23rd International Conference on Modelling and Applied Simulation, 003
21st International Multidisciplinary Modeling & Simulation Multiconference

2724-0037 © 2024 The Authors.
doi: 10.46354/i3m.2024.mas.003

ECO-CHARGE: Sustainable Decision Making for EV Charging Station Production

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Abstract

Electric vehicle (EV) charging stations play a crucial role in urban sustainability, supporting the transition to zero-emission transportation. Their widespread presence alleviates "range anxiety" and promotes cleaner energy models. However, the environmental impact of charging station production remains largely unexplored. This research assesses the lifecycle environmental impact of aluminum cabinet production for EV charging stations through detailed Life Cycle Analysis (LCA). The research examines the interactions between production stages, identifying environmental "hotspots" for improvement. The findings guide innovation toward more sustainable e-mobility infrastructure, ensuring a greener transportation future. The OpenLCA was used in combination with modeling of the process in WITNESS Horizon software. The results show that improvements are needed, particularly in the supply chain processes, as the manufacturing of the single cabinet has the climate impact scenario of 1,287 kg of CO_2 eq. In terms of the impacts on human life toxicity and freshwater aquatic pollution, the impacts are 3,870 kg 1,4 DB and 1,316 kg 1,4 DB respectively. However major impact contribution is coming out from the production of raw materials i.e. aluminum, polycarbonate, and energy generation that has been used in cabinet manufacturing, while the overall share of the operations carried out in the industry is low.

Keywords: Charging stations; Electric vehicle; LCA; Environmental impacts; Sustainability

1. Introduction

In the context of the energy transition implemented on a continental scale in Europe, electric mobility plays a crucial role (D'Adamo et al., 2023). Electrification is one of the main tools within the European Green Deal, which aims to reduce emissions by at least 55% by 2030, with the final goal of achieving climate neutrality by 2050 (Hainsch et al., 2022). The importance and spread of electric vehicles is evidenced by the significant growth in their market share. Registration figures considering the European Union area, Efta and Great Britain, witness an increase of 20.7% compared to the same period last year. In the January-August 2023 period, this increase stands at 17.9%, with a total of 8,516,943 units registered. However, an even more significant increase is noted when referring to 2019, with a percentage increase of 21.4% (Mauritzen 2023). Increasing sales of electric vehicles catalyzes, or at least should catalyze, the growth and enhancement of the entire supply chain associated with it. A crucial element in the vitality of this supply chain is charging stations, characterized by a market valued at about $26.09 billion in 2023 (Alrubaie et al., 2023). Projections indicate a compound annual growth rate (CAGR) of 25.94 percent over the period between 2023 and 2028, with a forecast to reach a market value of $85.65 billion by 2028 (Hopkins et al., 2023). These data highlight the strategic importance of charging infrastructure in the context of expanding electric mobility and provide a clear perspective on the economic opportunities associated with this transition. However, charging stations are not simply energy supply points, but strategic pillars of an infrastructure that must grow synergistically with the adoption of electric vehicles (Gupta et al., 2023). Indeed, these represent critical points within the energy supply chain that are essential to ensure the success and sustainability of the transition itself (Ravindran et al., 2023). Accessibility to an extensive network of charging stations is a key factor in increasing demand for electric vehicles. The perception of a reliable and widespread network of charging infrastructure alleviates concerns about range, thus serving as a substantial incentive for the adoption of electric-powered vehicles. This phenomenon not only drives demand for electric vehicles but also stimulates innovation and competitiveness in the automotive sector (Kłos et al., 2023). At the same time, charging stations play a key role in overcoming technical challenges related to electric vehicle charging, such as the need for reduced charging times and standardization of charging protocols. The continuous evolution of these infrastructures helps to increase efficiency and accessibility, ensuring an optimal charging experience for end users (Sultanuddin et al., 2023). And again, the implementation and operation of charging stations not only promote more sustainable mobility but also generate significant economic implications. The expansion of this infrastructure creates employment opportunities through the design, installation, and maintenance of the columns, thus helping to energize the renewable energy and electric transportation sectors (Hassanin et al., 2023). To date, charging infrastructure is cited as the major obstacle to faster deployment of zero-emission vehicles (Aghalari et al., 2023). According to studies conducted by the environmental organization Transport & Environment, at least 44 million electric cars are needed to reach the target set for 2030 by the European Commission, and as a result, nearly 3 million public charging points will be needed to meet the growing charging needs of these vehicles. As of December 2022, there were only 450,478 publicly accessible charging points across Europe (Szumska 2023). To facilitate the deployment of these devices and overcome this significant limitation that characterizes the electric car supply chain, a new law was enacted in March 2023 by the European Parliament for the implementation of state-of-the-art charging stations with a power of at least 400 kW every 60 kilometers by 2026 on the main road axes indicated in the European Transport Priority Networks (Ten-T) with the power of the network increasing to 600 kW by 2028 (European Commission 2023) . What has been said so far shows an evolving and fast-growing scenario in the context of such a radical transformation as the energy transition. This research is placed on this scenario by trying to analyze a topic that now seems quite unexplored in the field of research, which is that of the environmental impact that characterizes electric car charging stations . An issue of paramount importance, according to these authors, as it can be contradictory to invest and produce systems to reduce transportation-related environmental impacts without worrying about how much these devices impact their life cycle. The objective of this study is to develop an environmental impact analysis using life cycle assessment methodology of an aluminum cabinet used as an electric car charging station.

The main objective of this research is to conduct a comprehensive environmental impact analysis using the life cycle assessment (LCA) methodology specifically on an aluminum cabinet utilized as an electric car charging station. This study seeks to address a critical yet underexplored issue in current research: the environmental implications associated with the infrastructure necessary for electric mobility, despite its goal of achieving zero-emission transportation. By focusing on the life cycle of these charging stations, the research aims to highlight the potential contradictions between promoting cleaner mobility and the environmental footprint of producing and operating such infrastructure. This investigation serves as a foundational step towards future research efforts aimed at reconciling the dual imperatives of advancing sustainable mobility and minimizing the ecological impacts inherent in the lifecycle of infrastructure like electric vehicle charging stations.

The rest of the article reports in section 2 the literature review. Section 3 introduces the materials and methods of the study. The case study is described in section 4 while section 5 shows the results obtained. The paper ends in the section 6 with conclusions.

2. Literature overview and gaps

The rapid advancement of electric mobility has brought the issue of electric car charging stations to the forefront of scientific attention (Jagwani 2023). In a context where the transition to electric vehicles represents a milestone in mitigating climate change and reducing greenhouse gas emissions, the creation of an efficient and advanced charging infrastructure has become essential (Li et al., 2022) . This imperative has catalyzed a growing interest prompting researchers, engineers, and scholars to explore a wide range of issues related to charging stations (Bartłomiejczyk et al., 2022). The centrality of the role of electric charging stations to sustainable mobility is underscored by the large number of articles in the literature. An initial search done by querying the

Scopus database returned 1033 results by typing keywords such as:

"charging" AND "stations" AND "electric" AND "cars"

However, this research is concerned without the production of these devices and their environmental impact. Therefore, to the first search string was added "production" to the keywords obtaining only 51 articles.

The first articles date back to 2010 after which there is a growing trend with a significant peak of publications in the current year (2023) even though the data are still partial as shown in Figure 1. This is a testimony to the importance of this topic in the scientific literature, underscoring how research in the field of charging stations not only responds to immediate needs but also constitutes fertile ground for technological and scientific developments that will shape the future of sustainable mobility.

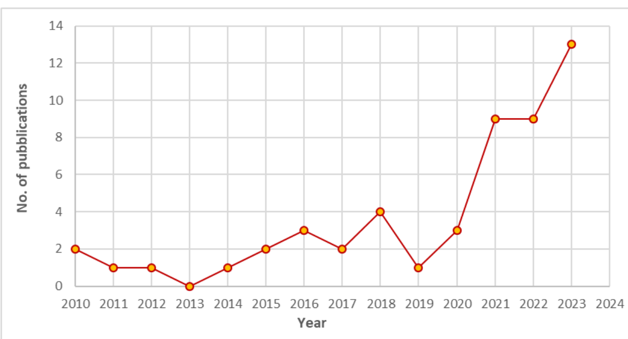

Figure 1. Temporal distribution of documents

Another interesting aspect concerns the geographical distribution, based on the affiliation of the first author. Italy is the country with the highest number of articles published (11.8%), followed by China, India and Poland (7.8%); while Germany comes in third place along with the United States (5.9%) as shown in Figure 2. This result shows an interest in this topic not only from the countries playing a leading role in the market for charging stations but also from other, mostly western territories.

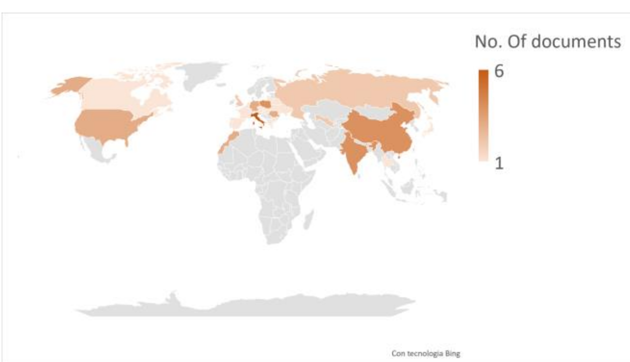

Figure 2. Countries of origin of selected documents

The most interesting subject areas concerning the production of electric car charging stations are shown in Figure 3. "Engineering", "Energy" and "Computer science" have the most publications on this topic, followed by "Mathematics" and "Environmental science". The result is not surprising considering the fundamental role that charging stations play in transforming the mobility landscape, acting as a crucial bridge between the vision of electric vehicles and an environmentally sustainable reality in an ever-advancing technological scenario.

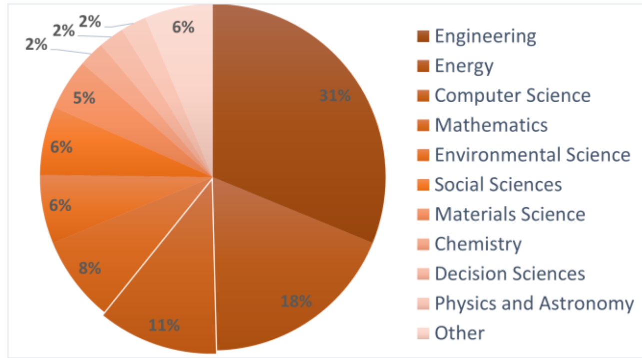

Figure 3. Subject areas of selected documents

This research concerns the environmental impact that characterizes the life cycle of electric car charging systems. Therefore, continuing the literature study, a search was conducted to check for another research on this topic. However, by adding "Life Cycle Assessment " AND/OR "Environmental Impact" to the previous search strings, the database returned no results.

The lack of a detailed analysis of the environmental impact associated with the production of electric car charging stations appears to be an omission in existing scientific treatises.

The present work arises as a response to this lack, proposing to fill a knowledge gap that is crucial to the complete understanding of the electric mobility ecosystem. The importance of this work lies not only in the possibility of filling a gap in academic research but also in the intent to clarify the connections between the production of charging stations and the environmental context. As the transition to electric vehicles continues at a rapid pace, it is imperative to understand the overall impact of each component of this revolution, including elements such as charging stations.

3. Materials and Methods

To evaluate the environmental impact of aluminum cabinets installed as electric car charging stations, a research methodology consisting of three macro-phases shown in Figure 4 was applied. The methodological framework within which the research takes shape, helping to ensure the reproducibility and consistency of the results obtained. It emphasizes the rational and systematic approach followed, which is fundamental to the scientific validity and credibility of the investigation.

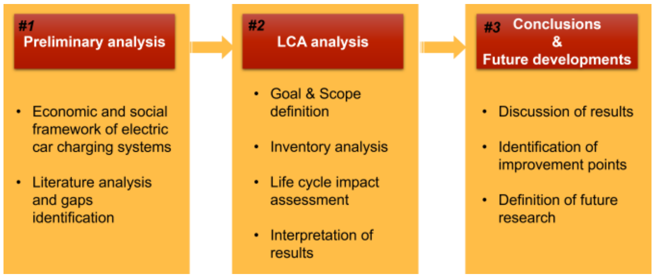

Figure 4. Research Methodology

The first phase (#1) of the research provides a solid foundation for understanding the broad context and shades surrounding electric car charging infrastructure, exploring not only their social and economic value, but also the greater implications they carry. Through a careful review of existing literature, it was possible to outline the current landscape of studies in this area, while identifying key knowledge gaps. This approach paves the way toward understanding the complexities inherent in the manufacturing process of charging systems, selected as a case study. This detailed examination is crucial to the development of the life cycle analysis (LCA), which is explored in more detail in the next phase of the research. In the second phase (#2), the focus shifts to the LCA methodology, proceeding through its four basic steps: from defining the objectives and scope (goal & scope) to interpreting the results. This analytical pathway provides a comprehensive view of the environmental impacts that characterize the process and product. The last phase (#3) is aimed at critical analysis of the data that emerged, with a specific focus on potential "hot spots" that significantly influence the environmental profile of these systems. The exploration of technological and technical aspects aims not only to quantify existing impacts but also to identify innovative solutions that can mitigate them. It concludes by intercepting future studies needed to expand research on this topic and stay abreast of the changing environment.

3.1. Life Cycle Assessment Analysis

The Industrial Revolution started in the late 18th century when the transition started to create goods from hand to machine. After this, many newer manufacturing techniques rose to prominence quickly from research to global industrial production stages, and they also drew attention because of their environmental consequences (Bruzzone et al., 2023). All those conventional manufacturing techniques started in the industry were not been subjected to much scrutiny by environmentalists and industrial ecologists till the early 2000s, this was the time when environmental concerns led the manufacturing industry to get more proactive in designing and creating cleaner processes. Furthermore, the phenomenon of industrial ecology and design for the environment emerged significantly, in both these processes environmental tools were developed, and one of them was Life Cycle Assessment (LCA), which is considered a benchmark tool to quantify the environmental impacts of a product, a service, or a process. In recent decades, LCA has become an essential tool when it comes to reducing environmental impacts throughout the product life cycle, as this quantifying method can produce the most accurate results. However, getting exemplary results requires a high-quality of data and giving attention to small details of all processes.

Life Cycle Assessment (LCA) is a systematic methodology aimed at assessing the environmental impacts attributable to products, processes or services throughout their life cycle, extending from the production phase to decommissioning. This approach allows for a holistic analysis, focused on quantifying the environmental loads associated with each operational phase, with the primary objective of identifying critical points amenable to optimization to enhance environmental performance. This, in turn, supports the formulation of business and policy decisions geared toward sustainability (Bahadori et al., 2023). The present research adopts the LCA methodology following the guidelines outlined in the international standards ISO 14040 and ISO 14044 (ISO, 2006a; ISO, 2006b). This ensures that the analysis is performed with consistency, transparency, and reliability, promoting comparability between different assessments and ensuring the veracity of the environmental information conveyed . According to the mentioned ISO standards, LCA analysis consists of interconnected and mutually dependent steps, as shown schematically in the attached figure 5.

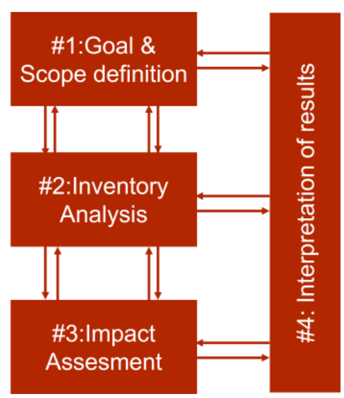

Figure 5. LCA methodology

The Life Cycle Assessment (LCA) methodology is developed through four structured phases, each with specific aims and procedures. The methodological approach adopted aims to provide a detailed and quantitative understanding of the environmental impacts associated with products, processes or services, from production to end of life.

1. Goal and Scope definition: The initial phase focuses on developing a clear framework for the

study, specifying the objectives and outlining the scope of application. This includes determining the boundaries of the system, which can be geographic, temporal, and technological, as well as selecting the level of detail and defining the target audience. The selection of system boundaries is critical, as it determines which processes will be included in the analysis and directly influences the accuracy and relevance of the results.

2. Life Cycle Inventory (LCI): This phase is concerned with the comprehensive collection of data on the inputs (e.g., energy, raw materials) and outputs (e.g., air emissions, releases to water, waste generation) of the system studied. The data may be primary, collected directly from the specific operations under study, or secondary, obtained from existing databases and literature. The distinction between primary and secondary data is critical to ensure the accuracy of the LCI, with a preference toward primary data for greater specificity and reliability.
3. Environmental Impact Assessment (LCIA): The focus of this phase is the transformation of the LCI quantitative data into an analysis of environmental impacts. The LCIA uses standardized methods to associate system inputs and outputs with specific impact categories. The accuracy of the LCIA depends on the selection of relevant impact categories and the use of appropriate characterization factors to quantify environmental effects.
4. Interpretation: The concluding step integrates the results of the previous steps to provide an understandable synthesis that is consistent with the objectives of the study. This interpretation process assesses the reliability of the data, the appropriateness of the impact assessment methodologies, and identifies key areas of environmental interest or concern. Critical analysis of the results allows opportunities for environmental improvement to be highlighted and concrete recommendations to reduce adverse impacts to be made.

4. Experimental Scenario

The main steps of Life Cycle Assessment (LCA) are based on the standards and guidelines of the ISO 14040 and ISO 14044.

The goal and scope definition of this study is to study the environmental impacts associated with the manufacturing of aluminum cabinet production. The functional unit in this regard is the supply chain and processes that are involved in the manufacturing of the aluminum cabinet in the industrial plant in Italy. Each process is modeled considering the “cradle to shipping” approach that includes transportation of materials, laser cutting, welding, and packaging. However, painting activities were excluded from this study. The data was modeled using OpenLCA software (Curran, 2017).

The data for the Life Cycle Inventory (LCI) was taken from the industry in Italy, where these aluminum cabinets have been manufactured. Furthermore, due to a lack of primary data required for life cycle analysis, an additional database of Exiobase which is a global detailed multi-regional supply and use dataset, and Agribalyse which is a French database for the agriculture and food sector were added to complete the model. The results and data were normalized in the context of conditions in Italy so that they could be more aligned with the objective of this study (Gursel et al., 2014).

For Life Cycle Impact Assessment (LCIA) OpenLCA comprehensive dataset package of environmental impact assessment was used. Where the impact categories were grouped related to their main contribution and effects.

4.1. LCA model

The basic elements required for creating a model in OpenLCA are flows, processes, and Product Systems, which lead to determining the impacts of a single Project. The analysis and evaluation system in OpenLCA starts with creating a new database in OpenLCA with checking the settings and preferences for units and number formats. Then the first step is creating a new flow under the Flow category, we selected Flow Type as Product and Flow Reference as Number of Items, the Flow has been created for the manufacturing of one aluminum cabinet. This was followed by creating a new process under the Process tab, we created a single process covering both the structure and door of the cabinet and entered the product supply chain process of the cabinet. Figure 6 shows the Inputs/Outputs of the aluminum cabinet manufactured in the industry in Italy. The input parameters are those involved in the product supply chain, while output parameters include the main product, materials that can be used for recycling, and other wastes. Additionally, a new product system was created under the Product System category, which is taken as a unit process. Figure 7 illustrates a model graph of the system which is taken for a unit process.

To determine the life cycle impact assessment of the product, a new impact assessment was created under the Impact Assessment Method category, in this tab all the flows, processes, and product systems created were added as impact factors, and finally, the calculate button was clicked to generate the results.

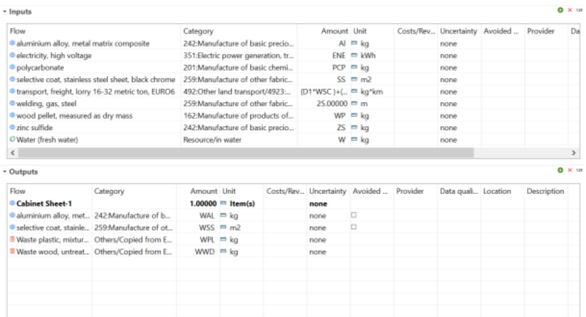

Figure 6. Inputs/Outputs of the Aluminum Cabinet Manufacturing

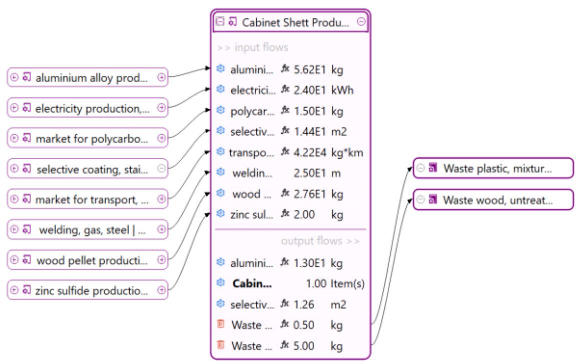

Figure 7. Model Graph of the Aluminum Cabinet

5. Results and Discussion

For the assessment of results, we selected the CML impact assessment baseline method, which is used to measure the environmental impacts that are caused by the product (Abyar et al., 2020, Fareed et al., 2023). The results were tabulated and interpreted in categories. Moreover, the results show the top 5 contributions to impact within a category. Figure 8 demonstrates the results measuring Global Warming Potential (GWP 100a), which is one of the most common metrics used to quantify greenhouse gas (GHG) emissions over 100 years (Thoma et al., 2014). The results show that 96.989 Kg is the highest value of GHG equivalent to CO_2 gas coming out from a single process of heat production and industrial furnace, while other processes such as aluminum production, and electricity production also contributed to these emissions. It is also important to note that the total CO_2 emissions coming out from the manufacturing of a single aluminum cabinet is 1,287.71 kg of CO_2 eq. in which processes such as aluminum alloy production, generation of electricity, and transportation of materials mark the major contribution.

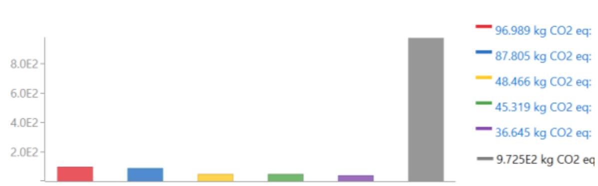

Figure 8. Impact Assessment Result of Global Warming Potential (GWP 100a)

Figure 9 shows the results measuring eutrophication which describes an excess of nutrients and chemicals such as nitrogen and phosphorus in a body of water that may lead to dense growth of plants, which may result in a deficiency of oxygen (Henderson, 2015). The result shows the highest value for eutrophication is 0.632kg of phosphate (PO_4) which comes out from the treatment of spoil from hard coal mining for the process, while the other processes such as hard coal ash, residual filling, and generation of gas also contribute to this impact category (López Cabeza et al., 2023). The total impact assessment result of eutrophication is 2.75 kg of PO4 mainly coming out from the production of aluminum alloy, polycarbonates, and untreated waste plastics.

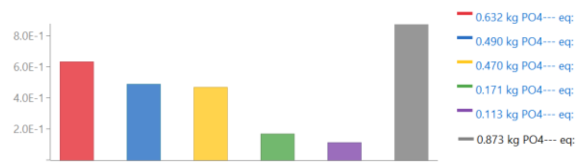

Figure 9. Impact Assessment Result of Eutrophication

Figure 10 represents the results measuring human toxicity, this index determines the release of harmful chemicals which has been released to the environment (Hertwich et al., 2001). The highest impact value of human toxicity in this process is 882.3 kg 1,4 dichlorobenzene (1,4 DB), while the total impact value is 3,870 kg 1,4-DB. The major processes contributing to these impacts are gas welding, polycarbonate, production of aluminum alloy, and untreated waste plastic.

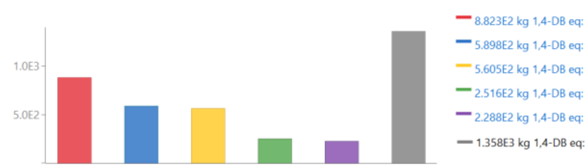

Figure 10. Impact Assessment Result of Human Toxicity

Table 1 displays the overall results of all the impact categories related to the manufacturing of single aluminum cabinet.

Table 1. Overall Impact Analysis result.

Impact category	Result	Reference unit
Abiotic depletion	0.055918509	kg Sb eq
Abiotic depletion (fossil fuels)	12904.70204	MJ
Acidification	6.351015111	kg SO2 eq
Eutrophication	2.749844845	kg PO4--- eq
Freshwater aquatic ecotox.	1316.535419	kg 1,4-DB eq
Global warming (GWP100a)	1287.711963	kg CO2 eq

Human toxicity	3870.885101	kg 1,4-DB eq
Marine aquatic ecotoxicity	3886949.221	kg 1,4-DB eq
Ozone layer depletion (ODP)	9.19452E-06	kg CFC-11 eq
Photochemical oxidation	0.403111022	kg C2H4 eq
Terrestrial ecotoxicity	19.4612782	kg 1,4-DB eq

The results shown above are the impact assessment results of the manufacturing of a single aluminum cabinet, and each impact category poses a value that cannot be sidelined whether it be abiotic depletion, global warming potential, freshwater aquatic ecotox, ozone layer depletion, etc., Additionally, if we further breakdown the contribution of each impact category, we get to know that production of aluminum alloy, marketing of polycarbonate, and energy (fuel and electricity) used during transportation and manufacturing contributes the highest impacts during this whole process in manufacturing the cabinet. The evaluation of the life cycle assessment provides a clear picture of how this whole process can be more environmentally friendly and more efficient in the future. Thus, this life cycle assessment helps in selecting alternative processes that are more sustainable in nature and might also provide extra feasibility in terms of economics throughout the life span.

6. Conclusions

The issue of manufacturing waste and the environmental problems associated with it has been growing for the last many years. Integrating environmental assessment of all the major manufacturing processes has proven to be an important breakthrough toward efficient and sustainable manufacturing. The goal of this study was to compare the manufacturing process of aluminum cabinets in an Italian company with its environmental impacts. This study shows that if LCA guidelines and its assessment are conducted in the manufacturing process can give a competitive advantage as compared to its conventional process. Environmental assessment can help in reducing material waste, transportation waste, less consumption of energy, and can also help in developing a scenario where the organization can expand its operations. While comparing the model of the process in this study, it was evident that the majority of the environmental impacts of the operation will come out from the transportation of material, and consumption of electricity, hence from the economic and strategic point of view the organization will also be saving more resources and more time by implementing the guidelines recommended by LCA. Thus, manufacturing processes which are more aligned with environmental assessment are more beneficial to sustainable manufacturing, which also provides additional advantages of environmental, and economic gain over its competitors. However, several limitations regarding this research are worth noting. One of these is the exclusive focus on the production of aluminum cabinets, which narrows the scope of the analysis to the specific impacts of that material, excluding other vital components of charging stations. This methodological choice may not capture the full range of environmental impacts associated with more complex charging stations that incorporate different materials and technologies. An additional constraint is the exclusion of some manufacturing processes, such as painting, from the LCA analysis. The omission of these steps could lead to an underestimation of overall environmental impacts, as these processes can have significant implications in terms of harmful emissions or resource consumption. Finally, the study examines a range of environmental impacts such as greenhouse effect and human toxicity but does not fully explore other potentially relevant impacts. Future research should therefore aim to overcome these methodological and contextual barriers, promoting more sustainable development and effectively informing policy and industry decisions in the field.

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