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Assessing the mitigation potential of environmental impacts from sustainability strategies on steel construction value chain: a case study on two steel products in Italy

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Abstract

Life Cycle Assessment (LCA) plays a crucial role in sustainability evaluations and impact assessments, especially in the field of environmentally and eco-friendly materials or system production and building design for the construction sector. However, stakeholders and professionals tend to use LCA mainly to develop an Environmental Product Declaration (EPD) or assess building sustainability certification. This research investigates the possibility of using the LCA results to assess the potential for further mitigation of the environmental impacts in the construction industry. Starting from a previous study on the steel construction value chain performed by authors to develop two steel product datasets for the Italian LCA database, this work aims to identify how sensitivity analysis can guide industries in choosing sustainability strategies to mitigate their impacts further. The study focuses the sensitivity analyses only on one specific sustainability strategy for each of the two previously analyzed steel products (A. beams and angles and B. hollow sections), thus potentially limiting the generalizability of findings to a broader range of sustainability strategies but demonstrating the feasibility of the proposed method and its replicability to other products and production scenarios.

Keywords: Life cycle assessment (LCA), construction sector, steel building materials, environmental impact, sensitivity analysis

1. Introduction

The construction sector is a major contributor to global greenhouse gas (GHG) emissions and energy consumption, responsible for nearly 40% of global energy use and approximately 38% of all energy-related carbon dioxide emissions. In particular, the Breakthrough Agena Report of the International Energy Agency (IEA) [1] reported that the buildings sector emissions in 2022 represented around a third of total energy system emissions, including buildings operations (26%) and embodied emissions (7%) associated with the production of materials used for their construction. To get on track with the Net Zero Emissions Target set by the European Green Deal [2], the operational emissions need to fall by about 50% from their 2022 level by 2030, and embodied emissions need to fall by 25%.

Across the world in 2020, around 1900 million tons of crude steel were produced, with just over 50% of that used for buildings and infrastructure [3]. The steel used in buildings accounts for around 8% of the world's carbon emissions, and on average, every ton of steel produced leads to the emission of 1.85 tons of CO_2 into the atmosphere [4]. This makes the steel industry the single most significant contributor to industrial emissions, and at the same time, it has the vital challenge of reducing its CO_2 emissions, an action that involves important technological changes [5].

Various latest studies [11]-[10][9] deal with the sustainability assessment of the steel industry to highlight the potential route to decarbonizing steel production and to individuate the factors that contribute towards carbon emission through the whole life cycle of steel products used for buildings. Moreover, the literature underlined the increased global awareness of environmental issues and the consequent increase of pressure on the construction industry to mitigate its environmental impact through assessment methodologies that cover the whole building life. In this context, Life Cycle

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Assessment (LCA) has emerged as a vital tool in this effort, offering a comprehensive approach to evaluating the environmental impacts associated with all stages of a building's life cycle—from raw material extraction, manufacturing, and construction, to use, maintenance, and disposal. LCA allows for a detailed assessment of energy use, emissions, and other environmental effects, providing crucial insights that can help reduce the carbon footprint of construction activities and support more sustainable practices [11][12].

The use of LCA in the construction sector has been supported by the development of dedicated databases that provide specific environmental data for various construction materials and practices. For instance, in Italy, the Banca Dati Italiana LCA (BCI-LCA) [13], a database developed by the ARCADIA project, offers comprehensive data on local construction practices, including those based on steel, which can be used to perform more accurate LCAs [14][15]. These databases represent a source of reliable reference data to be used by professionals or stakeholders to identify strategies to reduce environmental impacts both at the material choice phase of building design and at the material production phase of industries.

However, many companies in the steel construction sector face significant challenges in applying LCA data effectively. There is often a lack of understanding about how to integrate or use those data into their operational strategies to improve the overall sustainability performance and boost the decarbonization path. The sector's dependence on long-lasting, high-emission materials and technologies limits the transition to lower-emission alternatives since those materials can be used for decades, thereby "locking in" higher emissions levels [16].

Furthermore, while various international and national initiatives encourage the reduction of GHG emissions in the construction sector, the practical application of these guidelines remains challenging. Companies often struggle to interpret LCA results. For the steel industry, understanding the impacts' variation of the various scenarios, starting from the LCA results, is crucial for making informed choices regarding materials and processes that could cause minor impacts. The LCA use can identify critical areas where changes in material use or production methods could substantially reduce carbon emissions, such as the shift from blast furnaces to electric arc furnaces [17].

Despite the growing availability of LCA tools and environmental data, there is still a gap between the full potential of LCA to improve sustainability and its practical implementation within the steel construction sector [18]. This paper seeks to address this gap by examining how LCA results can further support the evaluation of specific sustainability strategies along the entire steel value chain and consequently assess their implementation feasibility to boost further reductions in GHG emissions. On this basis, the research question that guided the overall study has been defined.

RQ: *How can the steel construction industry leverage its product LCA data results to identify, study, and choose the most suitable sustainable strategies to reduce its carbon footprint?*

To reach this goal and to reply to the RQ, the study has been grounded on the definition and conduction of sensitivity analysis of LCA results to explore potential sustainability strategies that steel construction stakeholders can adopt to support the industry's transition towards a more sustainable practice.

Specifically, the study begins as a follow-up research activity of the ARCADIA project, which ends with the LCA report of two selected steel products for buildings, chosen among the others as the most used in the Italian context, and the development of their respective datasets implemented in the BDI-LCA. The authors used the LCA results of this prior study [19] as input for their new sensitivity analysis to evaluate the respective impacts' variation on the steel value chain of two selected Sustainable Strategies (SSs): 1) the implementation of renewable energy sources for the steel production; 2) the shift from blast furnace method to electric arc furnace technologies for the steel production.

After the contextualization and motivation of the study definition in this introduction, coupled with RQ and overall contents, Section 2 describes the methodology defined and followed in this study. Section 3 presents the sensitivity analyses in detail, clarifying the boundary conditions and motivating the choices made to set up the work. Section 4 focuses on the summary of the results and their critical discussion, reviewing the most relevant impact categories for all the studied scenarios. Finally, Section 5 concludes the article by summarizing key insights, underlining practical and theoretical contributions of using sensitivity analysis on LCA product results as a supporting tool for the decision-making process of corporate sustainability reporting for construction industries, and outlining potential avenues for future research and sustainable practices.

2. Methodology

In this section, the methodology followed for the study is described and graphically summarized in Figure 1. As mentioned in the introduction, the main scope of the work is to perform sensitivity analysis to address the presented RQ. Accordingly, the study has been divided into five interrelated phases.

Phase 0, presented in Section 1, illustrates the research framework which focuses on the steel value chain for construction and the inputs of this study, i.e., the LCA datasets assessed for two selected steel building products (beams and angles - product A and square and rectangular hollow sections - product B) implemented in the BDI-LCA, developed by the ARCADIA project with the support of stakeholders of the steel value chain. The RQ derived by those industries, which - after having provided Environmental Product Data for the study - and verified their impacts, would like to deeply understand the results of the LCA report with the scope to enhance LCA integration in practice and its potentialities along the entire value chain for the construction sector.

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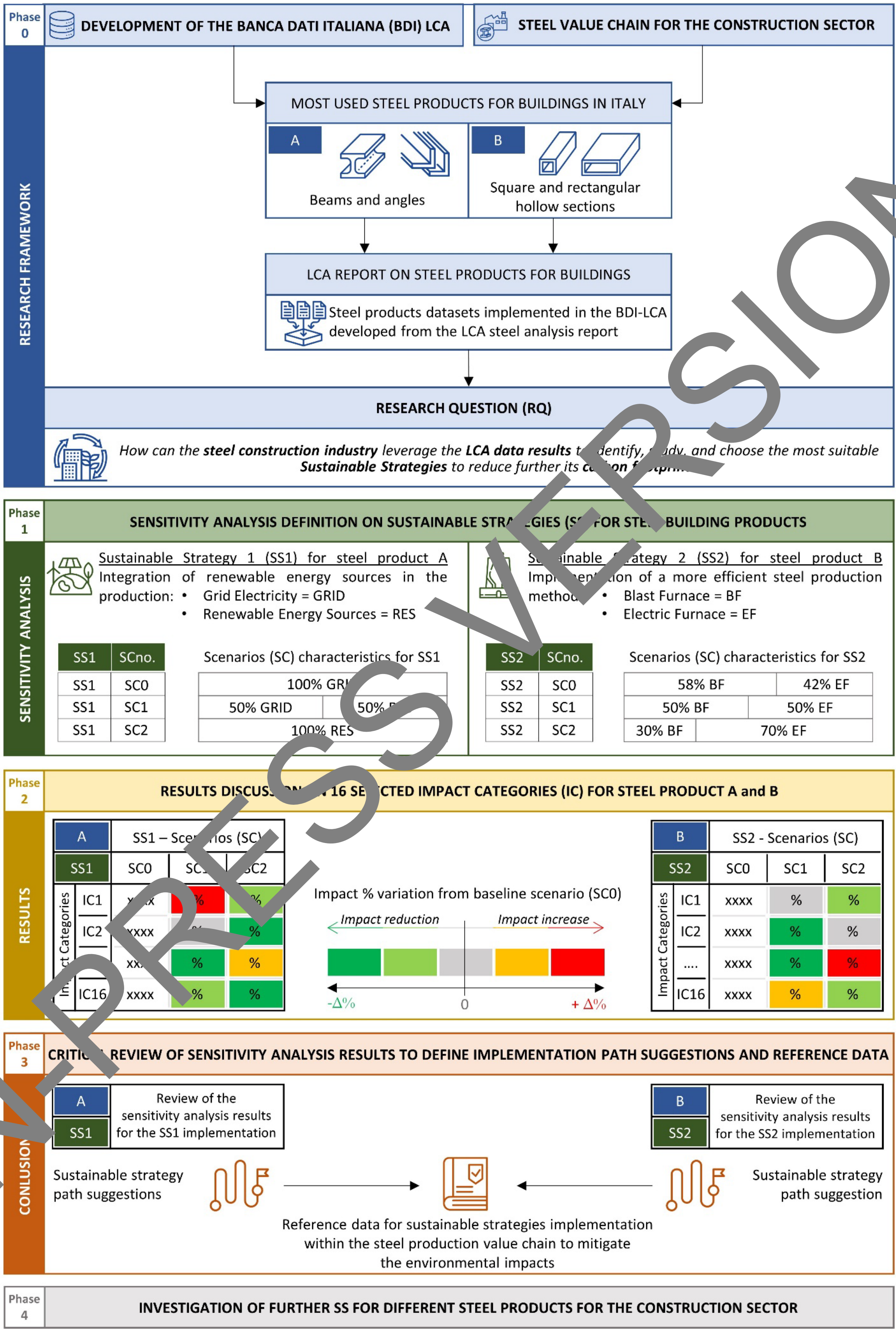

Figure 1. Graphical summary of the study methodology

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Phase 1 illustrates the definition and structure of the sensitivity analysis performed to explore the environmental impacts of two sustainable strategies, one per each steel building product studied. The choice of the Sustainable Strategy for each steel product is derived from direct interaction with the respective business owner considering their industry investment in sustainability.

For steel product A, the industry, having already implemented new technologies for steel production, requests to investigate the possibility of reducing electricity consumption by integrating renewable energy sources (Sustainable Strategy 1 – SS1).

For steel product B, the Sustainable Strategy 2 (SS2) chosen by the second business owner has been the implementation of a more efficient steel production method. Three scenarios have been studied for each Sustainable Strategy to examine different levels of implementation of the sustainable strategies and their correlated impacts: Scenario 0 (SC0), which corresponds to the baseline scenario, Scenario 1 (SC1), and Scenario 2 (SC2).

Phase 2 focuses on the elaboration and discussion of the results based on 16 selected impact categories (IC), defined within the Environmental Footprint (EF) 3.0 method by the European Commission's Product Environmental Footprint (PEF) initiative [20]. The analysis has been performed by calculating the percentage of impact variations for each scenario compared to SC0 for each sustainable strategy, with the final goal of studying their influence on specific environmental impacts. The graphical representation of the results helps to identify the potentialities and barriers associated with each scenario.

Phase 3 aims to critically review the results of the sensitivity analyses to define implementation path suggestions and practical recommendations useful for the stakeholders' choice concerning the adoption of the investigated SS for mitigating their environmental impacts. This method will facilitate identifying and evaluating critical environmental factors associated with each stage, providing valuable insights for sustainable decision-making.

Finally, Phase 4 outlines potential future research directions based on the findings and limitations of the current analysis. Further research may explore a broader range of steel products and sustainability strategies to address these limitations and enhance the method's robustness and applicability.

3. Sensitivity analysis

Sensitivity analysis is a well-known method for understanding how variations in input parameters can affect the environmental impacts of products and processes. In the steel construction sector, where production processes are highly energy intensive and contribute significantly to global environmental impacts, the application of sensitivity analysis can help identify factors influencing environmental performance and facilitate the application of more efficient sustainability strategies.

Prior studies [21][22][23] have highlighted the benefits of the application of different sustainable strategies in the steel industry. For instance, Suer et al.[24] conducted a comprehensive review of LCA methodologies for steel production and highlighted the potential for renewable energy integration to significantly reduce greenhouse gas emissions and environmental impacts.

The authors remarked that the integration of renewable energy sources and the transition to electric arc furnaces could substantially reduce the carbon footprint of the steel industries. Some other recent research works [25][26] noted the high potentialities of LCA methodologies and, in particular, the relevance of their results analysis to support the corporate sustainability plan definition to invest in a more circular supply chain, with the final aim to enlarge the company sustainability framework and the choice of the applicable strategies that can provide a more significant impulse on carbon footprint reduction.

In this context, this study focuses on the sensitivity analysis definition for two steel products, A and B, considering 16 selected Impact Categories (IC), summarized in Table 1, according to the IC EF 3.0 method, which includes the key environmental indicators such as global warming potential, ozone depletion potential, and particulate matter, to provide a comprehensive understanding of the environmental impacts of different steel production strategies.

The Sustainable Strategies analyzed, as anticipated in the methodology description, are two (SS1- integration of renewable energy sources; SS2 - implementation of a more efficient steel production method), and they are investigated for steel products A and B, respectively.

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Code	Impact Category name	Unit
IC1	Climate change	kg CO_2 eq
IC2	Ozone depletion	kg CFC11 eq
IC3	Ionizing radiation	kBq U^{235} eq
IC4	Photochemical ozone formation	kg NMVOC eq
IC5	Particulate matter	Disease incidence
IC6	Human toxicity, non-cancer	CTUh
IC7	Human toxicity, cancer	CTUh
IC8	Acidification	mol H^+ eq
IC9	Eutrophication, freshwater	kg P eq
IC10	Eutrophication, marine	kg N eq
IC11	Eutrophication, terrestrial	mol N eq
IC12	Ecotoxicity, freshwater	CTUe
IC13	Land use	Dimensionless (Pt)
IC14	Water use	m^3 depriv.
IC15	Resource use, fossils	MJ
IC16	Resource use, minerals, and metals	kg Sb eq

Table 1. List of the Impact Categories (IC) chosen for the sensitivity analysis

3.1 SS1: Integration of renewable electricity sources in the production process

Sustainable Strategy 1 (SS1), applied to steel product A, integrates renewable energy sources to cover the steel production process per different quantities of percentages. As explained in the methodology, the SS1 choice derives firstly from the request of the business owner to investigate this SS, having already invested in a more efficient method of steel production covered by electricity consumption and needing to cover this energy consumption by more sustainable sources. Therefore, the integration of renewable energy sources, such as photovoltaic, wind, or solar systems, can cover part of all electricity consumption and, consequently, reduce greenhouse gas emissions and other environmental impacts.

Besides the baseline scenario SC0, which represents the current industry situation, two other scenarios have been investigated concerning the percentage of integration of renewable energy sources. In SC0, the production process relies entirely on grid electricity; in SC1, a 50% mix of grid and renewable energy is considered, reflecting an intermediate level of transition towards sustainable practices, and SC2 corresponds to the complete shift to renewable energy sources, to demonstrate the maximum potential reduction of this strategy.

3.2 SS2: Implementation of more efficient steel production methods

Sustainable Strategy 2 (SS2), applied to steel product B, focuses on enhancing the efficiency of steel production by optimizing the use of electric furnaces over traditional blast furnaces. The business owner of product B chose this strategy to evaluate the innovation investment in electric furnaces, which offer a more sustainable alternative with lower emissions and improved energy efficiency, particularly those powered by renewable energy sources.

Similarly to the SS1, even for the SS2, three scenarios have been evaluated to explore the impact of different furnace technology mixes. The baseline scenario SC0 presents a mix of 58% blast furnace and 42% electric furnace. SC1 proposes an equal mix of 50% blast and 50% electric furnaces, while SC2 presents a 30% blast furnace and 70% electric furnace mix. This range of scenarios can help evaluate the environmental benefits of progressively increasing the proportion of electric furnace use in steel production.

In both SS, as anticipated in the methodology, the selected strategies highly depend on the starting point and the needs of the industry, as well as the specific steel product considered. Therefore, the study focuses on the comparative assessment of each specific chosen strategy to identify the most efficient setup for the steel product studied. Future research should incorporate a wider range of sustainability strategies to cross-analyze the overall strategies and identify the optimum solutions.

4. Results and discussions

This section presents the sensitivity analysis results for each sustainability strategy (SS1 and SS2) applied to steel products A and B, respectively. The results are detailed in Table 2, highlighting, for each scenario, the environmental

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impacts across the 16 selected ICs defined in Table 1.

The results for steel product A on Sustainable Strategy 1 show that the ICs with the highest values in SC0 are the ecotoxicity freshwater (IC12) and the use of fossil fuel resources (IC15), respectively, with values of 8.66 CTUe and 13.1 MJ. Those high values highlight significant environmental impacts associated with using the electricity grid in the production process. In contrast, the categories with the lowest impact values in SC0 are IC6 and IC7, both related to human toxicity, indicating minimal impacts in these areas. SC1 and SC2 have the same ICs with the highest and lowest values as SC0, but while IC12 and IC15 show reduced values in line with the percentage increase of electricity produced from renewable energy sources, the categories related to impacts on human health (IC6 and IC7) show higher values in SC1 and SC2 compared to SC0.

Similar to SS1, the results for steel product B on SS2 also show that the ICs with the highest values in each scenario are the freshwater ecotoxicity (IC12) and the use of fossil fuel resources (IC15). SC1 shows reductions in most categories like human toxicity, non-cancer (IC6), and Land use (IC13), reflecting the benefits of a higher percentage of steel produced by electric furnaces. However, ionizing radiation (IC3) and human toxicity, cancer (IC7) increase slightly, indicating similar trade-offs as observed in SS1 and suggesting that while comprehensive strategies reduce many impacts, some categories may still experience adverse effects.

Comparing SS1 and SS2, both strategies effectively reduce the environmental impacts in most categories, such as ecotoxicity, freshwater (IC12), resource use, and fossils (IC15). While SS2 achieves a higher reduction in Human toxicity, non-cancer (IC6) from SC0 to SC2 compared to SS1, the latter significantly reduces the impact of Ionizing radiation (IC3).

However, both strategies show increases in specific categories, such as human toxicity cancer (IC7), highlighting situations where applying sustainability measures for specific impacts may require implementing different strategies.

IC	Product A - Sustainable Strategy 1 (SS1)			Product B - Sustainable Strategy 2 (SS2)		
	SC0	SC1	SC2	SC0	SC1	SC2
IC1	9.33E-01	8.08E-01	6.63E-01	1.60E+00	1.47E+00	1.13E+00
IC2	1.24E-07	1.02E-07	8.20E-08	7.78E-08	7.30E-08	6.05E-08
IC3	9.30E-02	7.60E-02	5.85E-02	1.26E-01	1.31E-01	1.45E-01
IC4	3.03E-03	2.80E-03	2.51E-03	6.77E-03	6.14E-03	4.50E-03
IC5	1.18E-07	1.17E-07	1.15E-07	1.12E-07	1.04E-07	8.33E-08
IC6	8.42E-09	1.55E-08	1.[illegible]0E-08	3.50E-08	3.21E-08	2.46E-08
IC7	1.90E-09	3.93E-0[illegible]	3.92E-0[illegible]	2.05E-08	2.16E-08	2.46E-08
IC8	3.64E-03	3.09E-03	2.47E-03	7.02E-03	6.51E-03	5.20E-03
IC9	2.28E-04	[illegible].10E-04	1.79E-04	7.78E-04	7.22E-04	5.77E-04
IC10	8.76E-04	8.03E-04	7.10E-04	1.58E-03	1.47E-03	1.17E-03
IC11	9.25E-03	8.[illegible]8E-03	7.48E-03	1.62E-02	1.49E-02	1.19E-02
IC12	8.66E+00	8.65E+00	8.02E+00	3.36E+01	3.03E+01	2.17E+01
IC13	1.27E+00	1.24E+00	1.13E+00	4.29E+00	3.86E+00	2.75E+00
IC14	2.75E-01	2.08E-01	1.40E-01	3.64E-01	3.56E-01	3.35E-01
IC15	1.31E+01	1.08E+01	8.62E+00	1.72E+01	1.61E+01	1.32E+01
IC16	2.[illegible]5E-07	2.63E-07	2.62E-07	1.71E-05	1.49E-05	9.21E-06

Table 2. Results of the sustainability analysis conducted on product A for SS1 and product B on SS2, respectively, for three different scenarios (SC0-SC1-SC2)

In the following paragraphs, a more in-depth discussion of the results is carried out to identify the potential and barriers associated with each sustainability strategy and scenario analyzed.

4.1 SS1: Integration of renewable electricity sources in the production process

The sensitivity analysis for SS1 reveals significant potential reductions in environmental impacts. Figure 2 displays the results across the 16 ICs, comparing the percentage variations (Δ%) between the baseline scenario (SC0) and SC1 or SC2, providing indications of the efficacy of each strategy.

The graph presents a color legend illustrating the percentage impact variations between the scenarios to better understand the results for each IC. The color legend ranges from dark green, representing a Δ% reduction of at least 50% compared to scenario SC0, to dark red, corresponding to a Δ% increase greater than 100%. This color gradient helps

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quickly identify which impact categories are most affected by integrating renewable energy sources to cover electricity needs.

Data show a substantial reduction in several key impact categories in line with the proportion of integration of renewable energy sources. For example, in scenario SC1, there is a notable decrease in ozone depletion (IC2) by 17.8% and in ionizing radiation (IC3) by 18.3%. The reductions are even higher in SC2, with a decrease of 34.0% and 37.1%, respectively. These results suggest that transitioning to renewable energy sources can significantly mitigate stratospheric ozone degradation and reduce radioactive releases that account for adverse health effects.

Furthermore, the impact category related to water use (IC14) presents the highest percentage of impact reduction in both scenarios, reaching almost a 50% decrease in SC2 compared to SC0. This reduction highlights the potential of renewable electricity sources to contribute to global sustainability goals of lower water consumption and promote a circular economy. On the contrary, a few impact categories, such as human toxicity (IC6 and IC7), show increases in both SC1 and SC2, with a maximum increase of 107.0% for IC7 in SC1 compared to SC0. This trend indicates potential trade-offs, where the shift from fossil to renewable electricity sources increases human toxicity, likely due to the materials and processes involved in the production of renewable energy technologies. In this case, a dedicated investigation should be conducted to identify which strategy, in combination with the analyzed one, could balance the impact variation.

In conclusion, the results of SS1 reveal a general environmental benefit in shifting towards renewable energy sources. However, the increase in a few impact categories highlights the need for a balanced approach that considers all environmental dimensions to avoid unexpected consequences. Moreover, it is essential to remark that the presented results refer to the use of a specific energy mix in a reference year. The results and the environmental benefits of this SS1 could vary in dedicated scenarios considering different geographical contexts and the temporal evolution of the national energy mix.

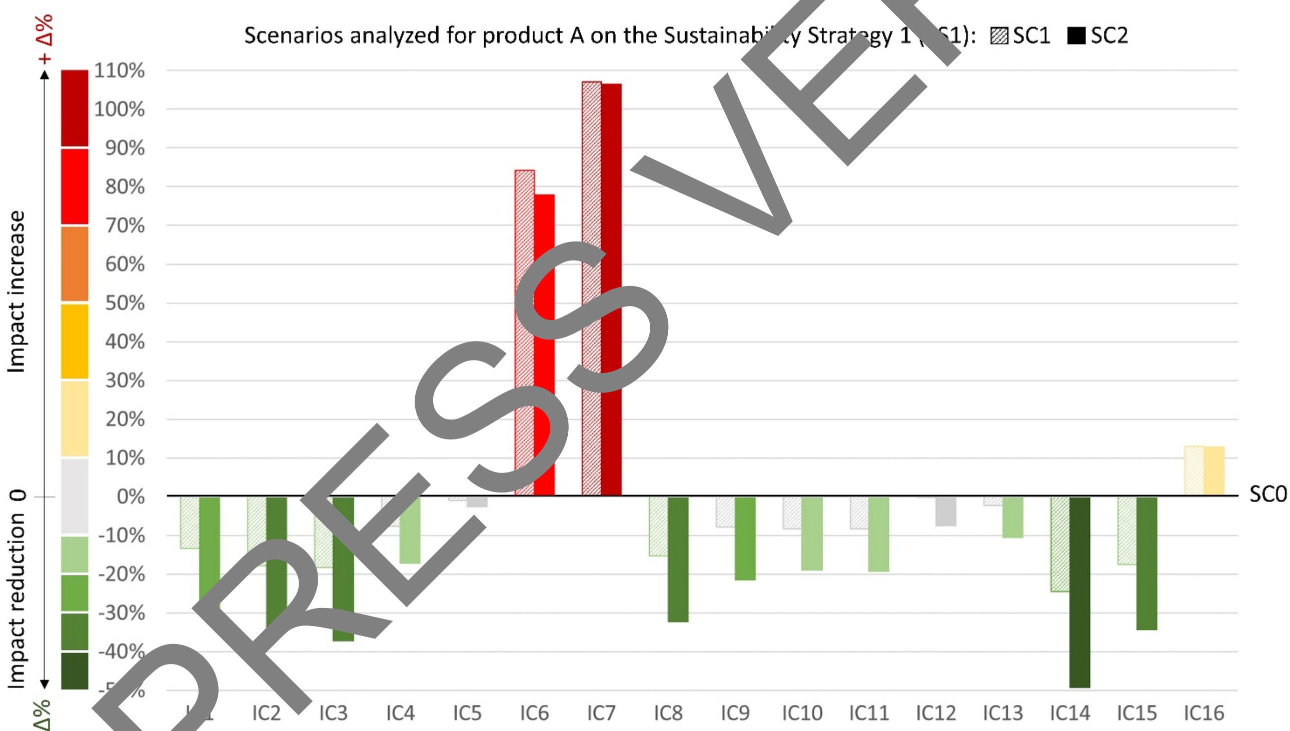

Figure 2. Percentage impact variations between baseline scenario (SC0) and the analyzed scenarios (SC1 - SC2) for product A (beams and angles) on the Sustainability Strategy 1

4.2 Implementation of more efficient steel production methods

The sensitivity analysis for SS2 focuses on implementing a more efficient steel production method for steel building product B. Similarly to the analysis conducted for SS1, Figure 3 shows the results across the 16 ICs, using the same color legend to illustrate the percentage variations (Δ%) between scenarios.

The results demonstrate how a higher percentage of electric furnace steel could provide environmental benefits across most impact categories. The mineral and metals resource use category (IC16) shows the highest Δ% reduction in both scenarios, reaching 46.3% less resource use in SC2 compared to SC0. This outcome supports the adoption of electric furnaces, as they reflect less material input and waste generation compared to traditional blast furnace methods.

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Furthermore, in SC2, three other ICs, photochemical ozone formation (IC4), freshwater ecotoxicity (IC12), and land use (IC13), present Δ% reduction higher than 30%.

In SC1, there are moderate reductions in climate change (IC1) by 8.2% and acidification potential (IC8) by 7.2%. The most significant improvements are observed in SC2, in which IC1 decreases by 29.3%, and acidification potential IC4 reduces by 25.8%, indicating that electric furnaces, which are generally more energy-efficient and produce fewer emissions, can help reduce the environmental footprint of steel production.

However, two impact categories, ionizing radiation (IC3) and human toxicity cancer (IC7), show increases in both SC1 and SC2, reaching 15.0% and 20.1%, respectively. These increases could be attributed to higher electricity consumption and related emissions when the electric furnace is used more intensively. This observation suggests that while electric furnaces are beneficial for reducing specific emissions, their overall environmental performance may be influenced by the source of electricity and the efficiency of the technology.

In summary, the results for SS2 demonstrate that increasing the proportion of electric furnace use can lead to significant environmental improvements, particularly in reducing greenhouse gas emissions and resource use. However, the observed increases in certain impact categories highlight the need for a more in-depth analysis of all potential effects when designing sustainability strategies. The balance between maximizing environmental benefits and minimizing trade-offs is crucial for achieving long-term sustainability goals in the steel industry.

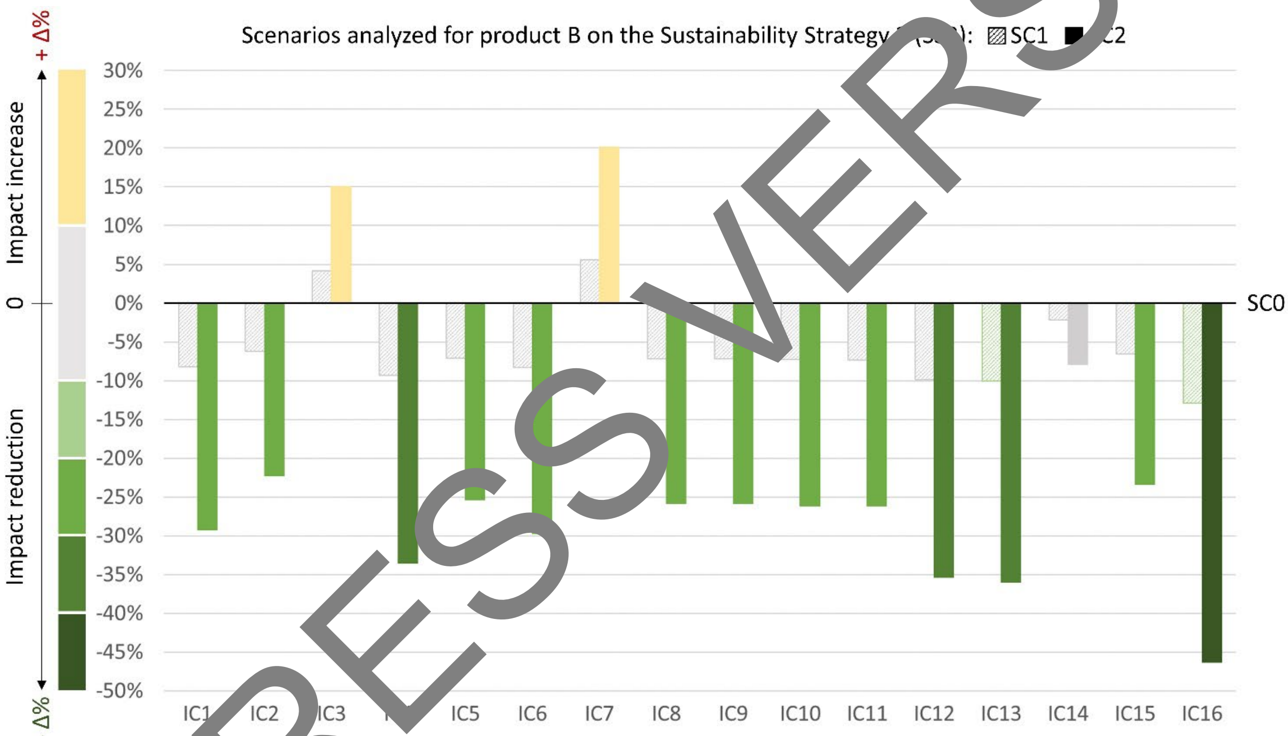

Figure 3. Percentage impact variations between baseline scenario (SC0) and the analyzed scenarios (SC1 - SC2) for product B (square and rectangular hollow sections) the Sustainability Strategy 2

5. Conclusions

This research has undertaken a sensitivity analysis of LCA data results of two selected steel products to support the steel companies in evaluating their environmental sustainability, proposing sustainable strategies for improvement, and verifying their applicability to further reduce their carbon footprint. Various scenarios were examined to reduce environmental impacts by analyzing two specific sustainable strategies for two steel construction industries, compared with the baseline model corresponding to the current situation.

The significance of this research lies in its ability to contribute valuable insights and guidance for industry stakeholders and policymakers. By quantifying the variation in the environmental impacts compared to the baseline scenario and recommending sustainable options, this study can support decision-makers with the necessary tools to implement sustainable practices in the steel construction sector. However, it is important to underline that the results presented in Section 4 are limited to the specific product and the analyzed industry; therefore, to generalize the effects and to implement the studied sustainability strategies effectively, the stakeholders should adopt a multi-faceted approach that takes into consideration their own production line, products portfolio, geographical context, technological innovations, policy support, and market needs.

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In the following, some specific suggestions for implementing each sustainable strategy are given.

For SS1, the integration of renewable energy sources should be pursued alongside investments in cleaner, less resource-intensive technologies for renewable energy production. Industry stakeholders could explore partnerships with renewable energy providers to ensure the shift to renewables does not increase other environmental impacts. Moreover, adopting advanced energy management systems could optimize energy use and minimize emissions. Velimirovic et al. [27] suggest that using smart grids and energy-efficient technologies can further enhance the benefits of renewable energy integration in industrial processes.

For SS2, maximizing the use of electric furnaces should be complemented by measures to improve energy efficiency and reduce emissions from associated processes. This could include adopting best practices for scrap selection and handling to minimize impurities and enhance furnace efficiency and investing in advanced filtration and waste management systems to mitigate increases in impact categories such as ionizing radiation. Additionally, policies that incentivize the use of recycled materials and the development of cleaner steel production technologies will be crucial in driving the adoption of these practices. Majumder et al. [28] highlight the role of policy frameworks in supporting technological innovation and promoting sustainable practices in the steel industry.

To facilitate the adoption of these strategies, it is recommended that the steel construction sector develop a comprehensive, regularly updated database of LCA data for different production methods and sustainability strategies. Such a database would allow stakeholders to make informed decisions based on current and accurate information.

However, even if the methodology for LCA sensitivity analyses conducted in this study can offer valuable insights into the field of eco-design and prospective life cycle results valid for the decision-making process of corporate sustainability reporting for steel industries, it is important to acknowledge certain limitations of the study.

Firstly, the geographical coverage and the reliance on specific data sources introduce a level of uncertainty to the results. Not all the data used for the analysis rely on specific and verified data sources, such as BDI-LCA, but some are statistical data that may have limitations in terms of accuracy or comprehensiveness, potentially impacting the overall reliability of the findings. Moreover, these assumptions imply that results are related to a specific location in a reference year. At the same time, it could be interesting to investigate their variation considering different geographical contexts and the temporal evolution of other data (such as the national energy mix).

Secondly, the coverage of products and sustainable strategies is another limitation to consider. This study focused its analysis on two specific products and one particular sustainability strategy for each of them, potentially limiting the generalizability of findings to a broader context. Nevertheless, in terms of computational aspects, this application of the proposed method allowed a first round of verification of its usability, avoiding a more resource-intensive validation on more complex products and scenarios that could lead to longer analysis times and higher costs, making it less feasible.

Despite these limitations, the method presented in this research holds promise as a tool for evaluating sustainable strategies and solutions, and it complements traditional life cycle assessment results by providing a quantitative perspective on future developments. Researchers and practitioners should consider these limitations when applying this method and interpreting the results. Further research may explore strategies to address these limitations and enhance the method's robustness and applicability. Given these limitations, future research should incorporate a broader range of steel products and sustainability strategies coupled with dynamic life-cycle assessment models that reflect real-time data and technological advances, providing a more in-depth understanding of the long-term impacts of companies' carbon footprint and developing a collection of reference data for different products for the construction sector.

6. Author Contributions

Conceptualization of the research, M.M.S., F.S., F.C. and C.R.; conceptualization of the paper, M.M.S. and F.S.; methodology, M.M.S. and F.S.; investigation, M.M.S., F.S., F.C. and C.R.; data curation, M.M.S.; writing - review and editing, M.M.S. and F.S., data visualization M.M.S.; supervision, F.C. and C.R. All authors have read and agreed to the published version of the manuscript.

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