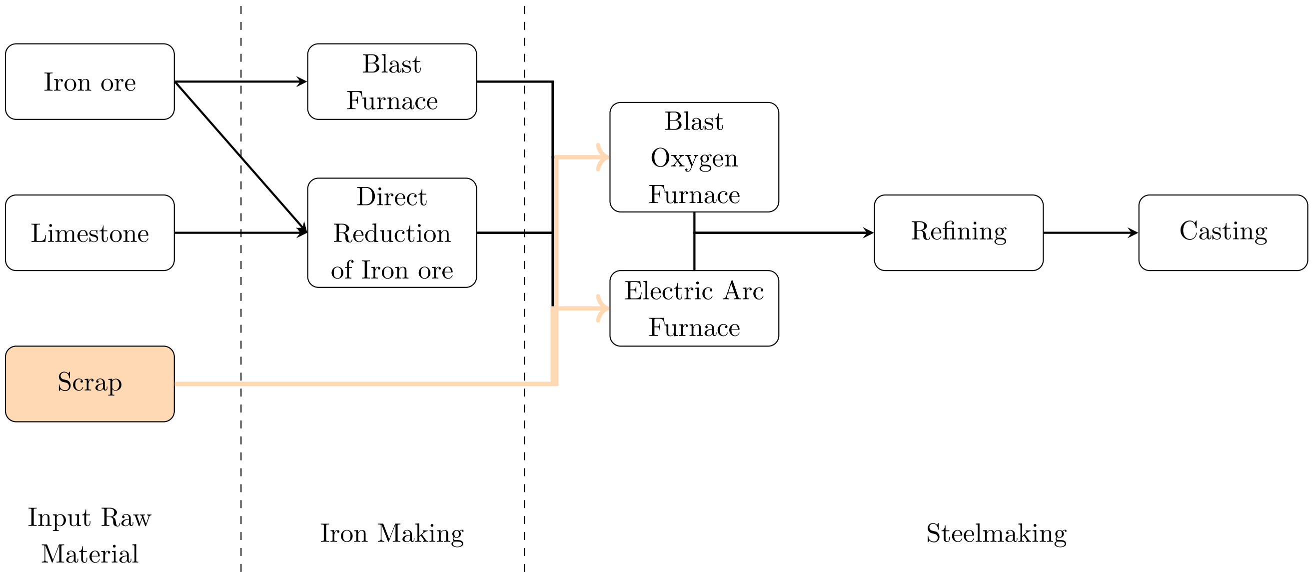

Figure 2: Production process of Steel

2.3.4 Alternative Production Processes for Steel

MPP also provides a report regarding decarbonization of the steel industry [Missions Possible Partnership, 2023b]. In the same regard as the report on aluminium, this report is assessing future carbon intensity of these technologies, their costs and the volume of production in different region of the world.

First of all, as well as for aluminium, the report advocates for the electrification of steel production, particularly through the use of green hydrogen. It argues that replacing fossil fuels with hydrogen—produced from renewable energy sources—can significantly reduce the carbon footprint of steel production. Devlin et al. [2023] agree with this view and argue that green hydrogen offers a substantial reduction in CO_2 emissions compared to traditional fossil fuels in industrial processes. Complementing this, Hassan et al. [2024] underlines the potential of green hydrogen to decarbonize energy, asserting that its integration with renewable energy could lead to significant emissions reductions.

Moreover, recycling is a key solution in MPP report, allowing the economy to decrease its dependence on raw material extraction and primary production and drastically lower its carbon footprint [Missions Possible Partnership, 2023b]. According to the World Steel Association improved recycling can lower the energy intensity of steel production and substantially cut CO_2 emissions [World Steel Association, 2020b]. W. Hagedorn et al. shows that boosting recycling rates can lower overall emissions by reducing the need for new raw materials and decreasing the energy required for steel production [Hagedorn et al., 2022].

Finally, MPP also emphasizes Carbon Capture and Storage (CCS) as a pivotal technology for reducing CO_2 emissions in the steel industry [Missions Possible Partnership, 2023b]. According to Leeson et al. [2017], CCS has significant potential to mitigate emissions across various industrial sectors, including steel, especially when combined with other technologies. Besides, the MPP report suggests that CCS can substantially lower emissions by capturing CO_2 from steel production processes and storing it underground [Missions Possible Partnership, 2023b]. Indeed, Benavides et al. [2024] highlight CCS's essential role in deep decarbonization strategies, particularly in hard-to-abate sectors like steel, and outline its contribution to substantial emission reductions. Table 2 summarizes all technologies for steel.

Production type	Technology	Carbon intensity ($kgCO_2/t$ of steel)
BF - BOF	Classic	2.8×10^3
	Carbon Capture usage and storage (CCUS)	2.9×10^2
DRI -EAF	Classic	1.9×10^3
	CCS	1.2×10^2
	with 100% green H_2	1.2×10^2
	with 50% green H_2	8.1×10^2
DRI - BOF	Classic	1.0×10^4
	with 100% green H_2	5.8×10^1
	with CCUS	1.2×10^2
EAF	scrap-based	6.7×10^2

Table 2: List of levers and carbon intensity for steel production Missions Possible Partnership [2023b]

2.4 Environmental Impact Assessment

Environmental Impact Assessment (EIA) is a crucial process used to evaluate the potential environmental consequences of proposed development activities before they are carried out. To conduct a comprehensive EIA, three key components are typically employed: Life Cycle Inventory (LCI), Life Cycle Assessment (LCA), and Life Cycle Impact Assessment (LCIA). The overal eia process is summarized in Figure 3.

The first step in the assessment process is the Life Cycle Inventory (LCI). LCI involves collecting and quantifying all inputs and outputs associated with a product or process throughout its entire life cycleBruijn et al. [2002]. This includes raw materials, energy consumption, water usage, emissions, and waste generation. For industrial processes, LCI requires detailed data collection from various stages of production, including resource extraction, manufacturing, transportation, use, and disposal. The accuracy and completeness of the LCI data are critical for the subsequent stages of the assessment.

Following the LCI, a Life Cycle Assessment (LCA) is conducted to evaluate the environmental impacts associated with all stages of a product's life cycle. LCA provides a holistic view of the environmental aspects and potential impacts related to the product or process under study. Results are mainly specific environmental issues like global warming potential, water acidification, etc called mid-points.

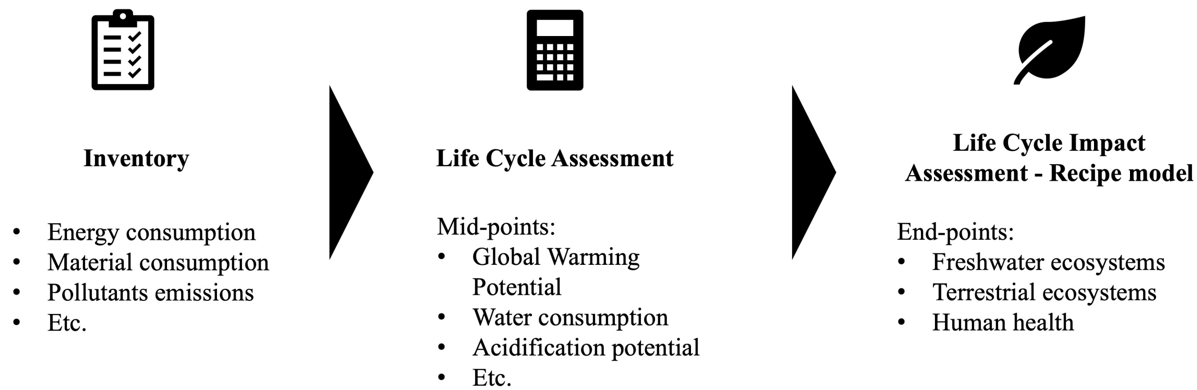

Figure 3: Environmental Impact Assessment process

The final stage is the Life Cycle Impact Assessment (LCIA), which translates the LCI results into potential environmental impactsFinnveden et al. [2009]. LCIA categorizes and quantifies the environmental effects of the emissions and resource uses identified in the LCI. The results are called end-points and quantify broader environmental implications of production processes. It helps in assessing the relative significance of different environmental impacts and can guide the development of targeted mitigation strategies. LCIA results are often used to support environmental decision-making, product development, and regulatory compliance in industrial settings.

By integrating these three components - LCI, LCA, and LCIA - industries can gain a comprehensive understanding of their environmental footprint and identify opportunities for improvement. This systematic approach to environmental impact assessment is essential for promoting sustainable industrial practices and minimizing negative environmental consequences.

3 Literature review

As LCA and LCIA have become important tools for evaluating the environmental impacts of metal production processes, particularly for energy-intensive industries like aluminium and steel manufacturing. This review examines key LCA and LCIA studies on aluminium and steel production, focusing on the different environmental impacts of both materials.

3.1 Aluminium Production

The environmental impacts of aluminium production have been extensively studied using Life Cycle Assessment methodologies. These studies consistently identify the smelting process as the primary contributor to life cycle impacts, particularly for global warming potential and energy use Liu and Müller [2012]. However, the results vary significantly due to differences in methodologies, system boundaries, allocation methods, and data sources.

LCA studies have revealed substantial regional variations in environmental performance. For instance, Li et al. [2019] found that China, the world's largest aluminium producer, shows higher environmental impacts compared to global averages, primarily due to its coal-dominated electricity mix. This disparity underscores the critical importance of improving energy efficiency and increasing renewable energy use in the aluminium industry, especially in regions heavily reliant on fossil fuels.

Recognizing the significant contribution of the smelting process to environmental impacts, researchers have explored technological innovations to mitigate these effects. Norgate et al. [2007] investigated the potential of inert anodes, which could reduce CO_2 emissions by up to 50%. However, the implementation of such innovations varies across regions, leading to substantial differences in environmental performance.

Recent studies have also explored the feasibility of integrating green hydrogen into aluminium production as a means of reducing environmental impacts. Hasanbeigi et al. [2021] conducted a techno-economic analysis of green hydrogen utilization in aluminium smelting, highlighting the potential for substantial CO_2 emission reductions. Their findings suggest that while the initial capital costs may be higher, the long-term environmental benefits and potential cost reductions through economies of scale make green hydrogen an attractive option for the aluminium industry.

Despite these advancements, several research gaps remain. There is a need for more comprehensive and standardized LCA methodologies specific to the aluminium industry to ensure comparability of results across different studies and regions. Additionally, further research is required to assess the full life cycle impacts of emerging technologies such as inert anodes and green hydrogen integration, including their potential trade-offs and long-term sustainability.

Furthermore, the environmental impacts of secondary aluminium production (recycling) compared to primary production need more detailed investigation, particularly in the context of a circular economy. Das [2014] emphasized the importance of exploring various pathways to carbon neutrality for the aluminium industry, highlighting the need for a holistic approach that considers both production technologies and end-of-life management strategies.

In conclusion, while significant progress has been made in understanding and mitigating the environmental impacts of aluminium production, there remains a critical need for continued research and innovation to address the industry's environmental challenges and move towards more sustainable production methods.

3.2 Steel Production

The environmental impacts of integrated steel mills are largely dominated by the blast furnace and basic oxygen furnace stages, as revealed through detailed inventories of material and energy flows. Internal recycling of process gases and materials within steel production facilities has shown promise in mitigating some of these impacts [Renzulli et al., 2016b].

When comparing different steelmaking routes, the integrated route, which combines blast furnaces and basic oxygen furnaces, typically exhibits higher environmental impacts across most categories than the electric arc furnace route. This disparity is primarily due to the integrated route's greater energy consumption and raw material requirements [Burchart-Korol, 2013].

In response to the pressing need for reducing the industry's environmental footprint, emerging technologies such as hydrogen-based direct reduction and electrolysis have come to the forefront. These innovative steelmaking processes show potential for significantly reducing CO_2 emissions compared to conventional routes. However, challenges remain regarding their large-scale implementation and the sourcing of electricity to power these processes [Cavaliere, 2019a]. Further research and development are crucial to fully understand and optimize these emerging technologies for sustainable steel production.

Recent studies employing Life Cycle Impact Assessment models have further refined our understanding of these impacts. For example, Olmez et al. [2016] utilized the ReCiPe method to evaluate the environmental performance of steel mills, identifying significant contributions to acidification and eutrophication from emissions associated with the steelmaking process. These assessments underscore the importance of comprehensive modeling in capturing the full spectrum of environmental impacts.

In terms of technological advancements, hydrogen-based direct reduction is gaining attention as a viable alternative to traditional methods. This process, which uses hydrogen as a reducing agent instead of carbon, has the potential to drastically cut CO_2 emissions if powered by renewable energy sources [Cavaliere, 2019a]. Similarly, the development of electrolysis for iron production offers a pathway to decarbonize the steel industry, though its commercial viability remains contingent on overcoming technical and economic barriers.

3.3 Comparative Studies and Methodological Issues

Some studies have compared aluminium and steel production processes within the same analytical framework. Norgate and Haque [2010] conducted a comparative LCA of metal production processes, including aluminium and steel. Their analysis revealed that primary aluminium production generally has higher environmental impacts per unit mass than steel production, particularly for energy use and global warming potential.

Several researchers have addressed methodological challenges in metal production LCAs. Van der Voet et al. [2013] discussed issues related to allocation in multi-output processes, which are common in both aluminium and steel production. They proposed a hybrid allocation approach combining mass, economic, and substitution methods to provide a more comprehensive assessment.

Gauffin and Pistorius [2018] examined the treatment of recycling in metal LCAs, comparing different allocation methods for end-of-life recycling. Their work highlighted how methodological choices can significantly influence results, particularly for metals with high recycling rates like aluminium and steel.

3.4 Research Gaps and Future Directions

Despite the extensive literature on aluminium and steel LCAs, several research gaps remain that align with the proposed research questions. There is a need for more studies incorporating recent technological developments, such as carbon capture and storage in steel production or low-carbon alumina refining processes, which could help address potential trade-offs between carbon reduction and biodiversity impacts.

While most studies focus on global warming potential and energy use, more comprehensive assessments of other impact categories are needed, particularly those related to biodiversity. This includes developing and refining methodologies to measure the biodiversity impacts of emerging production technologies in the metal industry. Such assessments could provide insights into whether carbon reduction strategies, like those recommended in the MACC project, remain valid when considering broader environmental concerns, including biodiversity.

Furthermore, many LCA studies rely on aggregated or outdated data, which may not capture the full spectrum of impacts on local ecosystems and biodiversity. There is a need for more detailed, facility-level analyses using recent data to capture technological and regional variations in both carbon emissions and biodiversity impacts. This could help identify potential conflicts or synergies between carbon reduction strategies and biodiversity conservation efforts in different geographical contexts.

4 Methodology

This chapter outlines the overall framework of the study and the approach used to compare traditional and alternative production processes. Since a LCIA is employed to quantify biodiversity impacts, a comparison between two LCIA models is conducted to determine the most suitable option. This leads to the selection of the ReCiPe model, followed by an explanation of its structure and the calculation of end-points within the model. The chapter concludes with a description of alternative methodologies used to calculate mid-points, considering the availability of LCA and LCI data.

4.1 Project Framework

The project is based on the comparison of classic production processes with alternatives ones. These alternatives are coming from Missions Possible Partnership [2023a,b]'s studies. The comparison is made on several indicators from carbon intensity to impacts on terrestrial and freshwater ecosystems and also human health. These indicators are calculated through a LCIA model detailed in the next sections. To make this comparison possible the different indicators are being assess through a relative impact percentage.

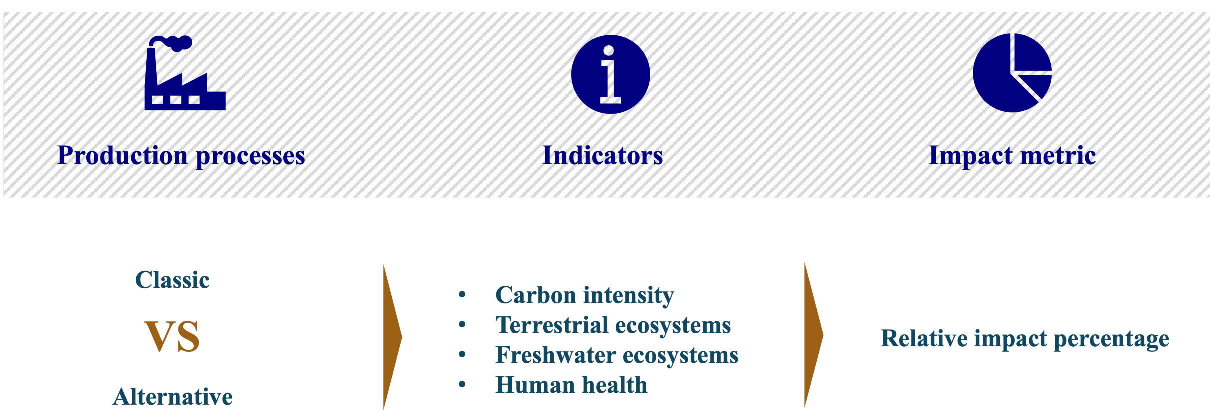

Figure 4: Project framework

The central focus of this study is the comparison of various production technologies. For aluminium, the comparison is divided in different stages of the production. First, the overall production process is compared between classic production and secondary production. The secondary production involves high scrap used (around 80%). Then, it is the digestion stage which is analysed. The classic digestion is compared to MVR, Green H_2 and electric boilers. The electric boilers use renewable electricity as well as the production of Green H_2. The next stage is the calcination with Green H_2 boilers as alternative technology. Finally, the smelting stage is the last stage analysed. The comparison is made between classic and a classic production which a CCS technology is added to. Table 3 summarizes the comparison between the different technologies for aluminium. In the case of steel, BF-BOF is considered as the classic production process and all the other technologies as alternatives.

Stage of production	Comparison between technologies	
Overall Production	Classic	Secondary
Digestion	Classic	MVR Green H_2 Electric Boilers
Calcination	Classic	Green H_2
Smelting	Classic	CCS

Table 3: Summarize of technologies comparison for Aluminium

4.2 Choice of LCIA model

This study uses LCIA model to quantify biodiversity impacts. To choose the most relevant one, two scoring methods have been investigated: ReCiPe 2016 and Global Biodiversity Score. ReCiPe 2016 and the Global Biodiversity Score (GBS) by CDC Biodiversité are two prominent tools used for environmental impact assessment, each with distinct methodologies and applications.

On the one hand, ReCiPe 2016 is an integrated LCIA method that translates emissions and resource extraction into impacts on human health, ecosystems, and resource availability. This method uses a midpoint-to-endpoint approach, allowing impacts to be expressed at both detailed midpoint levels (e.g., climate change, eutrophication) and aggregated endpoint levels (e.g., damage to human health, ecosystem quality) [Huijbregts et al., 2016].

On the other hand, the Global Biodiversity Score (GBS) developed by CDC Biodiversité focuses specifically on assessing the impact of economic activities on biodiversity. The GBS aims to quantify the biodiversity footprint of businesses by evaluating how different pressures, such as land use change, climate change, and pollution, affect biodiversity across different geographies and sectors [CDC Biodiversité, 2020].

Damiani et al. [2023] highlight the strengths and limitations of different LCA approaches, emphasizing the need for more comprehensive and accurate biodiversity assessments in LCA. The Table 5 shows the coverage of the different methods regarding pressures (emissions and resources), ecosystems (terrestrial, aquatic, etc) and the number of taxonomic groups covered by the method. Damiani et al. [2023] assert that ReCiPe 2016 is an effective method for incorporating biodiversity considerations into its framework. Their review advocates for the use of ReCiPe 2016 due to its comprehensive range of impact categories and its ability to convert complex biodiversity impacts into practical insights [Damiani et al., 2023].

When comparing the frameworks of GBS and ReCiPe 2016, distinct differences emerge. GBS focuses specifically on biodiversity, using detailed metrics like Mean Species Abundance (MSA) to provide in-depth insights into biodiversity impacts [CDC Biodiversité, 2020]. This narrow focus allows for thorough assessments of biodiversity-related impacts, particularly beneficial for businesses seeking to mitigate their biodiversity footprints. Conversely, ReCiPe 2016 offers a broader environmental impact assessment, encompassing multiple impact categories beyond biodiversity [Huijbregts et al., 2016]. While this comprehensive approach provides a holistic understanding of environmental impacts, it may dilute the focus on biodiversity-specific impacts compared to the more targeted GBS methodology.

Furthermore, data requirements of GBS and ReCiPe 2016 differ significantly. GBS requires specific biodiversity data, such as species abundance and habitat information, which ensures detailed biodiversity assessments but can pose challenges due to data intensity [CDC Biodiversité, 2020]. This can be a limitation for companies without access to detailed biodiversity datasets. On the other hand, ReCiPe 2016 utilizes extensive environmental data to assess various impact categories, providing generalized assessments that can be beneficial for overall environmental impact studies but may lack the precision needed for detailed biodiversity impact analysis [Huijbregts et al., 2016]. The complexity of ReCiPe 2016 requires expertise in LCA methodologies, potentially limiting its accessibility for businesses without dedicated LCA specialists.

Aspect	Global Biodiversity Score (GBS)	ReCiPe
Developer	CDC Biodiversité	RIVM, CML, PRé Consultants, and others
Purpose	Assess biodiversity impacts of companies	Harmonized life cycle impact assessment method
Scope	Global	Global
Focus	Biodiversity	Multiple environmental impacts
Methodology	Species richness and abundance	Midpoint and endpoint indicators
Metrics	Mean Species Abundance (MSA)	Multiple (e.g., ecosystem quality, human health)
Applicability	Companies and organizations	Products and processes
Impact Categories	Land use, climate change, etc.	Climate change, human health, ecosystem quality, resource scarcity
Normalization	Not specified	Provided for different regions
Endpoint Indicators	Biodiversity intactness	Disability-Adjusted Life Years (DALY), species loss, resource scarcity
Strengths	Company-specific, detailed biodiversity focus	Comprehensive, widely used in LCA community
Limitations	Limited to biodiversity	Complexity, data-intensive

Table 5: Comparison of Global Biodiversity Score (GBS) and ReCiPe

ReCiPe 2016 stands out as a robust and comprehensive LCIA method due to its integration of midpoint and endpoint indicators, scientific rigor, flexibility, and user-friendliness. Its updated characterization factors and global relevance make it an invaluable tool for conducting accurate and meaningful environmental impact assessments. Integrating the Global Biodiversity Score (GBS) further enhances ReCiPe 2016's ability to address biodiversity impacts. Insights from Damiani et al. [2023]'s critical review underline the method's strengths and suggest pathways for further refinement. By leveraging these tools and insights, practitioners can achieve a more holistic and effective assessment of environmental impacts, supporting sustainable decision-making.

4.3 Introduction to ReCiPe 2016 model

ReCiPe aims to quantify the potential environmental impacts of a product or process throughout its life cycle, from raw material extraction to end-of-life disposal. This model evaluates impacts on human health, ecosystem quality, and resource scarcity. The human health indicator measures damage through the concept of Disability-Adjusted Life Years (DALY) [Goedkoop et al., 2008], which quantifies the years of healthy life lost due to premature death and years lived with disability caused by disease or health conditions [World Health Organization, 2019]. The ecosystem quality indicator assesses impacts on freshwater and terrestrial ecosystems, using species loss over time (species.year) as the unit of measure [Huijbregts et al., 2016]. Finally, ReCiPe considers resource scarcity by modeling the risk of resource depletion and its economic consequences, using 2013 U.S. dollars (USD2013) as the metric [Huijbregts et al., 2016].

This study focuses on ecosystem quality and human health, which represent critical areas of environmental impact that are highly relevant to sustainability assessments. These endpoints enable a comprehensive evaluation of how human activities affect both people and nature. By focusing on these areas, decision-makers can better understand the broader implications of their choices on human populations and the natural world, facilitating more holistic and balanced approaches to environmental management and policy-making [Huijbregts et al., 2016].

Additionally, the ReCiPe model offers different scenarios to account for various cultural perspectives and time horizons, allowing for a more comprehensive assessment of environmental impacts under different assumptions and value judgments [Huijbregts et al., 2016]. The three scenarios—individualistic, hierarchist, and egalitarian—are summarized in Table 6, each reflecting different cultural values and priorities [Thompson et al., 1990].

The Individualist perspective focuses on the short term and maintains an optimistic belief in technological solutions. It assumes that future innovations will address many environmental challenges and emphasizes well-established impact pathways. As a result, this perspective generally leads to lower impact scores, reflecting its confidence in human adaptability and technological advancements.

On the other hand, the Hierarchist perspective, often viewed as the default model, strikes a balance between short- and long-term considerations. Frequently used in scientific models and policymaking, it incorporates impacts that are either scientifically proven or widely accepted. This balanced approach places it between the more extreme views of the other two perspectives.

In contrast, the Egalitarian perspective adopts a long-term outlook, grounded in the precautionary principle. It accounts for the broadest range of potential impacts, including those with less scientific certainty, and operates under the assumption that environmental issues could result in catastrophic outcomes.

	Individualistic	Hierarchist	Egalitarian
Description	Based on technological optimism with regard to human adaptation	Based on scientific optimism with regard to the time frame	Based on the longest time frame and all impact pathways for which data is available
Timeframe	Short-term (20 years)	Mid-term (100 years)	Long-term
Level of Precaution	Low	Medium	High
Rational	Prioritizes immediate, tangible effects, suitable for stakeholders driven by economic and market considerations	Default scenario balancing short and long-term impacts, aligning with many environmental policies and regulations	Emphasizes the protection of future generations and minimizes long-term, potentially catastrophic environmental impacts
Effects on biodiversity	Short-term effects	Effects known by the scientific community	All effects even those without scientific consensus

Table 6: Description of different ReCiPe's perspectives

4.4 ReCiPe framework

To calculate an endpoint, the model uses midpoints. These midpoints are derived from Life Cycle Assessment (LCA) results when available, or they are calculated manually. The process for manual midpoint calculation is detailed in Chapter 4.5. For endpoint calculation, the score s_i for endpoint i is determined using Equation 1, which accounts for the sum of n converted midpoints $m_{p,converted,j}$ in the endpoint's metric. This approach ensures a comprehensive assessment by aggregating multiple midpoint indicators into a single endpoint score.

$$s_i = \sum_{j=1}^{n} m_{p,converted,j} \tag{1}$$

The mid-point $m_{p,j}$ is converted through equation 2 using a conversion factor CF_j provided by ReCiPe model. These conversion factor are located in Appendix 1 in Table 9.

$$m_{p,converted,j} = m_{p,j} \cdot CF_j \tag{2}$$

ReCiPe is providing a link between mid-points and areas of protection, Figure 5 is summarizing these links. Mid-points' units are located in Table 10 in the Appendix. Starting with freshwater ecosystems, they are threaten by global warming, over consumption of water, terrestrial ecotoxicity and eutrophication. Freshwater ecotoxicity refers to potential harmful effects of a toxic substance on aquatic ecosystems. Regarding eutrophication, it is a natural process where bodies of water become overly enriched with nutrients, often due to human activities like sewage discharge. This causes excessive algae and aquatic plant growth, leading to oxygen depletion (hypoxia) as they decompose. This harms aquatic life, reduces biodiversity, and can lead to toxic algal blooms, posing risks to both aquatic life if they contaminate drinking water or seafood.

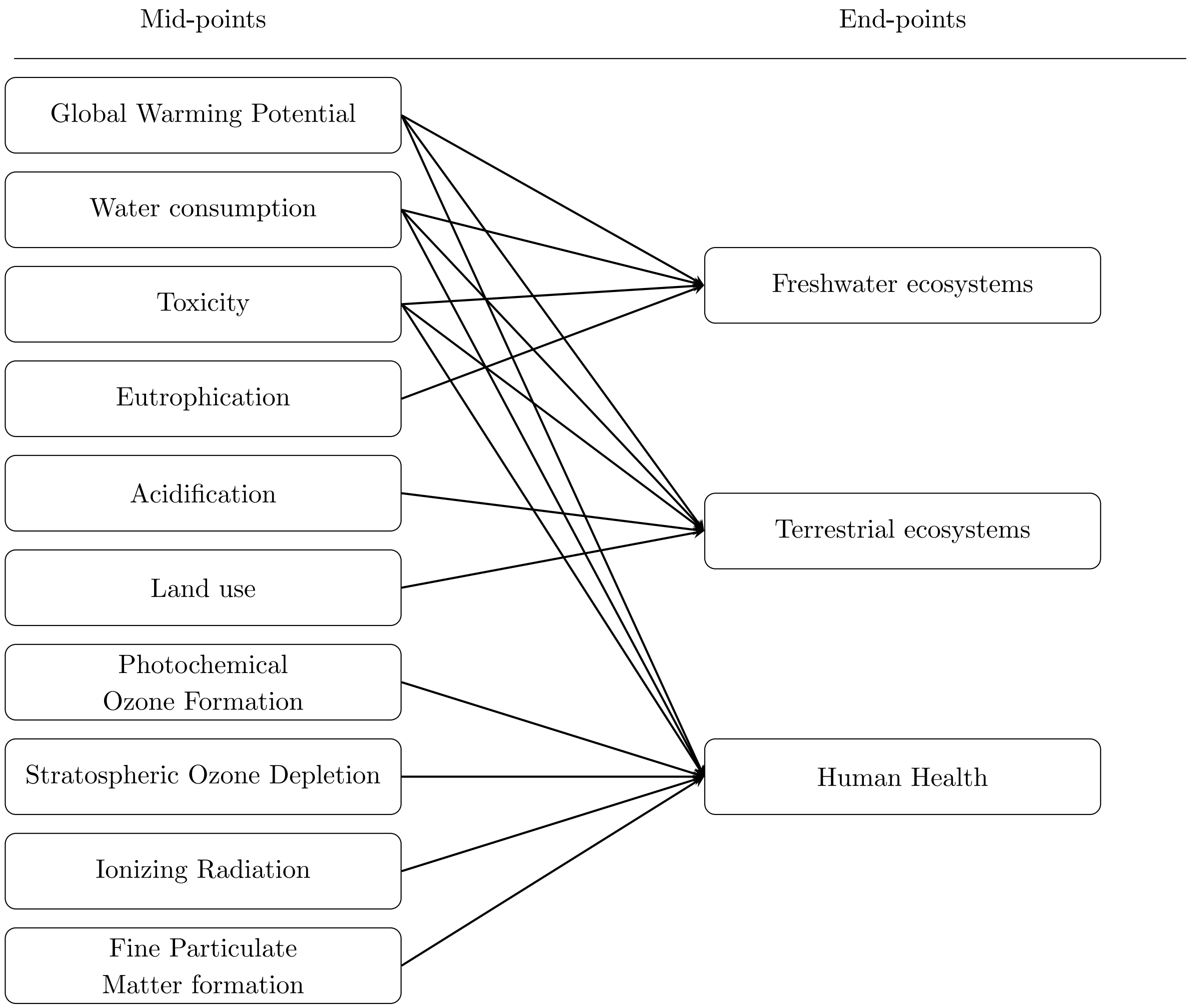

Figure 5: Mid-point and end-point links

Then, terrestrial ecosystems which is linked to global warming, water consumption, terrestrial toxicity, acidification and land use. The acidification of terrestrial ecosystems refers to a process where the soil and vegetation in land-based environments become more acidic over time. This acidification is primarily caused by the deposition of acidic pollutants, such as sulfur dioxide and nitrogen oxides, from sources like industrial emissions, vehicle exhaust, and agricultural activities.

Finally, human health impacts include global warming, water consumption, human health toxicity, photochemical ozone formation, stratospheric ozone depletion, ionizing radiation, and fine particulate matter formation. For simplification, freshwater, terrestrial and human toxicity were grouped within the toxicity card in figure 5. Fine particulate matter refers to particles or droplets in the air that are 2.5 micrometers or smaller, formed through combustion from vehicles, industrial processes, and natural sources like wildfires. These particles can be inhaled deeply into the lungs, posing significant health risks[Hondula et al., 2015]. Moreover, ionizing radiation, which can liberate electrons from atoms to create ions, originates from natural sources like radon gas and cosmic rays, as well as man-made sources such as X-ray machines and nuclear power plants. Exposure to high levels can increase the risk of cancer and other health issues [World Health Organization, 2021]. Then, stratospheric ozone depletion, caused primarily by human-made chemicals like chlorofluorocarbons (CFCs), reduces the ozone in the Earth's stratosphere. This depletion allows more harmful ultraviolet (UV) radiation to reach the Earth's surface, increasing risks of skin cancer, cataracts, and other health issues. And finally, photochemical ozone formation results from reactions between pollutants such as nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight, leading to ground-level ozone and contributing to smog. This poses health risks to humans and damages vegetation.

4.5 Mid-point indicators calculation

As outlined in ReCiPe framework, LCA results typically provide mid-point indicators. However, in some instances, these mid-points may not be available through standard LCA methods. To address this, two alternative methodologies has been used to calculate unabated technologies' mid-point indicators. The first implying the technology's LCA and the second one the LCI. If neither of them is available, the mid-point is simply not considered in the model for the unabated technology and also the decarbonization levers linked to it. Figure 6 summarizes the overall methodology.

The first alternative involves using midpoint indicators from LCA results. In this study, all midpoints are derived from the same LCA: aluminium data is sourced from International Aluminium [2019], and steel data is sourced from World Steel Association [2020a].

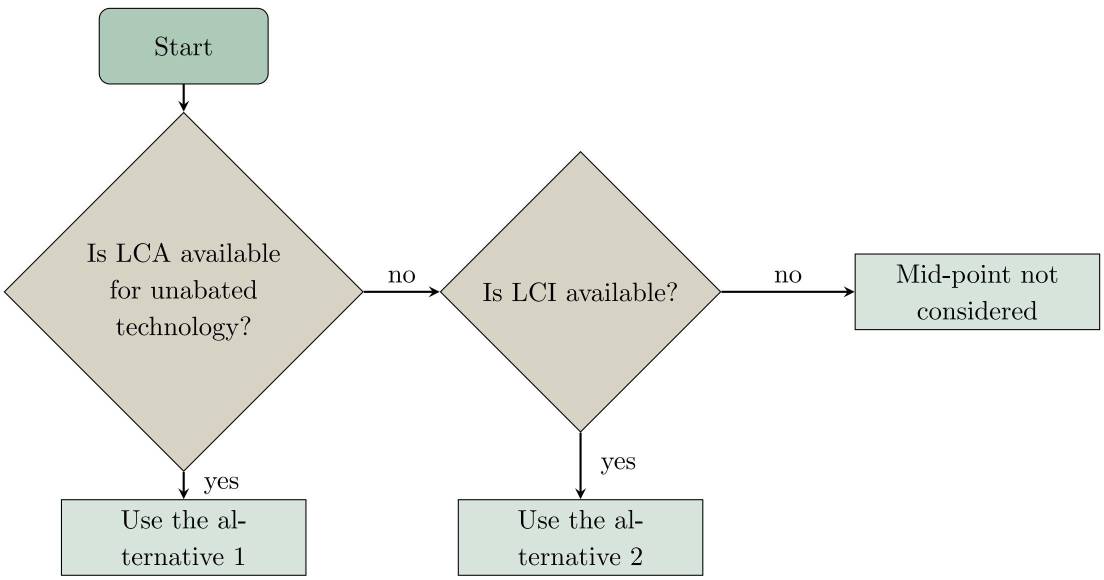

Figure 6: Flowchart representing the overall methodology for each mid-point indicators related to unabated technologies

The second alternative arises when Life Cycle Assessment (LCA) does not provide midpoint indicators. In this scenario, the midpoints must be calculated manually. The process begins by compiling an emission inventory from Life Cycle Inventory (LCI) data sources, such as World Steel Association [2020a] for steel and International Aluminium [2019] for aluminium. This LCI data includes information on the quantities of various pollutants released and resources consumed throughout the product or process life cycle. By multiplying the amount of each emitted substance by its respective characterization factor, the contributions to each midpoint category can be calculated. This results in a set of numerical values representing the environmental impacts across different categories. Equation 3 is describing the process for a mid-point $m_{p,j}$. This mid-point is using n data called x_k (with $k \in [0; n]$) on the pollutants emissions and resources consumed. F_k is the characterization factor provided by ReCiPe associated to x_k.

$$m_{p,j} = \sum_{k=0}^{n} x_k \cdot F_k \tag{3}$$

For decarbonization levers, the alternative methodologies used for unabated technologies are not applicable. Most decarbonization technologies are still under development and have not undergone Life Cycle Assessment (LCA). To generate midpoint indicators for these technologies, two alternative approaches were employed: the first involves calculating midpoints based on the energy consumption data of the technologies, and the second uses conservative estimates. A summarize of the whole methodology is represented in flowchart 7.

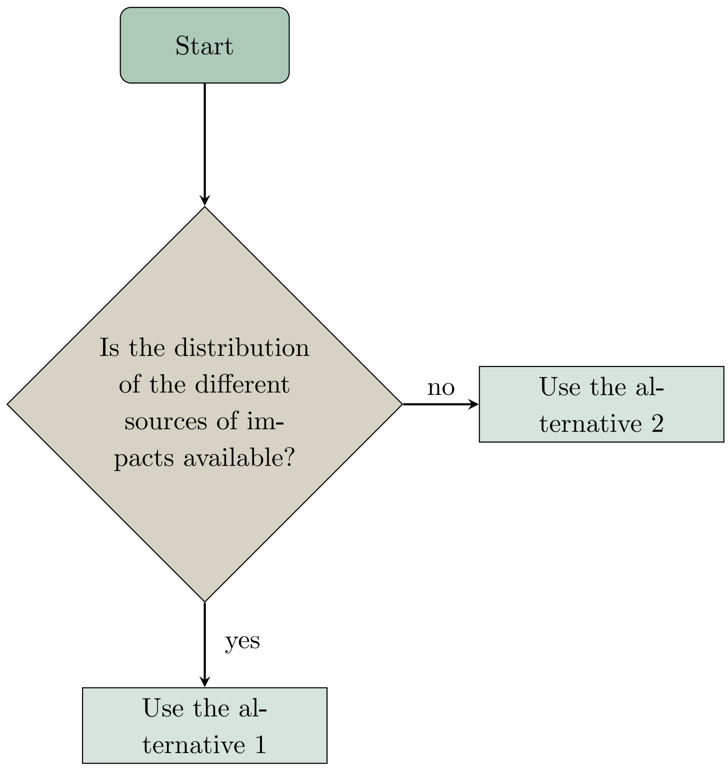

Figure 7: Flowchart representing the overall methodology for each mid-point indicators related to decarbonization technologies

Alternative 1 Impacts can stem from various sources like transportation, electricity consumption, direct processes, and more. These impact sources are typically mapped out in the LCA analysis. To illustrate the first alternative, the following example is about the calculation of a mid-point j for a technology t. Equation 4 is describing the impact score $s_{j,t}$ split in two scores, the impact coming from the energy sources s_e and the impact not coming from the energy sources s_{ne}.

$$s_{j,t} = s_e + s_{ne} \tag{4}$$

Starting with the impact score not coming from energy sources, the calculation is using the total impact score $s_{u,j}$ for an unabated technology u and a mid-point j. This score is multiplied by $\sum_{l=0}^{k} p_l$ the proportion of the k impact sources not related to energy e.g ancillary, transport, etc. This proportions are found in the LCA's analysis of the unabated technology.

$$s_{ne} = s_{u,j} \cdot \sum_{k=0}^{l} p_k \tag{5}$$

Calculating the energy source score s_e relies on the specific technology involved. Table 7 consolidates various methodologies based on technology families. To calculate s_e, the total impact score for the energy source e and the unabated technology u, $s_{e,u}$ is required. In Appendix, Table 12 summarizes data used for this alternative.

Type of technology	impact score for energy sources s_e
CCS	$s_{e,u} \times \begin{cases} 0\% & \text{if emissions are directly link to carbon} \\ 100\% & \text{if not} \end{cases}$
H_2	$m_{H_2} \cdot s_{m,H_2}$ with s_{m,H_2} : the impact of H_2 production per kg of H_2
Electrification	$r \cdot s_{e,u}$ with r increase/decrease potential rate
Energy efficiency	$r \cdot s_{e,u}$with r increase/decrease potential rate

Table 7: Calculation methods for different technologies

For hydrogen based technologies, the idea is to take a look at hydrogen combustion and assess hydrogen mass m_{H_2}. In this case, hydrogen is supplying the same amount of energy as a regular production process. When possible, the energy usage is split between transport, boilers, etc. When it is not, the entire process energy demand has been used. First, the hydrogen's combustion reaction is described in equation 6.

$$\mathrm{H}_{2(\mathrm{g})} + \frac{1}{2}\,\mathrm{O}_{2(\mathrm{g})} \longrightarrow \mathrm{H}_2\,\mathrm{O}_{(\mathrm{g})} \tag{6}$$

Then, using the Hess' law (described in equation 7 [Pressbooks, 2023]) in equation 8 to describe the enthalpy of reaction $\Delta_r H^0$. The enthalpy of reaction is linked to the energy of the combustion E by the equation 9 and the amount of substance x.

$$\Delta_{reaction} H^0 = \sum n \cdot H_f^0(\text{products}) - \sum n \cdot H_f^0(\text{reactants})^1 \tag{7}$$

$$\Delta_r H^0 = H_f^0(H_2O) - \frac{1}{2}\Delta H_f^0(0_{2(g)}) - \Delta H_f^0(H_{2(g)}) \tag{8}$$

$$E = x \cdot |\Delta_r H^0| \tag{9}$$

The following enthalpy of formation and density are used for the calculations.

$$\Delta H_f^0(H_2O) = -241.8 kJ.mol^{-1}$$
$$\Delta H_f^0(0_{2(g)}) = 0 kJ.mol^{-1}$$
$$\Delta H_f^0(H_{2(g)}) = 0 kJ.mol^{-1}$$
$$M(H_2) = 2 g.mol^{-1}$$

Then, looking into the reaction equation in Table 8 to assess x.

[1]with n the schiometric number, ΔH_f^0 the enthalpy of formation

$H_{2(g)}$	$+$	$\frac{1}{2}O_{2(g)}$	$\longrightarrow$	$H_2O_{(g)}$
x_i		excess		0
$x_i - x_{max}$		excess		x_{max}

Table 8: Chemistry progress table for dihydrogen combustion

Furthermore, being in stoichiometric reaction, is allowing the following assumption:

$$x_i - x_{max} = 0$$
$$\text{and } x_i = x_{max}$$
$$\text{and } x = \frac{m_{H_2}}{M(H_2)}$$

Finally, the mass required to produced one ton of product is:

$$m_{H_2} = \frac{E}{|\Delta_r H^0|} * M(H_2) \quad (10)$$

For water consumption, it is different, equation 10 is used to assess the volume of water consumed. According to the International Renewable Energy Agency and Bluerisk [International Renewable Energy Agency and Bluerisk, 2023]), the volume of water consumed by one kilogram of hydrogen produced is:

$$V_{\text{consumed for Green } H_2} = 0.024 m^3/kgH_2$$

Finally, the water consumed during the production of a mass of Hydrogen m_{H_2} is described by the equation 11.

$$V_{\text{water consumed}} = V_{\text{consumed for Green } H_2} * m_{H_2} \quad (11)$$

Alternative 2 With limited data access, it is necessary to rely on conservative inputs or to consider energy as the sole contributor. In some cases, it may be better to simply exclude the mid-point altogether. This alternative represents the worst-case scenario.

Using the same methodology for all technologies is crucial to keep coherence between data and be able to compare them to each other. Moreover, alternative 1 should always be prioritized because 2 is more conservative.

4.6 Comparison of technologies' impacts

After calculating the various end-points and collecting the carbon intensity of each technology, the next step involves comparing the technologies' impacts to the classic production process. As a reminder, this study aims to compare classic and alternative production processes. For a technology $p \in [0, n]$, its impact relative to the classic technology for a given end-point i is calculated by dividing its end-point score $s_{p,i}$ by the end-point score for the classic production process $s_{classic,i}$. This is expressed in equation 12 with $r_{p,i}$ the relative impact of the technology. The result is then expressed in percentage to allow easier comparison between all results.

$$r_{p,i} = \frac{s_{p,i}}{s_{classic,i}} \quad (12)$$

The relative impact r_p is expressed in a range from 0% to 100%. 100% means the highest relative impact and 0% the lowest. The classic technology comes to always be 100% as it is the reference.

5 Results

This chapter presents the results for aluminium and steel. For each scenario results, four different impacts are shown namely carbon intensity, freshwater ecosystems, terrestrial ecosystems and human health. In the results for aluminium, the classic production process is not shown as it represents the reference and is equal to 100% all the time. It allows better readability and avoid redundancy. It is important to keep in mind that alternative technologies are always compared to the classic production process.

5.1 Aluminium

The individualistic scenario, as depicted in Figure 13, reveals a complex relationship between Global Warming Potential and the three endpoints. While GWP is factored into the calculation of these endpoints, a linear correlation is notably absent. This complexity is particularly evident when comparing Mechanical Vapor Recompression and Electric Boilers.

MVR, which involves capturing and reusing process waste heat to generate electricity, is associated with a higher CO2 intensity (10%) compared to Electric Boilers (0%). However, despite its higher carbon footprint, MVR significantly outperforms Electric Boilers in terms of biodiversity impact. This discrepancy can be attributed to MVR's substantially lower electricity demand. In contrast, the transition to Electric Boilers merely involves switching the power source without altering the technology's overall energy consumption.

The Carbon Anodes + CCS technology presents intriguing results. While it effectively reduces carbon emissions by 90%, its impact on human health is less pronounced, with only a 21% reduction. This disparity underscores the importance of considering multiple environmental factors beyond carbon emissions alone. This result can mainly be explained by the necessity of digging pipelines' installation when building carbon storage facilities.

Secondary production emerges as the clear front runner among the technologies examined. It stands out as the only technology that achieves substantial reductions across all impact categories: approximately 95% in carbon intensity, 98% in human health impacts, and 95% and 97% in freshwater and terrestrial ecosystem impacts, respectively. The superior performance of secondary production can be largely attributed to its use of recycled scrap materials. This process requires significantly less energy and raw materials to produce the end product, explaining its lower environmental impact across all categories.

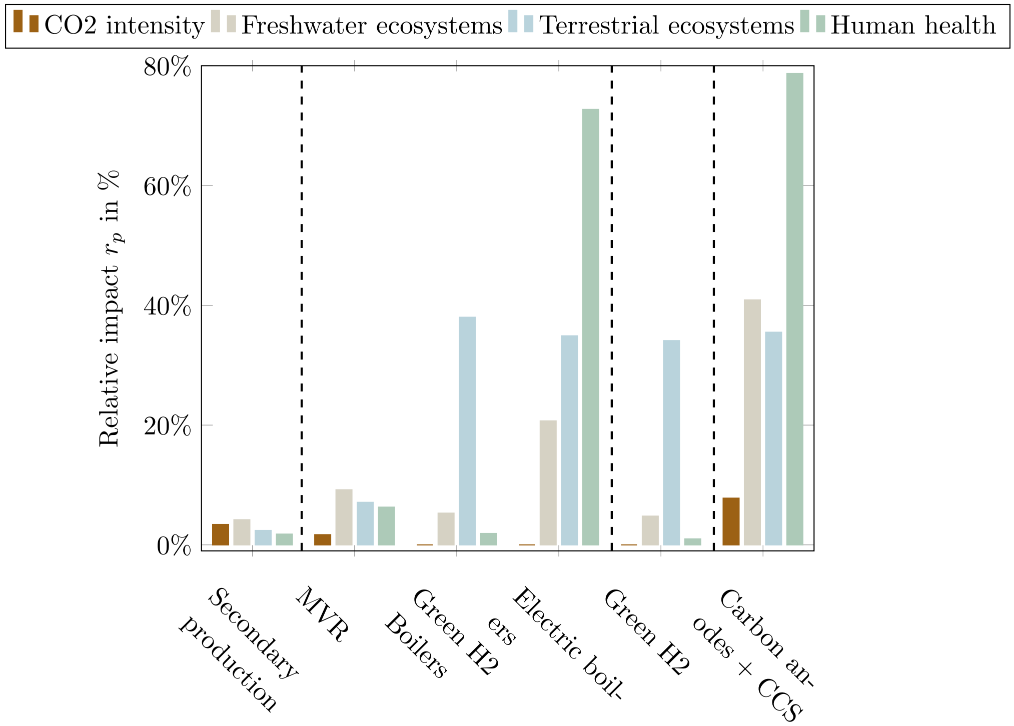

Figure 8: Relative impact's results individualistic scenario for aluminium

Then delving into the hierarchic scenario in Figure 9, MVR shows a notably different profile compared to the individualistic scenario. While its CO2 intensity remains low at 1.7% its impacts on ecosystems and human health are more closely aligned with those of secondary production. This suggests that in a hierarchic worldview, MVR's energy efficiency gains are valued alongside its broader environmental impacts.

Secondary production maintains its position as a leading technology, demonstrating consistently low impacts across all categories (CO2 intensity: 3.4%, freshwater ecosystems: 3.4%, terrestrial ecosystems: 3.1%, human health: 2.8%). This consistency underscores the environmental benefits of recycling in aluminium production, even when viewed through a hierarchic lens.

Furthermore, Carbon Anodes + CCS technology presents the highest impacts across all categories in this scenario (CO2 intensity: 7.8%, freshwater ecosystems: 16.2%, terrestrial ecosystems: 19.2%, human health: 26%). This suggests that in a hierarchic perspective, the benefits of carbon capture may be outweighed by other environmental concerns associated with this technology.

Green H2 technologies present an interesting case in this scenario. They maintain zero CO2 intensity but show varying impacts across other categories. Green H2 Boilers and direct Green H2 use have minimal impact on freshwater ecosystems (1.2%) and human health (0.3%), but their impact on terrestrial ecosystems is more pronounced (10.7% and 12.1% respectively). This highlights the trade-offs inherent in adopting hydrogen-based technologies and emphasizes the importance of a comprehensive environmental assessment.

Electric boilers, in contrast, show higher impacts on freshwater ecosystems (4.5%), terrestrial ecosystems (11.5%), and particularly on human health (18%). This stark difference from their performance in the individualistic scenario underscores the importance of considering broader environmental impacts beyond carbon emissions in a hierarchic worldview.

These results highlight the complexity of environmental impact assessment in a hierarchic scenario, where multiple factors are weighted more evenly. The scenario emphasizes the need for balanced technological solutions that address not only carbon emissions but also broader ecosystem and human health impacts in aluminium production.

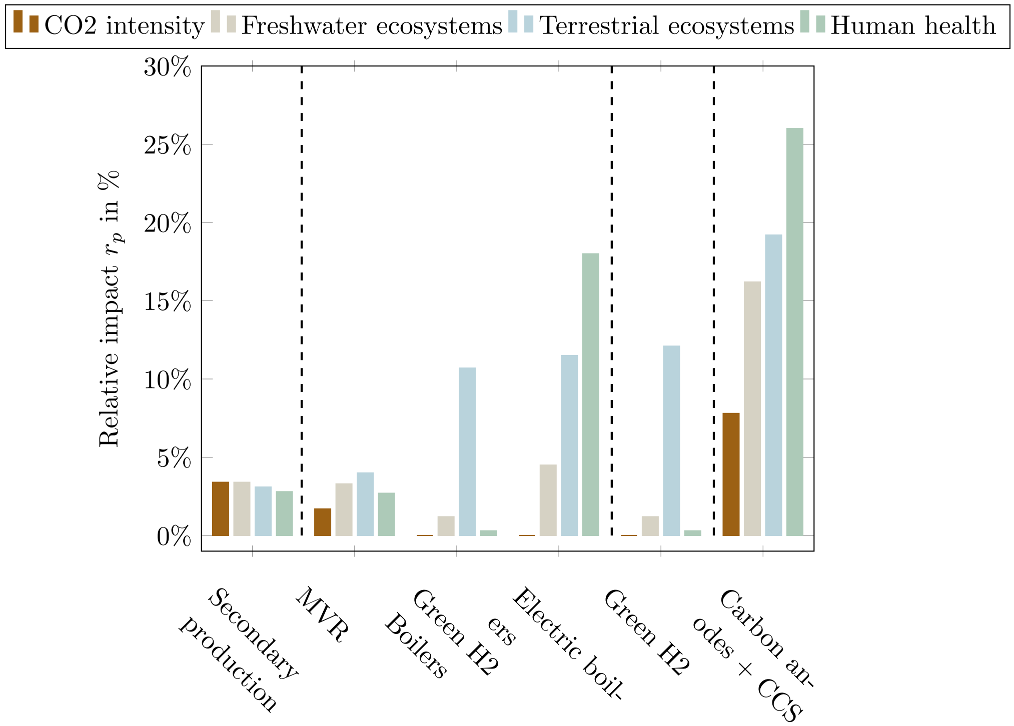

Figure 9: Relative impact's results hierarchic scenario for aluminium

Shifting our focus to the egalitarian scenario illustrated in Figure 10, we observe a different prioritization of environmental impacts. In this egalitarian view, secondary production emerges as the most environmentally friendly option, with consistently low impacts ranging from 3.1% to 3.4% across all categories. This balanced performance contrasts with the individualistic scenario, which might overly emphasize its impressive 95% reduction in carbon intensity. The egalitarian perspective appreciates secondary production's broader environmental benefits, aligning with its focus on overall ecosystem health and resource conservation.

MVR shows the second-best overall performance in the egalitarian scenario, with impacts ranging from 1.7% to 2.0%. This ranking differs from what we might expect in an individualistic scenario, where MVR's slightly higher CO2 intensity (1.7%) compared to zero-emission technologies could be seen as a significant drawback. The egalitarian view, however, recognizes MVR's efficiency in waste heat utilization, resulting in lower overall environmental impact.

The egalitarian perspective reveals subtle differences in the environmental impacts of electric boilers and green hydrogen technologies compared to the individualistic and hierarchic scenarios. While they have similar effects on terrestrial ecosystems (1.3-1.7%), Electric Boilers show slightly higher impacts on freshwater ecosystems (0.5%) and human health (1.7%) compared to Green H2 technologies (0.1% and 0% respectively). These nuances might be overlooked in a less comprehensive assessment.

As with the individualistic and hierarchic scenarios, carbon anodes + CCS technology does not allow for the same impact reduction across the three end-points (human health, freshwater and terrestrial ecosystems) in the egalitarian scenario. Compared to the hierarchic scenario, which might seek a balance between environmental impact and economic feasibility, the egalitarian view places greater emphasis on overall ecosystem health. This is evident in its favorable assessment of technologies with broader environmental benefits, such as secondary production and MVR.

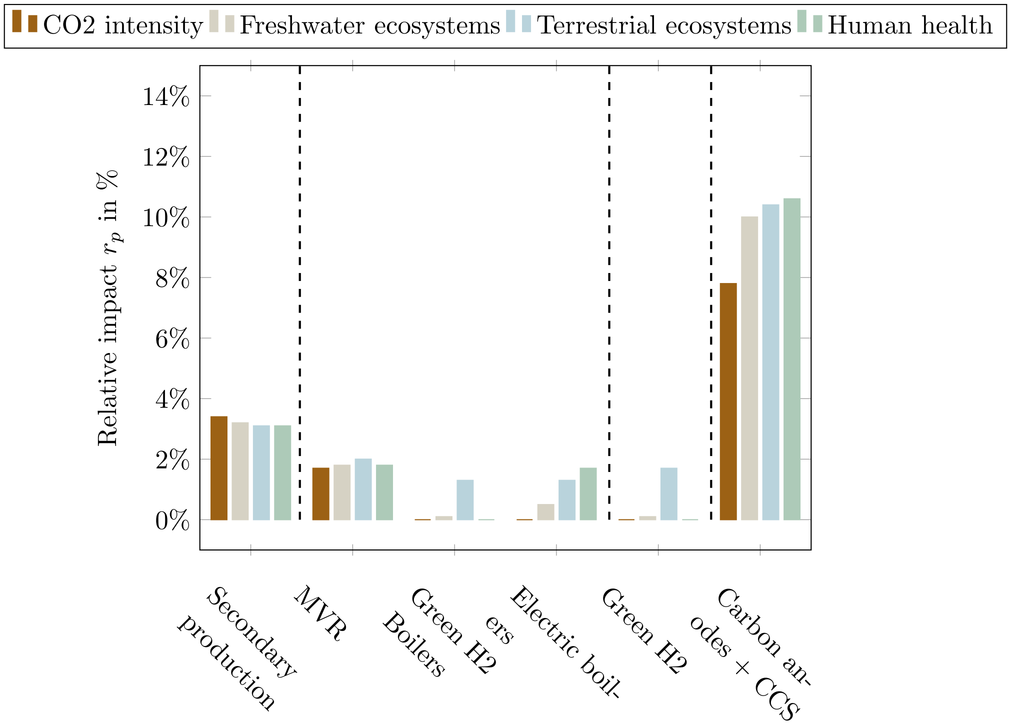

Figure 10: Relative impact's results egalitarian scenario for aluminium

Detailed results for each scenario can be found in Tables 13, 14, and 15 in the Appendix. Additionally, a contribution analysis has been conducted to show the impact of each midpoint on the endpoint calculations in Appendix 4 with Figures 14, 15 and 16. This contribution is expressed as a percentage (%) and is detailed for each scenario.

5.2 Steel

To begin with the individualistic scenario presented in Figure 11, the unabated technology remains the worst-case scenario across all four impact areas. In contrast, three technologies exhibit a similar pattern: BF-BOF + CCUS, DRI-BOF + CCUS, and DRI-EAF + CCS. These technologies significantly reduce carbon intensity by 90%, 96%, and 96% respectively. However, Figure 11 also highlights their substantial freshwater impacts, with increases of 92%, 79%, and 79% respectively. The common factor among these technologies is the integration of CCS technology with more conventional methods. It's important to note that carbon capture processes often require significant amounts of water for cooling and other purposes [Berkeley Chemistry, 2020]. This increased water usage likely contributes to the substantial freshwater impacts observed.

Furthermore, DRI-EAF and DRI-BOF show similar results to the aforementioned technologies concerning their impact on freshwater ecosystems, indicating that CCS technology does not mitigate these effects. However, a slight reduction in impacts on human health and terrestrial ecosystems is observed with CCS technologies. For example, DRI-EAF + CCS reduces the impact on human health by 34% compared to DRI-EAF alone.

Continuing with DRI-EAF, it was initially considered a favorable option for carbon reduction, but the preference has been shifting towards DRI-BOF. Nonetheless, with the incorporation of green hydrogen, DRI-EAF emerges as the optimal choice. When evaluating sustainable energy options, green hydrogen is particularly noteworthy for its potential to substantially decrease carbon emissions from 96% while having minimal impact on biodiversity (27% for human health, 33% for terrestrial impacts and 4% for freshwater ecosystems), making it a critical factor in future considerations.

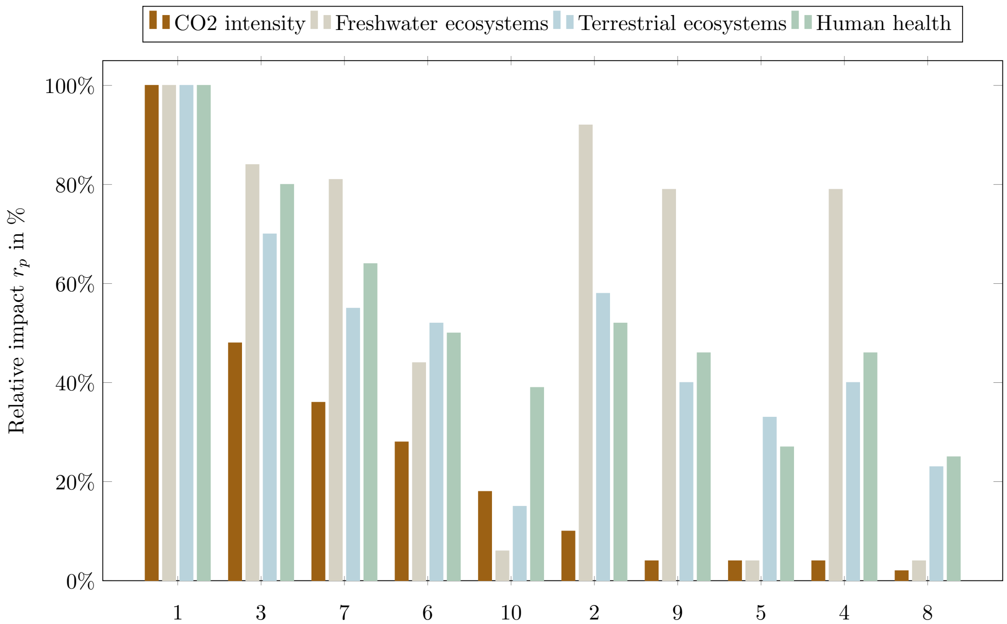

Figure 11: Relative impact's results individualistic scenario for steel

Note: 1:BF-BOF (Unabated technology); 2: BF-BOF + CCUS; 3: DRI-EAF; 4: DRI-EAF + CCS; 5: DRI-EAF + 100% Green H_2; 6: DRI-EAF + 50% Green H_2; 7: DRI-BOF; 8: DRI-BOF + 100% Green H_2; 9: DRI-BOF + CCUS; 10: Scrap-based EAF

Moreover, the scrap-based Electric Arc Furnace (EAF) is a particularly noteworthy technology. It utilizes recycled materials processed through an Electric Arc Furnace, offering significant environmental benefits. However, its current impact assessment is based on the global electricity grid mix, which does not consider the potential emissions reductions achievable with renewable energy sources. In the individualistic scenario, this technology competes with more robust options, achieving a substantial reduction in carbon emissions (around 80%) while exerting a lower impact on the other three environmental areas (e.g freshwater ecosystems 6%). Using less raw materials and energy during the manufacturing allow to significantly reduce impacts on different environmental areas.

Finally, regarding technologies using Green H_2, results seem giving promising results. DRI-EAF + 100% Green H2 hows remarkable performance across all impact categories. It reduces CO2 intensity by 96%, has minimal impact on freshwater ecosystems (4%), and significantly lower impacts on terrestrial ecosystems (33%) and human health (27%) compared to the unabated technology. Similarly, DRI-BOF + 100% Green H2demonstrates excellent results, with even lower CO2 intensity (98% reduction), the same minimal impact on freshwater ecosystems (4%), and slightly lower impacts on terrestrial ecosystems (23%) and human health (25%). These impressive results can be attributed to several factors. Green hydrogen, produced through electrolysis using renewable energy, eliminates direct CO2 emissions during the steel production process. This explains the dramatic reduction in CO2 intensity. The minimal impact on freshwater ecosystems is likely due to the absence of water-intensive carbon capture processes. The lower impacts on terrestrial ecosystems and human health may be attributed to the reduced pollution and resource extraction associated with fossil fuel-based production methods [Bellona, 2024].

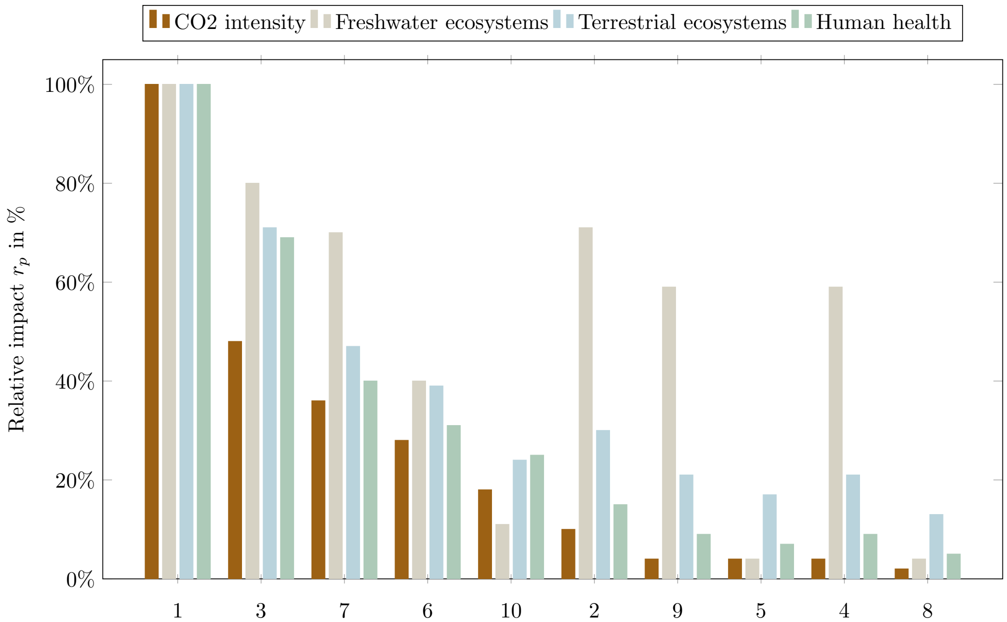

Figure 12: Relative impact's results hierarchic scenario for steel

Note: 1:BF-BOF (Unabated technology); 2: BF-BOF + CCUS; 3: DRI-EAF; 4: DRI-EAF + CCS; 5: DRI-EAF + 100% Green H_2*; 6: DRI-EAF + 50% Green* H_2*; 7: DRI-BOF; 8: DRI-BOF + 100% Green* H_2*; 9: DRI-BOF + CCUS; 10: Scrap-based EAF*

In the hierarchic scenario highlighted in Figure 12 most of the results remain similar as the individualistic with a slight reduction. However, CCS technologies (DRI-BOF + CCUS, DRI-EAF + CCS and BF-BOF + CCUS) outperform freshwater ecosystems impacts again. Moreover, DRI with green hydrogen continues to demonstrate substantial improvements across most impact categories, reinforcing its potential as an environmentally friendly technology. EAF technologies also maintain their strong performance, indicating their robustness as lower-impact alternatives to traditional methods.

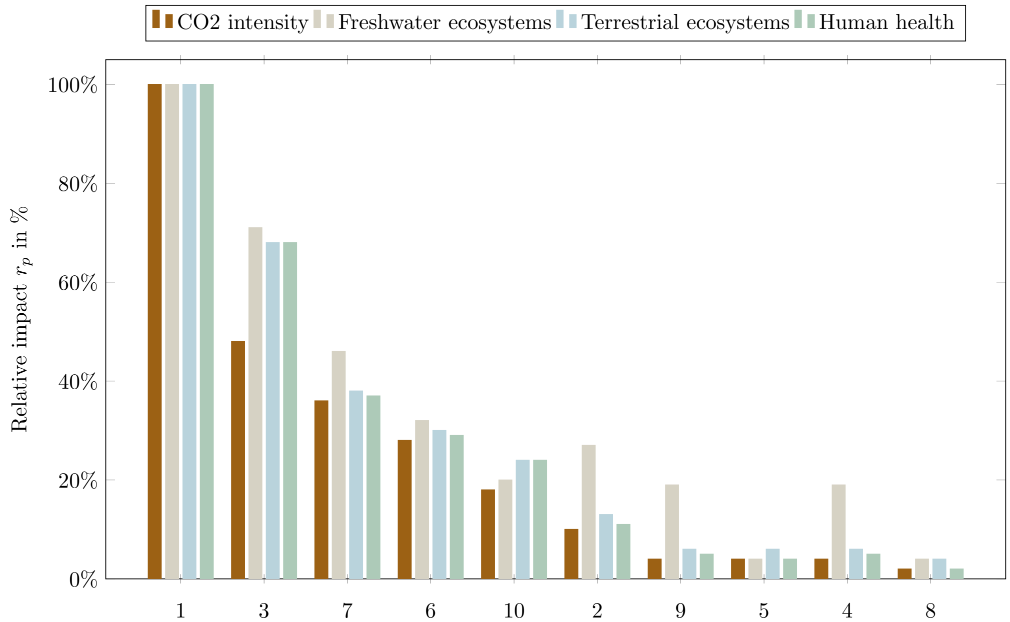

Figure 13: Relative impact's results egalitarian scenario for steel

Note: 1:BF-BOF (Unabated technology); 2: BF-BOF + CCUS; 3: DRI-EAF; 4: DRI-EAF + CCS; 5: DRI-EAF + 100% Green H_2; 6: DRI-EAF + 50% Green H_2; 7: DRI-BOF; 8: DRI-BOF + 100% Green H_2; 9: DRI-BOF + CCUS; 10: Scrap-based EAF

In contrast, the egalitarian scenario reveals less variation among technologies compared to the hierarchic view. This suggests that when considering very long-term impacts and more uncertain pathways, the differences between steel production technologies become less pronounced. However, even in this conservative scenario, green technologies like DRI with hydrogen and EAF methods still show improvements over unabated processes, albeit to a lesser degree.

An interesting trend across both scenarios is the consistent performance of certain technologies. For instance, DRI with green hydrogen maintains its position as a top performer in both views, suggesting its potential as a sustainable option regardless of the time horizon considered. The reduced differentiation in the egalitarian scenario highlights the importance of considering long-term impacts in technology assessment, as some apparent short-term benefits may diminish over extended periods.

Finally, detailed results can be found in the Appendix in Tables 16, 17, and 18. Similarly to aluminium, a contribution analysis has been conducted for steel, and the results are illustrated in Figures 17, 18, and 19 in Appendix 5.

5.3 Results discussion

This subsection presents a comprehensive analysis of our findings across three distinct scenarios, evaluating the potential of different approaches to reduce environmental impacts. Our discussion synthesizes our results with findings from relevant literature, placing our observations within the broader context of sustainable manufacturing research.

Secondary aluminium production demonstrates significant potential for environmental impact reduction across all three scenarios examined in this study. For terrestrial ecosystems, secondary production decreases impacts by 95.8% to 96.8%, a finding that aligns with the results reported in the Material Production

Project (MPP) study [Missions Possible Partnership, 2023a]. These results underscore a crucial reduction in biodiversity impacts due to secondary production, as it diminishes the need for environmentally disruptive primary mining activities. This observation is further corroborated by similar trends in steel production.

The benefits of secondary production are not limited to aluminium. In steel manufacturing, scrap-based production emerges as the most effective option, offering potential carbon reductions of up to 82%. Additionally, with an approximate 80% reduction in terrestrial environmental impacts, it is poised to play a crucial role in sustainable steel manufacturing. However, Suer et al. [2022] emphasizes that relying solely on scrap is not feasible due to the growing global demand for steel and insufficient scrap availability. This limitation underscores the need for a balanced approach that combines increased recycling efforts with improvements in primary production methods.

While Carbon Capture and Storage (CCS) technologies facilitate substantial carbon reduction, as highlighted by Leeson et al. [2017], our results for aluminium and steel across all scenarios indicate significant impacts on human health and ecosystems. This observation supports the findings of Volkart et al. [2013], who emphasize the various environmental burdens associated with CCS. These burdens include the energy demands of the CO2 capture process, the infrastructure requirements for carbon storage and usage, and the degradation of chemicals like monoethanolamine (MEA) used in the capture process. Indeed, Zapp et al. [2012] attributes these impacts to increased fuel consumption driven by the efficiency requirements of the capture process. These findings highlight the complexity of implementing CCS technologies and the need for a holistic approach to environmental impact assessment.

Green hydrogen technology shows promise in addressing both environmental and health concerns, with significant potential for future advancements. This aligns with the findings of Zhang et al. [2024], who highlight the potential of hydrogen as a clean energy carrier. However, it requires substantial development and investment to achieve the necessary level of maturity. In the interim, established technologies such as Direct Reduced Iron - Basic Oxygen Furnace (DRI-BOF) and Direct Reduced Iron - Electric Arc Furnace (DRI-EAF) remain viable alternatives for steel production [Vogl et al., 2018]. These technologies offer a balance between environmental impact reduction and technological readiness, providing a pathway for incremental improvements in the steel industry's environmental footprint.

In conclusion, while secondary production methods offer the most significant environmental benefits for both aluminium and steel, the limitations in scrap availability necessitate a multi-faceted approach to sustainable metal production. This approach should incorporate improvements in primary production methods, the strategic implementation of CCS technologies, and continued investment in promising technologies like green hydrogen. Future research should focus on optimizing these various approaches and exploring their synergies to achieve the most effective reduction in environmental impacts across the metal production industry.

5.4 Limitation

Using a single LCIA model in a study presents significant limitations. Each LCIA model is based on specific methodologies, assumptions, and characterization factors, which can lead to a narrow focus on certain environmental impacts while potentially neglecting others. This means that the study's outcomes are confined to the perspective of that particular model, which may not capture the full spectrum of environmental effects, especially those that might be better addressed by other models. Additionally, relying on one model can introduce bias, reduce the robustness of the results, and limit the ability to compare findings across different studies or contexts. Due to a lack of time and resources the sensitivity analysis could not be done.

6 Conclusion

This study, conducted within Schneider Electric's environmental team, evaluates the environmental impacts of aluminium and steel manufacturing, focusing on human health, terrestrial ecosystems, and freshwater systems in the context of SE's procurement activities. Utilizing the ReCiPe 2016 LCIA model, the research highlights the potential of technologies such as green hydrogen and electrification to significantly reduce both carbon emissions and biodiversity impacts.

To measure the biodiversity impacts of production technologies, this study employs the ReCiPe 2016 LCIA model, which provides a robust framework for quantifying these impacts and normalizing them relative to traditional methods. This approach helps to assess the environmental relevance of new technologies comprehensively.

Regarding the recommendations from the MPP's studies, this Master Thesis indicates that while the SE project's focus on carbon reduction remains valuable, it must be complemented with biodiversity considerations. The findings suggest that incorporating biodiversity impacts into sustainability strategies is essential for a balanced environmental assessment. Technologies such as green hydrogen, when combined with low-carbon processes like DRI-EAF, show promise for reducing both carbon emissions and biodiversity impacts. However, the limitations of CCS, particularly its impact on biodiversity, highlight the need for updated recommendations that account for these broader environmental concerns.

The study also emphasizes the importance of a circular economy approach, where scrap-based production can mitigate both carbon emissions and biodiversity impacts. Despite the benefits, the limited availability of scrap requires exploring additional strategies to ensure a sustainable supply of materials.

Finally, the analysis highlights a trade-off between carbon reduction and biodiversity impacts. While certain low-carbon technologies succeed in lowering carbon intensity, they can unintentionally harm biodiversity. This finding emphasizes the need for a comprehensive sustainability approach that balances both carbon reduction and biodiversity preservation. Moreover, it underscores the complexity of developing sustainability strategies, which must address multiple environmental challenges within a limited timeframe and gain the support of various company stakeholders.

To conclude, this study provides valuable insights into the relationship between carbon intensity and biodiversity impacts in aluminium and steel production processes. However, there are several avenues for future research that could further enhance our understanding and application of these findings. First, investigate how biodiversity impacts can vary across different geographical regions and ecosystems, considering local biodiversity hotspots and vulnerable species. This topic is not covered in this study and is a very important aspect. Finally, the analysis could be extended to include other critical materials used by Schneider Electric, such as copper and thermoplastics, to provide a more comprehensive view of the company's environmental impact.

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Appendices

Appendix 1: ReCiPe Resources

Table 9: Conversion factors from mid-point to end-point metric, ReCiPe 2016 [Huijbregts et al., 2016]

	Impact	Unit	Conversion factors		
			Individualistic	Hierarchic	Egalitarian
Human health	Global Warming Potential	$DALY/kgCO_{2e}$	8.12E-08	9.28E-07	1.25E-05
	Stratospheric ozone depletion	$DALY/kgCFC_{11e}$	2.37E-04	5.31E-04	1.34E-03
	Ionizing Radiation	$DALY/kBqCo-60$ emitted to air$_e$	6.80E-09	8.50E-09	1.40E-08
	Fine particulate matter formation	$DALY/kgPM2.5_{eq}$	6.29E-04	6.29E-04	6.29E-04
	Photochemical ozone formation	$DALY/kgNOx_e$	9.10E-07	9.10E-07	9.10E-07
	Toxicity (cancer)	$DALY/kg1,4-DCB$ emitted$_{eq}$	3.32E-06	3.32E-06	3.32E-06
	Toxicity (non-cancer)	$DALY/kg1,4-DCB$ emitted$_{eq}$	2.28E-07	2.28E-07	2.28E-07
	Water consumption	$DALY/m^3$	3.10E-06	2.22E-06	2.22E-06
Terrestrial ecosystems	Global Warming Potential	$Species.year/kgCO_{2e}$	5.32E-10	2.80E-09	2.50E-08
	Photochemical ozone formation	$Species.year/kgNO_{xe}$	1.29E-07	1.29E-07	1.29E-07
	Acidification	$Species.year/kgSO_{2e}$	2.12E-07	2.12E-07	2.12E-07
	Toxicity	$Species.year/kg1,4-DCB$emitted$_e$	1.14E-11	1.14E-11	1.14E-11
	Water consumption	$Species.year/m^3$	No Data	1.35E-08	1.35E-08
	Land use - occupation and transformation	$Species.year/m^2$	8.88E-09	8.88E-09	8.88E-09
Freshwater ecosystems	Global Warming Potential	$Species.year/kgCO_{2e}$	1.45E-14	7.65E-14	6.82E-13
	Eutrophication	$Species.year/kgP_e$	6.71E-07	6.71E-07	6.71E-07
	Toxicity	$Species.year/kg1,4-DCB$emitted$_e$	6.95E-10	6.95E-10	6.95E-10
	Water consumption	$Species.year/m^3$	6.04E-13	6.04E-13	6.04E-13

Table 10: Mid-point and units

Name	Unit
Global Warming Potential	$kgCO_{2e}$
Water consumption	m^3
Toxicity (freshwater, terrestrial, cancer and non-cancer)	$kg1,4-DBC$ emitted eq
Eutrophication	kgP_e
Acidification	$kgSO_{2e}$
Photochemical Ozone formation	$kgNO_{x,e}$
Stratospheric Ozone Depletion	$kgCFC11eq$
Fine particulate matter formation	$kgPM2.5eq$
Land use	m^2

Table 11: List of Hydrogen mid-point scores

Mid-point	Value	Unit	Source
Water consumption	2.4×10^{-2}	m^3/kg of H_2	IRENA [International Renewable Energy Agency and Bluerisk, 2023]
Acidification potential	1.18×10^{-2}	$kgSO_{2eq}/kg$ of H_2	Life Cycle Inventory [Mehmeti et al., 2018]
Photochemical Ozone Formation	3.9×10^{-3}	$kgNO_{x,eq}/kg$ of H_2	Same as above

Table 12: Data used for alternative 2 in case of decarbonization technologies

Technology type	Values chosen	Explanation
Hydrogen	0 emissions	Considering that burning of hydrogen do not participate to this mid-point score
CCS	Conservative value	CCS is capturing carbon but not other emissions
Electrification	Conservative value	too hard to determine

Appendix 2: Result Tables for Aluminium

Table 13: Aluminium - Results for individualistic scenario

ID	Levers	Freshwater ecosystems	Terrestrial ecosystems	Human health	CO2 intensity
1	Primary production	100.0%	100.0%	100.0%	100.0%
2	Secondary production	4.2%	2.4%	1.8%	3.4%
3	Refining [Digestion] - Unabated	100.0%	100.0%	100.0%	100.0%
4	Refining [Digestion] - MVR	9.2%	7.1%	6.2%	2.0%
5	Refining [Digestion] - Green H2 Boilers	5.3%	38.0%	1.9%	0.0%
6	Refining [Digestion] - Electric Boilers	20.7%	30.6%	72.6%	0.0%
7	Refining [Calcination] - Unabated	100.0%	100.0%	100.0%	100.0%
8	Refining [Calcination] - Green H2	4.8%	34.1%	1.1%	0.0%
9	Smelting - Unabated Carbon Anodes	100.0%	100.0%	100.0%	100.0%
10	Smelting - Carbon Anodes + CCS	40.9%	35.5%	78.7%	9.2%

Table 14: Aluminium - Results for hierarchic scenario

ID	Levers	Freshwater ecosystems	Terrestrial ecosystems	Human health	CO2 intensity
1	Primary production	100.0%	100.0%	100.0%	100.0%
2	Secondary production	3.4%	3.1%	2.8%	36.9%
3	Refining [Digestion] - Unabated	100.0%	100.0%	100.0%	100.0%
4	Refining [Digestion] - MVR	3.3%	4.0%	2.7%	2.0%
5	Refining [Digestion] - Green H2 Boilers	1.2%	10.7%	0.3%	0.0%
6	Refining [Digestion] - Electric Boilers	4.5%	11.5%	18.0%	0.0%
7	Refining [Calcination] - Unabated	100.0%	100.0%	100.0%	100.0%
8	Refining [Calcination] - Green H2	1.2%	12.1%	0.3%	0.0%
9	Smelting - Unabated Carbon Anodes	100.0%	100.0%	100.0%	100.0%
10	Smelting - Carbon Anodes + CCS	16.2%	19.2%	26.0%	14.0%

Table 15: Aluminium - Results for egalitarian scenario

ID	Levers	Freshwater ecosystems	Terrestrial ecosystems	Human health	CO2 intensity
1	Primary production	100.0%	100.0%	100.0%	100.0%
2	Secondary production	3.2%	3.1%	3.1%	36.9%
3	Refining [Digestion] - Unabated	100.0%	100.0%	100.0%	100.0%
4	Refining [Digestion] - MVR	1.9%	2.0%	1.8%	3.0%
5	Refining [Digestion] - Green H2 Boilers	0.1%	1.3%	0.0%	0.0%
6	Refining [Digestion] - Electric Boilers	0.5%	1.3%	1.7%	0.0%
7	Refining [Calcination] - Unabated	100.0%	100.0%	100.0%	100.0%
8	Refining [Calcination] - Green H2	0.1%	1.7%	0.0%	0.0%
9	Smelting - Unabated Carbon Anodes	100.0%	100.0%	100.0%	100.0%
10	Smelting - Carbon Anodes + CCS	10.0%	10.4%	10.6%	9.2%

Appendix 3: Result Tables for Steel

Table 16: Steel - Results for individualistic scenario

ID	Levers	Freshwater ecosystems	Terrestrial ecosystems	Human health	CO2 intensity
1	BF-BOF Unabated	100%	100%	100%	100%
3	DRI-EAF	84%	70%	80%	48%
7	DRI-BOF	81%	55%	64%	36%
6	DRI-BOF+50% Green H_2	44%	52%	50%	28%
10	EAF - scrap based	6%	15%	39%	18%
2	BF-BOF + CCUS	92%	58%	52%	10%
9	DRI-BOF + CCUS	79%	40%	46%	4%
5	DRI-EAF + 100% green H_2	4%	33%	27%	4%
4	DRI-EAF + CCS	79%	40%	46%	4%
8	DRI-BOF + 100% green H_2	4%	23%	25%	2%

Table 17: Steel - Results for hierarchic scenario

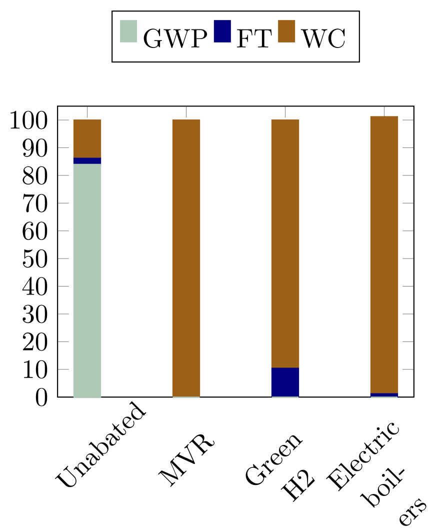
ID	Levers	Freshwater ecosystems	Terrestrial ecosystems	Human health	CO2 intensity
1	BF-BOF Unabated	100%	100%	100%	100%
3	DRI-EAF	80%	71%	69%	48%
7	DRI-BOF	70%	47%	40%	36%
6	DRI-BOF+50% Green H_2	40%	39%	31%	28%
10	EAF - scrap based	11%	24%	25%	18%
2	BF-BOF + CCUS	71%	30%	15%	10%
9	DRI-BOF + CCUS	59%	21%	9%	4%
5	DRI-EAF + 100% green H_2	4%	17%	7%	4%
4	DRI-EAF + CCS	59%	21%	9%	4%
8	DRI-BOF + 100% green H_2	4%	13%	5%	2%

Table 18: Steel - Results for egalitarian scenario

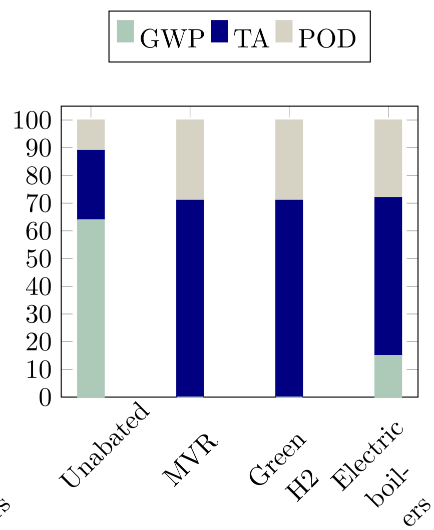
ID	Levers	Freshwater ecosystems	Terrestrial ecosystems	Human health	CO2 intensity
1	BF-BOF Unabated	100%	100%	100%	100%
3	DRI-EAF	71%	68%	68%	48%
7	DRI-BOF	46%	38%	37%	36%
6	DRI-BOF+50% Green H_2	32%	30%	29%	28%
10	EAF - scrap based	20%	24%	24%	18%
2	BF-BOF + CCUS	27%	13%	11%	10%
9	DRI-BOF + CCUS	19%	6%	5%	4%
5	DRI-EAF + 100% green H_2	4%	6%	4%	4%
4	DRI-EAF + CCS	19%	6%	5%	4%
8	DRI-BOF + 100% green H_2	3%	4%	2%	2%

Appendix 4:

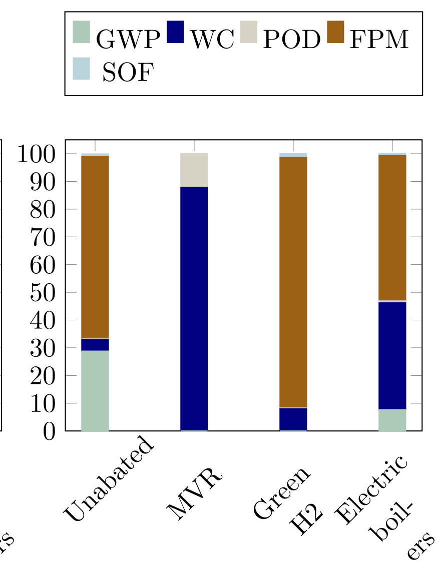
Figure 14: Aluminium - Mid-points' contribution in end-point calculation (Individualistic scenario)



(a) Freshwater ecosystems



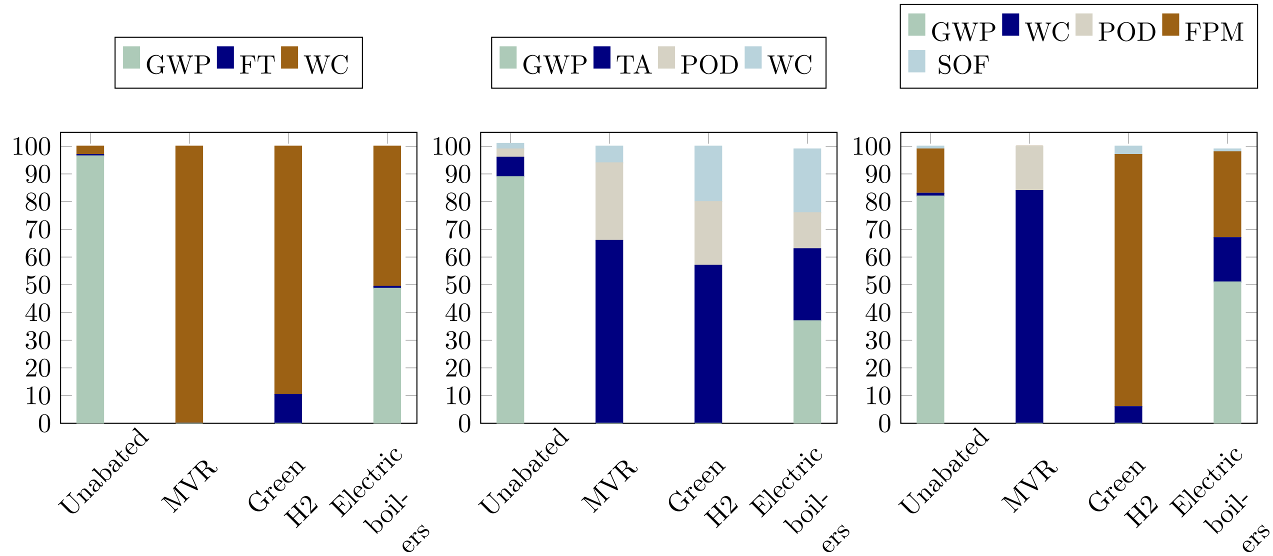
(b) Terrestrial ecosystems



(c) Human health

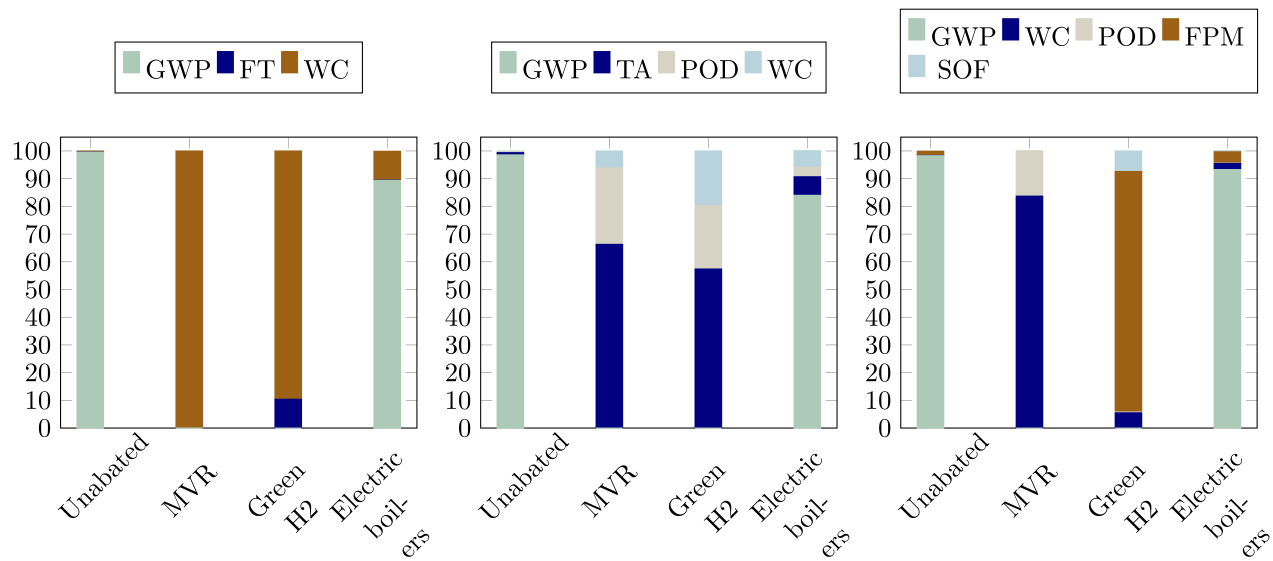
Note: GWP: Global Warming Potential; FT: Freshwater Toxicity; WC: Water Consumption; TA: Terrestrial Acidification; POD: Photochemical Ozone Depletion; FPM: Fine Particulate Matter; SOF: Stratospheric Ozone Formation

Figure 15: Aluminium - Mid-points' contribution in end-point calculation (Hierarchic scenario)



(a) Freshwater ecosystems (b) Terrestrial ecosystems (c) Human health

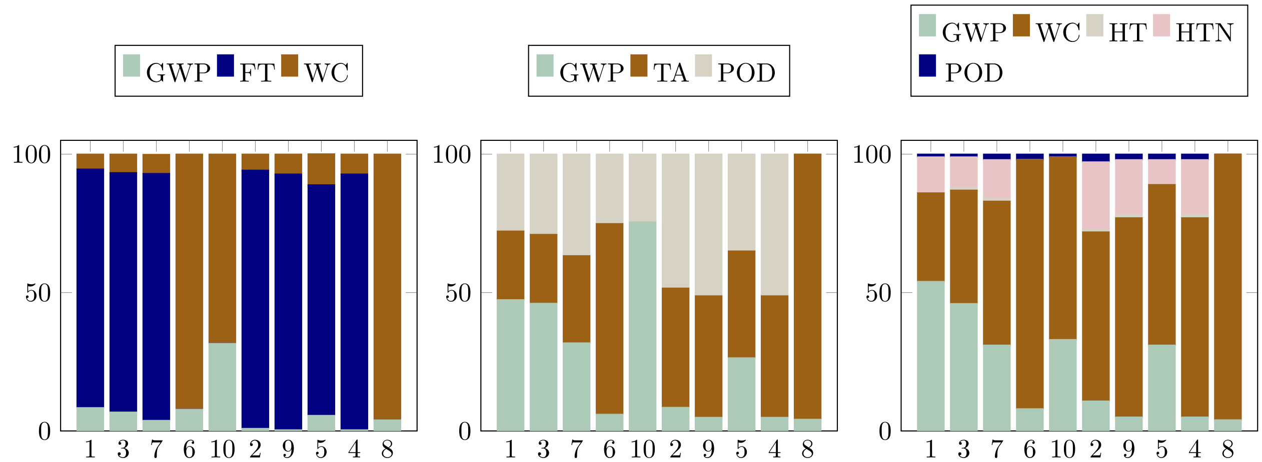
Figure 16: Aluminium - Mid-points' contribution in end-point calculation (Egalitarian scenario)



(a) Freshwater ecosystems (b) Terrestrial ecosystems (c) Human health

Appendix 5:

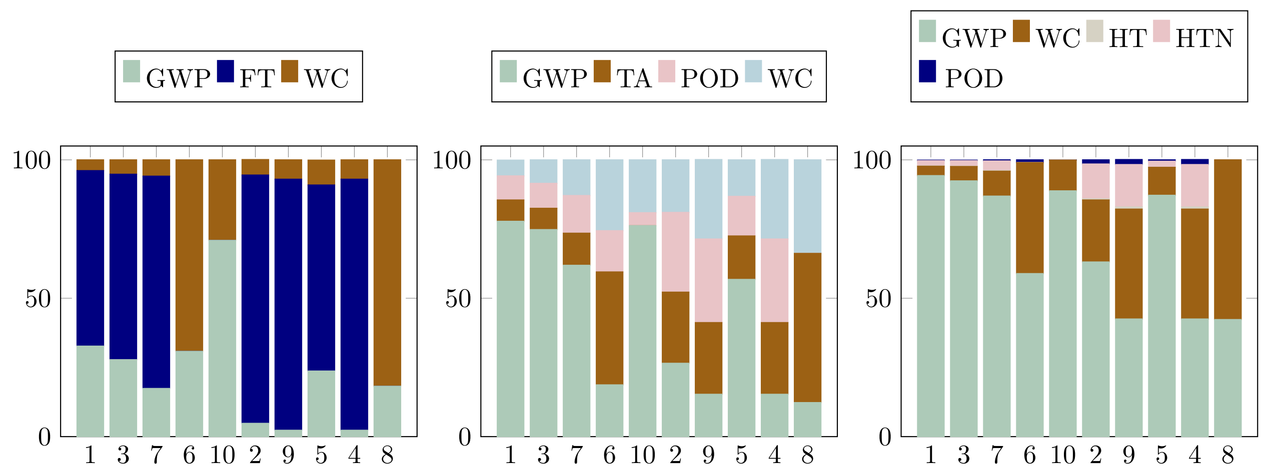
Figure 17: Steel - Mid-points' contribution in end-point calculation (Individualistic scenario)



(a) Freshwater ecosystems (b) Terrestrial ecosystems (c) Human health

Note:1:BF-BOF (Unabated technology); 2: BF-BOF + CCUS; 3: DRI-EAF; 4: DRI-EAF + CCS; 5: DRI-EAF + 100% Green H_2; 6: DRI-EAF + 50% Green H_2; 7: DRI-BOF; 8: DRI-BOF + 100% Green H_2; 9: DRI-BOF + CCUS; 10: Scrap-based EAF

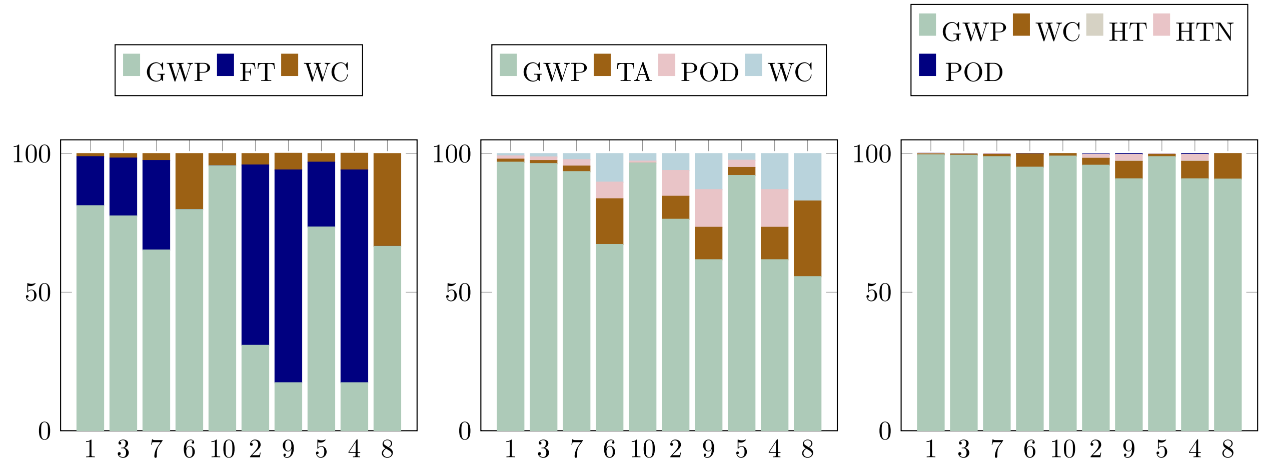
Figure 18: Steel - Mid-points' contribution in end-point calculation (Hierarchic scenario)



(a) Freshwater ecosystems (b) Terrestrial ecosystems (c) Human health

Note:1:BF-BOF (Unabated technology); 2: BF-BOF + CCUS; 3: DRI-EAF; 4: DRI-EAF + CCS; 5: DRI-EAF + 100% Green H_2; 6: DRI-EAF + 50% Green H_2; 7: DRI-BOF; 8: DRI-BOF + 100% Green H_2; 9: DRI-BOF + CCUS; 10: Scrap-based EAF

Figure 19: Steel - Mid-points' contribution in end-point calculation (Egalitarian scenario)



(a) Freshwater ecosystems (b) Terrestrial ecosystems (c) Human health

Note:1:BF-BOF (Unabated technology); 2: BF-BOF + CCUS; 3: DRI-EAF; 4: DRI-EAF + CCS; 5: DRI-EAF + 100% Green H_2; 6: DRI-EAF + 50% Green H_2; 7: DRI-BOF; 8: DRI-BOF + 100% Green H_2; 9: DRI-BOF + CCUS; 10: Scrap-based EAF