Electrifying Green Logistics: A Comparative Life Cycle Assessment of Electric and Internal Combustion Engine Vehicles

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Abstract: Green logistics is an approach aimed at reducing the environmental impact of transport, storage, and distribution practices, through low-emission vehicles, optimized routes, clean energy tech in warehouses, and efficient waste management. These solutions can contribute to achieving the sustainable development goals of the European Green Deal. The main research question of this paper is whether an electric vehicle has a lower environmental impact compared to a gasoline vehicle. This study presents a life cycle assessment (LCA) of an electric vehicle using lithium-ion battery technology (BEV) and compares it to an internal combustion engine vehicle (ICEV), considering the transportable load within the context of Italy. Through a gate-to-grave approach, both vehicles’ life cycle use and disposal phases were evaluated to identify the hotspots of environmental impact. The LCA methodology allows for an objective comparison and the results show that BEV emits slightly less kgCO₂eq than ICEVs. The primary contributor to the vehicles’ impact is the dependency of the electric energy primary source from fossil fuels. Therefore, a second analysis was conducted to analyse the benefit of photovoltaic panels to generate the electric energy, showing that it can result in a significant 50% reduction in impact, making the electric vehicle a valid solution for achieving green logistics objectives. However, the questions of electric energy production, management, and distribution together with the supply of raw material and disposal of lithium batteries remain open. This issue raises a concern regarding the BEV in a country like Italy where the lack of recharging points limits the adoption of electric vehicles in green logistics.

Keywords: green logistics; life cycle assessment; electric vehicle; combustion engine vehicles; electric energy production

1. Introduction

Climate change is already affecting the entire world, with extreme weather conditions like droughts, heatwaves, heavy rain, floods, and landslides becoming more frequent. Europe, as one of the most advanced regions globally, is taking a leading role in implementing the 2030 Agenda to combat pollution, recognizing the urgency of addressing environmental concerns on a broader scale. Other consequences of the rapidly changing climate include rising sea levels, ocean acidification, and loss of biodiversity [1].

In order to limit the increase in global warming to 1.5 °C (i.e., a threshold the Intergovernmental Panel for Climate Change (IPCC) suggests as safe), carbon neutrality by the mid-21st century is essential. This target is also laid down in the Paris agreement [2] signed by 195 countries, including the EU. In December 2019, the European Commission presented the European Green Deal [3], its flagship plan that aims to make Europe climate neutral by 2050.

In 2018, transport activities resulted in about 29% of total EU CO₂ emissions. Other studies confirm that the transportation sector is one of the highest contributors to greenhouse gas emissions [4–6].
Logistics companies connect firms to markets by providing various services, including multimodal transportation, freight forwarding, warehousing, and inventory management. They are important for global manufacturing, which is complex and multilocational.

During the COVID-19 pandemic period, consumers increasingly opt for, or are forced to use, home delivery services. So, the use of road transportation for home delivery of products has increased, and it has been estimated that, as purchasing habits have changed, it will continue to increase in the coming years. Ref. [7] estimates that the number of light-duty vehicles in operation will rise to about 1.3 billion by 2030 and 2 billion by 2050.

The growing attention towards the environment and the continuous growth of goods movements have driven the logistics industry to rethink its impacts and emissions, leading to the emergence of green logistics.

Green logistics, also known as sustainable logistics or eco-logistics, refers to the practice of integrating environmentally friendly principles and practices into the planning, implementation, and management of logistics activities. It focuses on minimizing the environmental impact of logistics operations, such as transportation, warehousing, packaging, and reverse logistics, by reducing energy consumption, emissions, waste generation, and promoting the use of renewable resources and sustainable supply chain practices. The goal of green logistics is to achieve a more sustainable and efficient logistics system while mitigating the negative effects on the environment and promoting long-term environmental stewardship.

Electric vehicles (EVs) hold promise in reducing greenhouse gas emissions, but a comprehensive assessment, taking into account various impact categories, is essential to gain a thorough understanding of their environmental benefits and limitations. In other words, when discussing battery EVs (BEVs), it is vital to consider the associated charging infrastructure. Therefore, one critical aspect that should not be overlooked is the capacity to generate an ample supply of electrical energy to meet the increasing demand as more BEVs become prevalent on the roads, particularly in terms of distribution, storage, and managing peak power demands.

The Fit for 55, a set of legislative proposals aimed at reducing the EU’s greenhouse gas emissions by at least 55% by 2030 [8], envisions the following scenario by 2030: 1.2 million plug-in hybrid electric vehicles (PHEVs), 6.3 million battery electric vehicles (BEVs), 0.75 light electric commercial vehicles (e-LCVs), 0.05 heavy electric commercial vehicles (e-HCVs), and 0.07 electric buses for local public transportation. The leading electricity transmission company in Italy, Terna SPA, has estimated that this will correspond to an increase in demand that will reach 38 TWh annually by 2050, assuming 19 million electric vehicles in circulation. Thus, it is claimed that generating this additional electrical energy will not represent a problem, as investments in renewables have already been planned [9]. However, the true challenge resides in efficiently distributing this energy to its required destinations and effectively storing surplus energy generated from sources like photovoltaics when it remains unused. Additionally, it is imperative to consider the adoption of a sophisticated charging management system to ensure optimal utilization of available resources. Various future scenarios are examined in [10] to understand the combined impact of charging infrastructure, control systems, and driver behaviour on the grid. Shifting charging from home to daytime hours positively affects grid performance across multiple factors, such as reducing the need for fossil fuel generation, storage, and emissions. Restricting home charging may hinder adoption and equity in EV ownership. Policymakers should promote convenient, affordable, widespread, and public-accessible daytime charging solutions.

Currently, Italy has 209,338 BEVs on the road, with 45,210 publicly accessible charging stations nationwide [11]. Motus-E, the first association in Italy consisting of industrial operators, the automotive industry, academia, and public opinion movements, aims to facilitate the achievement of the goal of having 4 million BEVs by 2030, which should be accompanied by at least 110,000 charging stations distributed throughout the country.
In accordance with the data published in December 2022 [12], the geographical distribution of publicly accessible charging points shows unevenness across the Italian territory, with approximately 58% of the facilities located in northern Italy, about 22% in the central region, and only 20% in the south and islands, as evident from Figures 1 and 2.

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It becomes immediately evident that a significant issue is the lack of available charging infrastructure in many Italian municipalities. In fact, a striking 58% of Italian municipalities presently do not have publicly accessible charging points within their boundaries. This statistic might not be overly concerning, considering the intricate administrative structure of Italy, which includes numerous small municipalities that could potentially rely on neighbouring ones. However, the drawback lies in the fact that municipalities without charging infrastructure are disproportionately concentrated in specific regions of Italy, particularly in the central-southern areas.

On average, there are approximately 6 charging points for every 10,000 inhabitants across Italy. Nevertheless, the actual distribution varies substantially among individual municipalities and locations. The logistics sector’s green transition in Italy must acknowledge and address these deficiencies. For instance, in corporate parking facilities, it is feasible to delegate the management of electrical energy to a system that initiates vehicle charging during off-peak hours and completes the charge according to the user’s preferred time settings.
In this paper, the following research questions arise and are worth investigation:

RQ1: Is it possible to make freight transportation sustainable through electric machinery?

RQ2: How much does the production of electric energy contribute to the impact of electric vehicles?

RQ3: Does an electric vehicle truly have a lower environmental impact compared to a gasoline vehicle?

To answer these questions, this study presents a life cycle assessment (LCA) of an electric vehicle using lithium-ion battery technology (BEV), a lightweight quadricycle capable of carrying up to 140 kg of goods, and compares it to an internal combustion engine vehicle (ICEV), a scooter that can carry only 25 kg. To ensure a fair comparison, the impact of the scooter was considered multiplied by six, allowing for a direct comparison of results.

This allows for us to focus on an innovative aspect in the field of green logistics, namely, the evaluation of the environmental impact of electric vehicles in relation to the load to be transported.

The LCA is conducted taking into account the entire life cycle of these vehicles within the context of Italy. Through a gate-to-grave approach, both vehicles’ use and disposal phases were evaluated to identify the key issues in this part of their life cycle. Furthermore, the impacts of battery electric vehicles (BEVs) will be assessed in a scenario where the energy source for charging is derived from either photovoltaic systems or a combination of energy sources. The LCA, conducted using the SIMAPRO® software (release version
Section 2, 4.0.2), allows us to evaluate if electric vehicles are a valid alternative to traditional means of transportation to limit greenhouse gas emissions and atmospheric pollutants.

The last-mile segment of urban transport systems is of paramount importance, as it interfaces directly with end-users and consumers. In this regard, the research emphasizes the potential of light quadricycles as a sustainable solution. The integration of these vehicles into last-mile transportation networks has the capacity to dramatically reduce pollution, particularly when coupled with a judicious utilization of renewable energy sources. A use case presented within this study serves as a practical illustration of this concept, demonstrating how the combination of BEVs and renewable energy strategies can significantly contribute to the reduction in pollution and align with the goals of environmentally responsible urban transport systems.

Several LCA studies [13–15] have been conducted to compare the environmental performance of EVs and non-electric vehicles. These studies consider the entire life cycle, including vehicle production, operation, and end-of-life stages. By examining multiple impact categories, such as greenhouse gas emissions, air pollutants, and resource depletion, these studies provide valuable insights into the environmental advantages and trade-offs associated with different vehicle technologies. While the aforementioned papers compare electric vehicles to various mechanical propulsion systems, no one had conducted a similar analysis focusing on the load to transport. To fill this gap, this research aims to provide a novel contribution to industry stakeholders offering a data-driven analysis to support decisions on the adoption of electric vehicles in freight transportation. The results of this analysis could have a substantial impact on the transition to more sustainable logistics.

This paper is structured as follows: Section 2 presents the literature review of related research papers; it provides a brief review of the results from life cycle assessment (LCA) analyses conducted on electric vehicles. Section 3 presents the methodology of life cycle assessment analyses. Section 4 presents the gate-to-grave LCA analyses conducted on the selected vehicles and compares the obtained results. In Section 5, results are discussed providing the answer to the research questions. Conclusions from results are drawn and a summary of the key points is presented to address future research directions in this field.

2. Literature Review

The transportation sector is a significant contributor to greenhouse gas emissions, air pollution, and resource depletion [16]. Traditional internal combustion engine vehicles powered by fossil fuels have long been recognized as major sources of these environmental impacts. The introduction of electric vehicles (EVs) has raised hopes for reducing emissions and transitioning to more sustainable transportation options. However, it is crucial to conduct rigorous assessments to understand the full environmental implications of EVs. The announced European Battery Regulation entails these goals by implementing recycled content shares and the environmental assessment of traction batteries (Council of the European Union, Regulation 2023/1542).

Ref. [17] presents the life cycle assessment of a BEV for Europe and compares it to an ICEV. The results of the hot spot analysis showed that the BEV manufacturing phase determined the highest environmental burdens mainly in the toxicity categories as a result of the use of metals in the battery pack. However, the greenhouse gas emissions associated with the BEV use phase were shown to be half of those recorded for the ICEV use phase. In a different paper, ref. [18] compares the performances of an EV and an ICEV paying particular attention to the production of electricity that will charge the EV. The study demonstrates that the EV proves to be able to reduce air acidification, photochemical oxidant formation, and greenhouse gases. EV car and battery manufacturing have higher impacts for all categories than ICEV car manufacturing. The impact of the energy used and greenhouse gas emissions for different types of advanced vehicles (hybrid electric vehicle, a plug-in hybrid electric vehicle, a BEV, and a Fuel Cell Vehicle) is investigated in [19], where a comparison against conventional vehicles is shown. The results indicate that all these fuel-efficient technologies improve the energy use and emissions throughout
the lifetimes of the vehicles. An automotive life cycle assessment (LCA) is being performed for conventional and alternative vehicles in Belgium [20]; the results show that the BEV has the best environmental score for all the considered impact categories whereas ICEVs have the worst impact on the greenhouse effect. The study [21] evaluates and compares the potential environmental effects of electric, hybrid, petrol, and diesel cars in Spain using a cradle-to-grave life cycle assessment approach, and it highlights that BEV life cycle CO$_2$-eq emissions are 48% lower than petrol ICEVs, but it will produce an increase in fine particulate matter formation, human carcinogenic and non-carcinogenic toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity relative to petrol vehicles. An LCA analysis from cradle to grave is conducted in [22]; the results indicate that, in the production phase, EVs have a higher environmental impact than ICEVs due to battery manufacturing. During the usage phase, EVs show a better environmental performance, which largely depends on the proportion of clean energy generation. In the recycling phase, repurposing and remanufacturing retired batteries contribute to enhancing the environmental benefits of EVs.

In this matter, the importance of the lithium-ion battery is highlighted in [23] that analyses the life cycle assessment of the related water-based manufacturing, finding reductions in energy consumption (4.5%) and in all environmental impact categories (3.0–85%) compared to the conventional battery pack. Focusing attention on the recycling phase of the batteries, ref. [24] conduct an LCA for two recycling processes, a hydrometallurgical and a direct recycling route. Both show ecological benefits compared to production with virgin material.

The reviewed LCA studies demonstrate the importance of adopting a comprehensive life cycle perspective when assessing the environmental impact of transportation and [25] identified important challenges regarding vehicle LCAs in terms of scope and methodology. Life cycle assessment (LCA) currently lacks spatially resolved data on exposure, which would enhance our ability to more effectively address toxicity impacts. This is particularly crucial when considering human exposure to pollutants in urban environments and during the raw materials extraction phase. To tackle this issue, ref. [26] suggests relying on general databases such as Ecoinvent or non-updated inventories because primary data of vehicles are difficult to collect. In another research paper [25], it was also pointed out that studies should account for changes along the vehicle life cycle concerning the electricity mix, the degrading fuel efficiency, and the emission control of ICEVs.

As shown with this review, while the literature has certainly made valuable contributions to the field of electric vehicles (EVs) and their comparisons with alternative propulsion technologies, this paper introduces a fresh perspective. It sheds new light on the potential of electric quadricycles as a sustainable solution for urban transportation systems, particularly in the last-mile segment.

3. Methodology: Life Cycle Assessment

Life cycle assessment (LCA) is a systematic approach used to evaluate the environmental impact of a product, process, or service throughout its entire life cycle. It assesses the environmental burdens associated with various stages, including raw material extraction, manufacturing, distribution, use, and disposal. LCA serves as a valuable tool for businesses and organizations as it provides a comprehensive understanding of the environmental impacts associated with their products or services. By conducting an LCA, companies can identify hotspots of environmental impact and make informed decisions to minimize negative effects. Additionally, LCA findings can be used for eco-labelling, eco-marketing, and sustainability reporting, allowing companies to demonstrate their commitment to environmental stewardship to stakeholders and consumers. Overall, LCA plays a crucial role in promoting sustainable practices within businesses by driving environmental consciousness, enabling informed decision making, and fostering the development of more environmentally friendly products and processes. LCA procedure, as a global en-
environmental management tool [27], is standardized in [28], as reported in the following Table 1.

Table 1. LCA ISO standard reference.

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>[28]</td>
<td>Environmental management—Life cycle assessment—Principles and framework</td>
</tr>
<tr>
<td>[29]</td>
<td>Environmental management—Life cycle assessment—Requirements and guidelines</td>
</tr>
<tr>
<td>[31]</td>
<td>Environmental management—Life cycle assessment—Data documentation format</td>
</tr>
<tr>
<td>[32]</td>
<td>Environmental management—Life cycle assessment—Illustrative examples on how to apply ISO 14044 [29] to goal and scope definition and inventory analysis</td>
</tr>
<tr>
<td>[33]</td>
<td>Environmental management—Life cycle assessment—Vocabulary</td>
</tr>
</tbody>
</table>

This standard specifies the framework, principles, and requirements to carry out the evaluation studies of a life cycle and to disseminate them by reports. The LCA process, as shown in Figure 3, entails:

1. Defining the goal and scope.
2. Compiling the Life Cycle Inventory.
3. Assessing the potential environmental impacts associated with these inputs and outputs.
4. Interpreting the results obtained during the inventory analysis phase and estimating their impact in relation to the study’s objectives.

![Figure 3. LCA flowchart.](image)

3.1. Goal and Scope

Life cycle assessment begins with defining the study’s objective and scope, describing the key assumptions and necessary hypotheses for conducting the analysis, and selecting the energy-environmental indices to calculate for result synthesis. The next step involves defining the functional unit (FU), which is defined as the element used as a reference unit in the study [28]. It must be compatible with the function performed by the system under examination and serves as the unit of measurement for the system’s performance.

In this study, the functional units are a minicar and a moped. Subsequently, the boundaries of the system under examination must be established. Life cycle assessment analyses can be categorized based on the established boundaries of analysis, as shown in Figure 4.

- Cradle to gate: This analysis begins by considering the extraction and processing of raw materials, which, through successive transformations, yield semi-finished products. It then encompasses the production and/or assembly phase of the product, concluding when the company introduces it to the market.
- Gate to gate: This intermediate phase starts when the semi-finished products enter the factory and ends when the finished product exits, ready for distribution in the market.
- Cradle to grave: Through this analysis, the life cycle of the product or service under examination is analysed, starting from the recovery of raw materials to its end-of-life...
stage. Throughout this process, the product can follow various paths: reuse of waste within the same production process, landfill disposal, use for energy recovery through incineration, and recycling of certain components for the production of the same product or others.

- Zero burden: With this fourth type of analysis, waste is considered from the moment it becomes waste until, through appropriate processes and treatments, the material ceases to be waste and gains a new life.

In this study, the gate-to-grave approach has been chosen, encompassing the vehicle operational lifespan and its disposal phase.

![Figure 4. LCA burden according to ISO14040: 2006 [28].](image)

### 3.2. Life Cycle Inventory

Life Cycle Inventory (LCI) is a fundamental component of the Life Cycle Assessment (LCA) process. It involves the systematic compilation and quantification of all inputs and outputs associated with a product or system throughout its entire life cycle. Life Cycle Inventory data encompass the extraction of raw materials, manufacturing processes, transportation, product use, and end-of-life scenarios. By meticulously collecting data at each stage, LCI provides a comprehensive snapshot of the environmental and resource-related aspects of a product or system. These data serve as a crucial foundation for subsequent phases of the LCA, enabling a holistic evaluation of its environmental impacts and sustainability performance. The data must be checked to verify and ensure their quality, validity, and reliability. Therefore, to ensure transparency and accuracy, it will be essential to include information such as the data’s age, the specific geographical region to which the data pertain, the reference technology, the methodology used for data sampling at each reported data point, the calculation methods employed to derive average values, and any deviations or anomalies identified during the measurements. This practice aligns with the guidelines outlined in [29].

### 3.3. Life Cycle Impact Assessment

In this phase, all incoming and outgoing flows considered in the LCI phase are translated into impact indicators related to human health, the environment, and resource consumption. According to [29] standards, impact assessment must necessarily include the following procedures:

- Selection of impact indicators, indicators, and characterization models;
- Attribution of LCI results to the selected impact categories (classification);
- Calculation of indicator results (characterization).

For an LCI assessment, data management and calculations can be quite complex, and software can help reduce the time required for analysis, prevent errors, handle data...
conversion with respect to the functional unit, organize data and systems, display results, and ultimately provide information on flows and processes through the documentation available in the software and databases. In this study, SIMAPRO® software (release version 9.4.0.2) was used.

3.4. Interpretation Analysis

The objective of this final phase is to assess and select options that lead to a reduction in the impacts and environmental burdens of the system under examination, aiming to improve its efficiency in relation to the company’s economic performance.

This phase is characterized by the following activities:
- Identification: analysing and comparing data from the earlier stages of the LCA with what was specified in the objective definition.
- Evaluation: verifying the completeness of data and results, conducting sensitivity analyses to analyse the effects on the final outcome, and ensuring consistency to confirm the correspondence between the obtained results and the predefined objectives.
- Conclusions, recommendations, and final report: the results are disclosed, and conclusions are drawn regarding any improvement actions to be taken based on the findings.

4. Case Study: BEV versus ICEV

In this paragraph, we delve into a comprehensive comparison between two distinct modes of urban transportation: Battery electric vehicles (BEVs) and internal combustion engine vehicles (ICEVs). The main focus centres on a rigorous life cycle assessment (LCA) to evaluate their environmental impacts and sustainability profiles. The selected BEV and ICEV will be introduced by presenting their technical specifications, outlining the methodology employed for the LCA analysis, and ultimately unveiling the illuminating results of this comparative study. By juxtaposing these contrasting modes of mobility, this study aims to provide valuable insights into the environmental implications of choosing between electric and gasoline-powered options for green logistics. To conduct the analysis, the following libraries, provided by SIMAPRO® were selected: Ecoinvent 3—allocation at the point of substitution system; Ecoinvent 3—consequential system; Industry data 2.0; and Methods.

4.1. Battery Electric Vehicle Using Lithium-Ion Battery Technology (BEV)

The BEV chosen for conducting the LCA analysis is a two-seater electric light quadricycle in the “cargo” configuration, where the passenger seat has been removed to expand the cargo space. Due to its size, it is hypothesized that it can be used for the so-called “last mile” delivery, which involves small-scale distribution of goods within urban centres. The technical specifications are listed in Table 2.

<table>
<thead>
<tr>
<th><strong>BEV</strong></th>
<th><strong>ICEV</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>6 kW</td>
</tr>
<tr>
<td>Torque</td>
<td>625 Nm</td>
</tr>
<tr>
<td>Cubic Capacity</td>
<td>NA</td>
</tr>
<tr>
<td>Battery Capacity</td>
<td>5.5 kWh</td>
</tr>
<tr>
<td>Charging Time</td>
<td>3 h</td>
</tr>
<tr>
<td>Range</td>
<td>75 km</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>45 km/h</td>
</tr>
<tr>
<td>Total Weight</td>
<td>478 kg</td>
</tr>
<tr>
<td>Storage Weight</td>
<td>140 kg</td>
</tr>
</tbody>
</table>

The minicar is powered by a 6 kW electric motor, supported by a 5.5 kWh lithium-ion battery. The car is classified as a light quadricycle in the L6e category and provides a range
of approximately 75 km, as declared by the automaker [34], with a maximum speed of 45 km/h. The speed is therefore quite low but suitable for urban speed limits. The torque is immediately available, making it responsive at roundabouts and traffic lights, thanks especially to its automatic transmission. The car can be charged at a 220 V electrical outlet, and a full recharge is achieved in 3 h. It is strongly recommended to park the vehicle in a sheltered location with a temperature between 0° and 40°, as exposure to extreme temperatures can damage the traction battery. The subsequent Figure 5 and Tables 3 and 4 depict the data entered in the software and the sequential steps taken to generate the analysis. A lifetime of 10 years and 11,200 km/year were considered for both vehicles. The kilowatt-hours consumed by the quadricycle over the course of 10 years were calculated as follows:

- The number of recharges required over a 10-year period to cover 11,200 km, equivalent to 1493.3 recharges, was considered, given the 75 km range per charge.
- The electrical energy consumed to recharge the battery in a period of 3 h, with an 8 A load and a nominal voltage of 230 V, was calculated, resulting in a total of 5520 W power supply.
- By multiplying the number of recharges over 10 years by the electrical energy consumed in a single recharge, a value of 8243 kWh was obtained.

### Figure 5. BEV data.

#### Table 3. Input data for LCA analysis.

<table>
<thead>
<tr>
<th></th>
<th>BEV</th>
<th>ICEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repair times</td>
<td>43</td>
<td>3</td>
</tr>
<tr>
<td>Number of Lead/Acid batteries replaced</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Consumption</td>
<td>8240 kWh</td>
<td>1490 kg gasoline</td>
</tr>
<tr>
<td>Plastic replaced</td>
<td>34.9 kg</td>
<td>NA</td>
</tr>
</tbody>
</table>

In order to analyse the end-of-life phase of the cells, data from the Ecoinvent module Disposal, Li-ion batteries, and mixed technology were used. This module represents a combination of two different technologies for treating lithium-ion batteries: pyrometallurgical and hydrometallurgical. The data pertain to the global context.

In Table 4, the term “Transport, freight, lorry” refers to the emissions generated by the transportation of the various disassembled parts of the two vehicles to the municipal landfill or recycling centres (plastic, aluminium, batteries, and steel). Because SIMAPRO® uses “kgkm” as the unit of measurement, the average distance considered was 30 km; this value was multiplied by the specific weight (in kg) of the waste or material each time.
Table 4. Input data for LCA analysis regarding end of life.

<table>
<thead>
<tr>
<th></th>
<th>BEV</th>
<th>ICEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic recycled</td>
<td>122 kg</td>
<td>NA</td>
</tr>
<tr>
<td>Li batteries recycled</td>
<td>110 kg</td>
<td>NA</td>
</tr>
<tr>
<td>Battery, Lead/Acid, recycled</td>
<td>40.2 kg</td>
<td>7.5 kg</td>
</tr>
<tr>
<td>Aluminium recycled</td>
<td>175 kg</td>
<td>30.2 kg</td>
</tr>
<tr>
<td>Steel recycled</td>
<td>NA</td>
<td>31.9 kg</td>
</tr>
<tr>
<td>Li batteries disposed in landfill</td>
<td>12.2 kg</td>
<td>NA</td>
</tr>
<tr>
<td>Other materials in landfill</td>
<td>140 kg</td>
<td>19.07 kg</td>
</tr>
<tr>
<td>Transport, freight, lorry</td>
<td>30 km</td>
<td>30 km</td>
</tr>
</tbody>
</table>

4.2. Internal Combustion Engine Vehicle (ICEV)

The selected ICEV (internal combustion engine vehicle) for comparison is a 50 cc moped, Euro 2, from 2005. Due to its compact size and design, it is well-suited for efficient deliveries. Technical specifications are provided in Table 2. This moped is powered by a 3 kW internal combustion engine. It delivers an estimated range of around 75 km with 1 L of fuel, as declared by the manufacturer in [35], perfectly aligning with urban distribution requirements, with a maximum speed of 45 km/h, in compliance with urban speed limits. This versatile moped significantly contributes to urban logistics, particularly in the context of “last mile” delivery, where its compact design and efficient performance shine. The following Figure 6 along with Tables 3 and 4 illustrate the input data fed into the software and the consecutive procedures applied to produce the analysis. A lifespan of 10 years and an annual mileage of 11,200 km were assumed for both vehicles.

![Figure 6. Internal combustion engine vehicle (ICEV) data.](image)

4.3. Analysis and Results

This section shows the results with the diagrams generated by SIMAPRO® software for the two vehicles. The thickness of the line indicates the total environmental load flowing between processes. While a red colour means an environmental load, green means a negative environmental load, or in fact an environmental benefit Figure 7, whose elements are described in Table 5, shows that for the BEV, the most impactful block is related to electric energy, specifically its production. The SIMAPRO® software (release version 9.4.0.2) considers energy produced from a mix of sources, including fossil fuels [36]. As for the ICEV, it is the fuel block (Figure 8, whose elements are described in Table 6).
Figure 7. BEV tree diagram.

Table 5. BEV tree diagram legend.

<table>
<thead>
<tr>
<th>Number</th>
<th>Type</th>
<th>Weight/Consumption</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BEV</td>
<td>471 kg</td>
<td>Life cycle</td>
</tr>
<tr>
<td>2</td>
<td>Maintenance electric passenger car</td>
<td>3 times</td>
<td>Transport</td>
</tr>
<tr>
<td>3</td>
<td>Battery cell, Li-Ion</td>
<td>122 kg</td>
<td>Material</td>
</tr>
<tr>
<td>4</td>
<td>Plastic flake</td>
<td>34.9</td>
<td>Material</td>
</tr>
<tr>
<td>5</td>
<td>Battery, Lead/Acid, Rechargeable</td>
<td>40.2 kg</td>
<td>Material</td>
</tr>
<tr>
<td>6</td>
<td>Electricity, low voltage (IT)</td>
<td>8240 kWh</td>
<td>Energy</td>
</tr>
<tr>
<td>7</td>
<td>Recycled aluminium</td>
<td>175 kg</td>
<td>Disposal process</td>
</tr>
<tr>
<td>8</td>
<td>Transport, freight, lorry</td>
<td>30 km × kg</td>
<td>Transport</td>
</tr>
<tr>
<td>9</td>
<td>Aluminium in car shredder residue</td>
<td>175 kg</td>
<td>Disposal process</td>
</tr>
<tr>
<td>10</td>
<td>Battery cell, Li-Ion</td>
<td>122 kg</td>
<td>Disposal process</td>
</tr>
<tr>
<td>11</td>
<td>Battery cell, Li-Ion</td>
<td>110 kg</td>
<td>Recycling process</td>
</tr>
<tr>
<td>12</td>
<td>Used Li-ion battery</td>
<td>12.2 kg</td>
<td>Disposal process</td>
</tr>
<tr>
<td>13</td>
<td>Recycled plastic</td>
<td>122 kg</td>
<td>Disposal process</td>
</tr>
<tr>
<td>14</td>
<td>Waste Poliethylene for recycling, sorted</td>
<td>122 kg</td>
<td>Recycling process</td>
</tr>
<tr>
<td>15</td>
<td>Landfill</td>
<td>87.3 kg</td>
<td>Disposal process</td>
</tr>
<tr>
<td>16</td>
<td>Municipal solid waste</td>
<td>87.3 kg</td>
<td>Disposal process</td>
</tr>
<tr>
<td>17</td>
<td>Battery, Lead/Acid, Rechargeable</td>
<td>40.2 kg</td>
<td>Disposal process</td>
</tr>
<tr>
<td>18</td>
<td>Recycled Battery, Lead/Acid</td>
<td>40.2 kg</td>
<td>Recycling process</td>
</tr>
</tbody>
</table>

Subsequently, a new analysis was conducted considering all the electrical energy consumed over 10 years by the battery electric vehicle (BEV) produced from a photovoltaic facility.

The method used for impact analysis and calculation is derived from the software SIMAPRO® [35]. Table 7 presents various impact categories and their values for the BEV, the BEV powered by photovoltaic panels (BEV + PS), and the ICEV. It is important to highlight that, because the BEV can transport up to 140 kg of goods and the ICEV can carry only 25 kg, it was assumed that six ICEVs have to be considered in order to transport an equivalent amount of goods. Thus, the values obtained from the ICEV analysis were multiplied by six to make the results comparable.
As evident from the comparison of the calculated results presented in Table 7, considering the kg of CO$_2$eq emitted by the vehicles, the BEV emits slightly less CO$_2$eq during its lifespan compared to six ICEVs. If the BEV is powered by energy generated from
photovoltaic panels, it emits 50% less. This difference is due to the methods of energy procurement, in particular, to the mix of sources used to produce energy, as already demonstrated by \[13,38,39\].

5. Discussion

The study conducted using SIMAPRO® software yielded two significant results. The first challenges the conventional assumption that electric vehicles have a much smaller environmental impact compared to gasoline vehicles. Surprisingly, the comparison presented a different scenario. When considering the same annual distance travelled and the energy required for refuelling (fuel for internal combustion engine vehicles or ICEVs and electricity for battery electric vehicles or BEVs) over a 10-year period, BEVs emitted a slightly lesser amount of CO\(_2\)eq, totalling 6418.58 kg CO\(_2\)eq, in contrast to six ICEVs emitting 8744.92 kg CO\(_2\)eq. If we analyse the individual contributions for the ICEV, we can state that 66% of each kg CO\(_2\)eq is generated by the fuel, and 44% is generated by regular maintenance. In the case of the BEV, 57.1% of each kg CO\(_2\)eq is generated by the electricity production process, and 43.4% is generated by regular maintenance. In this analysis, the SIMAPRO® software considers that the energy generated in Italy depends on a mix of sources, including fossil fuels. The data are based on the statistics from 2018 of the IEA World Energy Statistics and Balances \[36\].

Because the original analysis highlights the pivotal role of the energy source, a second scenario was considered, assuming that all the electricity required for the BEV would be generated exclusively from a photovoltaic system. This latter analysis sheds a new light on the individual contributions, and it can be observed that the kgCO\(_2\)eq emissions from electricity production can decrease to 17.6%, showing that the largest contribution depends on maintenance (83.4%).

Other impact categories analysed by SIMAPRO® indicated higher environmental impacts for BEVs. As for ecotoxicity, freshwater, and resource use, minerals and metals are almost exclusively linked to the presence of the lithium battery. Indeed, these values decrease very slightly when considering the energy produced by photovoltaic panels.

A second noteworthy result from Table 7 underscores the positive impact of installing photovoltaic systems at BEV charging stations. These systems, which can also serve other electric vehicles, can lead to an impressive reduction of approximately 50% in resource consumption and daily emissions. In the case of BEVs, the primary environmental concern is associated with the lithium batteries (30.7% of kgCO\(_2\)eq emitted by BEV powered by photovoltaic panels), which are the core components of these vehicles.

In light of the results obtained from the life cycle assessment (LCA), we can attempt to provide answers to the research questions (RQs) we had posed to ourselves.

RQ1: Is it possible to make freight transportation sustainable through electric machinery? If we consider the pollution due to exhaust gases in transportation, it has been tackled by adopting electric alternatives. But we must also consider the electricity production.

RQ2: How much does the production of electric energy contribute to the impact of electric vehicles? It is the primary contributor. In fact, electric vehicles can only make transportation sustainable if the energy they consume comes from renewable sources, such as wind and solar power.

RQ3: Does an electric vehicle truly have a lower environmental impact compared to a gasoline vehicle? If we confine our observation to emissions and consider electricity entirely generated from renewable sources, we can respond in the affirmative. However, if we were to expand our observation to include the production and disposal of lithium batteries, it is not guaranteed that the answer would remain affirmative.

6. Conclusions

The transformation of the logistics sector into green logistics is not merely a choice but an urgent necessity in the ongoing battle against global warming, as mandated by the European Green Deal. This transition necessitates a comprehensive evaluation of the
potential of electric vehicles (EVs) as a sustainable solution for reducing transport emissions. To this end, a gate-to-grave life cycle assessment (LCA) was conducted, comparing the environmental impacts of an electric minicar with those of a traditional 50 cc motorcycle.

The results of the LCA cast a nuanced light on the role of electric vehicles. Contrary to the common perception that EVs are inherently emission-free, our analysis revealed that EVs using lithium-ion battery technology are not exempt from greenhouse gas emissions. In fact, they produce slightly less emissions than their internal combustion engine counterparts, 6418.58 kg CO$_2$eq, in contrast to the equivalent number of ICEVs (six) required to transport the same load, emitting 8744.92 kg CO$_2$eq. An in-depth analysis of EV life cycle stages revealed that the primary environmental impact stems from electrical energy production. The SIMAPRO® software database considers various energy sources, including fossil fuels. To emphasize the role of the energy source, we conducted a separate analysis, assuming exclusive use of photovoltaic-generated electricity for the EV. In this scenario, the electric vehicle shows a 50% reduction in kgCO$_2$eq emissions, leading to key conclusions addressing our research questions.

The proposed analysis demonstrates that is indeed possible to make freight transportation sustainable through electric machinery, but the environmental impact of EVs versus gasoline vehicles is highly contingent on the source of electricity. The logistics industry’s contribution to achieving the goals of the European Green Deal can be significant by adopting electric minicars for urban distribution. However, a key condition for realizing this potential is ensuring that these vehicles are charged exclusively using 100% renewable energy sources like solar or wind power.

As far as it concerns the use case scenario of this research, focused in Italy, a crucial point not to be underestimated is that publicly accessible charging points are unevenly distributed. Therefore, a significant issue for implementing a sustainable freight transportation is the lack of available charging infrastructure in many Italian municipalities, as 58% of them currently do not possess publicly accessible charging points. Italy’s logistics sector must address these deficiencies in recharging point distribution, which vary significantly across municipalities and locations.

The future direction of our research will involve conducting a cradle-to-grave LCA of the two vehicle types, with a specific focus on the production and disposal phases of lithium-ion batteries. This holistic approach will yield a more comprehensive understanding of the environmental implications of EVs.

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**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. EEA Key Findings–Climate Change, Impacts and Vulnerability in Europe 2016; European Environment Agency: Copenhagen, Denmark, 2016.


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