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Review

Carbon Footprint of Electric Vehicles—Review of Methodologies and Determinants

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Abstract: The carbon footprint of a product and organization is one of the most important environmental indicators in many sectors, including transport. Consequently, electric vehicles (EV) are being introduced as an alternative to achieve decarbonization targets. This article presents an overview of methodologies for assessing the carbon footprint of electric vehicles, including a review of concepts, methods, standards, and calculation models based on the life cycle of the carbon footprint. The article also includes a systematic review of the results of EV carbon footprint analyses. The analysis of current knowledge on the carbon footprint focuses on road transport vehicles: Battery Electric Vehicles (BEV), Fuel Cell Electric Vehicles (FCEV), Hybrid Electric Vehicles (HEV), and Plug-in Hybrid Electric Vehicles (PHEV). Additionally, a review of factors determining the carbon footprint assessment of electric vehicles, considering their entire life cycle, has been conducted.

Keywords: carbon footprint; electric vehicles; road transport; life cycle assessment; decarbonization

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1. Introduction

Increasing legal requirements and, above all, the growing understanding of the environmental impact of organizational activities and product usage have led to the development of various assessment methods. One such method aimed at documenting the environmental burdens of products, technologies, or enterprises is carbon footprint assessment. Climate change is currently regarded as one of the most significant issues related to sustainable development. To effectively assess the environmental impact of human activities, environmental assessment methods, known as environmental footprints, are utilized. These footprints are derived from the Life Cycle Assessment (LCA) technique. LCA is employed to evaluate the environmental impact of products and services throughout their life cycle, from raw material extraction and processing for goods production, through the usage phase, to disposal at the end of their service life. Conducting an environmental footprint assessment comprises several stages: defining the purpose and scope of the analysis, identifying resources and emissions, assessing environmental impact, interpreting results, and developing a report. The assessment of environmental footprints for products and enterprises should adhere to principles of relevance, completeness, consistency, accuracy, and transparency. The carbon footprint is the most widespread among the family of environmental footprints. Currently, the carbon footprint (CF) is of interest not only to the scientific community but also to business leaders, who—recognizing its tangible benefits—utilize this tool as a fundamental approach to improving the environmental efficiency of business operations, as evidenced by the adoption of ESG (Environmental, social, and governance) reporting.

The European Commission has developed documents that outline the path for the European Union (EU) to achieve climate neutrality by 2050. This ambitious goal reflects the EU's commitment to combating climate change and reducing the environmental impact of various sectors, including energy, industry, transport, and agriculture. Achieving climate neutrality will require significant reductions in greenhouse gas (GHG) emissions and transformative changes across economic sectors. The European Green Deal [1] is a new growth strategy for the Union, aiming to transform the EU into a modern, resource-efficient, and competitive economy with net-zero greenhouse gas emissions by 2050. This strategy serves as a roadmap, detailing specific initiatives and actions needed to promote sustainable practices and encourage innovation in green technologies. The European Green Deal promotes sustainable development and the transition to a green economy within the European Union, emphasizing the importance of decoupling economic growth from resource use and environmental degradation.

The carbon footprint (CF) [2] is currently one of the most widely used environmental indicators. As a measure of the total greenhouse gas emissions caused by an entity, process, or product over its life cycle, the carbon footprint provides critical insight into the environmental impact of various activities. Numerous approaches, methodologies, and tools have been developed to assess CF, ranging from simplified calculators to more scientific and complex methods based on life cycle analysis. These tools enable organizations to quantify and monitor their carbon emissions, paving the way for targeted actions to reduce their overall carbon footprint. CF is generally focused on products and organizations, but the concept of CF can also apply to sectors, countries, individuals, etc., highlighting its versatility as an indicator for various scales of environmental impact.

One of the key documents introducing new legal obligations for organizations in EU countries concerning CF analysis within sustainability reporting (ESG) is the Corporate Sustainability Reporting Directive (CSRD) [3]. The CSRD mandates that companies disclose standardized information regarding their environmental, social, and governance (ESG) practices, ensuring greater transparency and accountability. The CSRD introduces a requirement to report data in the areas of environment (E), social responsibility (S), and corporate governance (G)- collectively known as ESG reporting. This directive aims to create a harmonized framework for sustainability reporting across the EU, allowing stakeholders to assess companies' ESG performance and make informed decisions. Climate-related issues are one of the key environmental areas to be reported, with particular emphasis on how companies are addressing their carbon emissions and contributing to the EU's climate goals.

ESG is a crucial element of organizational sustainability, including in the transport sector, making it increasingly important to understand the rules and scopes of mandatory analyses for both organizations and products in line with the European Commission's guidelines. In the transport sector, which is a significant contributor to greenhouse gas emissions, the adoption of ESG reporting standards can drive improvements in energy efficiency, the adoption of cleaner technologies, and the optimization of logistics and supply chain processes. ESG has become a new standard for non-financial reporting on an organization's activities and its impact on the environment. By setting clear standards and guidelines, ESG reporting encourages companies to adopt more responsible practices, enhancing their corporate reputation and building trust among investors, consumers, and regulators [4]. ESG reporting is based on the European Sustainability Reporting Standards (ESRS), which are mandatory for all enterprises subject to the CSRD [3]. These standards establish a structured approach to disclosing sustainability-related information, covering a broad range of environmental, social, and governance metrics that reflect the EU's priorities for sustainable development.

Non-financial reporting on Environmental, Social, and Governance (ESG) factors is a rapidly developing and increasingly important topic that has drawn significant attention from capital market participants in recent years [5,6]. The environmental aspect of ESG focuses on an organization's impact on the environment, encompassing efforts to reduce its carbon footprint, responsibly manage natural resources, and minimize environmental damage [7,8]. Therefore, in the transport sector, understanding the carbon footprint is essential for identifying factors that contribute most significantly to the environmental impact of both logistics-transport system organizations and the vehicles they operate. This article aims to review the literature on the carbon footprint of electric vehicles, which present an alternative to conventional fuel vehicles to mitigate greenhouse gas emissions.

Additionally, the article characterizes the key methods and standards for calculating the carbon footprint of organizations and products in the transport sector.

2. Carbon Footprint Management in the Logistics and Transport System

The assessment of the carbon footprint (CF) is one of the most critical aspects of environmental evaluation in the transport sector. CF is defined as the total sum of greenhouse gas emissions generated throughout the life cycle of a product, either directly or indirectly, by an individual, company, product, or service. The carbon footprint represents the sum of life cycle greenhouse gas emissions, accounting for both direct and indirect emissions at each stage of the life cycle. CF is expressed as carbon dioxide equivalent (CO_2e), which incorporates the Global Warming Potential (GWP) of individual greenhouse gases. It includes emissions of gases such as carbon dioxide, methane, nitrous oxide, or chlorofluorocarbons (CFCs), among others, which contribute to the greenhouse effect.

An organization's carbon footprint encompasses both direct emissions generated by the organization's facilities and processes, as well as indirect emissions from suppliers, transportation, energy consumption, and waste disposal. Carbon footprint analysis and assessment is the first step toward decarbonization. The next step is carbon footprint management through the monitoring and reporting of environmental indicators, which is essential for reducing environmental impact.

Climate change and the anthropogenic impact on global warming are currently among the primary topics of scientific debate. Reports from the Intergovernmental Panel on Climate Change (IPCC) have prompted governments worldwide to take action to reduce greenhouse gas emissions. The result of intergovernmental collaboration on greenhouse gas emission assessments has been the establishment of mandatory emissions reporting, which—depending on the region—has taken various forms: from emissions trading systems, such as the European Emission Trading System (EU ETS), to national greenhouse gas reporting programs. Calculating the carbon footprint offers tangible benefits, as illustrated in Figure 1.

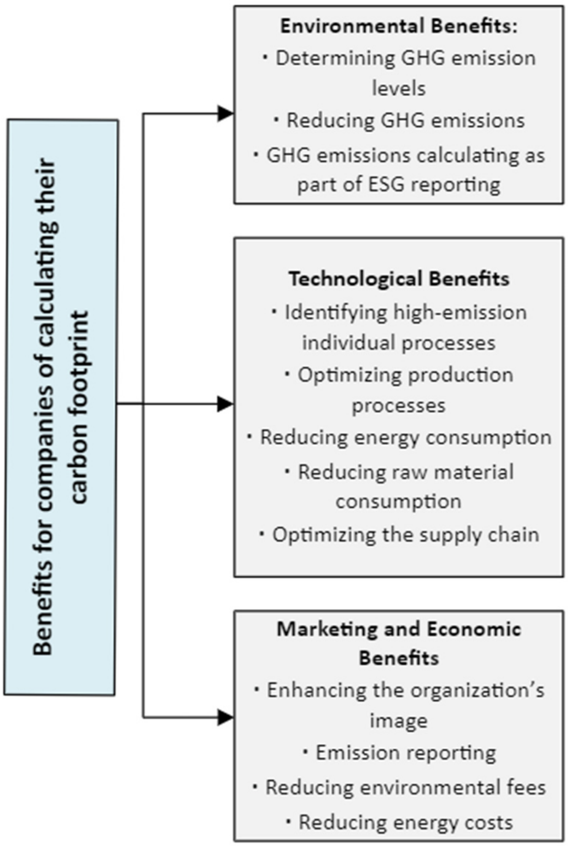

Figure 1. Main benefits of a carbon footprint assessment.

The key advantages of calculating the carbon footprint include minimizing the negative environmental impact of corporate activities, notably by enabling the quantification of greenhouse gas emissions throughout each product's production process [9]. A phased approach to carbon footprint calculation facilitates the identification of the specific element within the process that contributes most significantly to environmental degradation, known as the "hot spot". Identifying such critical points, for example, which is a particular process within the entire supply chain, allows for targeted environmental interventions, with a focused approach yielding optimal outcomes in terms of both environmental and economic efficiency. This also supports production process optimization. Essential actions include enhancing the efficiency of resource management, energy utilization, and waste management practices. Examples of measures to reduce the carbon footprint in logistics and transport systems include eliminating "empty runs" in transportation (i.e., underloaded trips), modifying packaging types for transported goods, and utilizing local suppliers. All environmental improvements stemming from carbon footprint quantification enable the development of "green" design concepts, reduce resource consumption, lower energy demands, and minimize waste generation, while also promoting partnerships with low-carbon suppliers, thereby indirectly reducing the footprint of the evaluated product or organization. Carbon footprint assessment in the transport sector informs decision-making on climate policy and supports initiatives aimed at reducing greenhouse gas emissions within logistics and transportation systems.

In recent years, increasing regulatory requirements regarding exhaust emissions, such as the Euro VI standards, have significantly influenced the development of technologies used in vehicles with internal combustion engines. The article by Milojevic et al. (2024) [10] emphasizes that the introduction of advanced technical solutions, such as high-pressure direct fuel injection systems and exhaust gas recirculation (EGR), has contributed to a significant reduction in particulate matter (PM) and nitrogen oxide (NOx) emissions. Moreover, the use of selective catalytic reduction (SCR) systems effectively reduces NOx emissions, which is crucial for meeting strict regulatory requirements.

An important element is the use of real driving emissions (RDE) tests, which are a key addition to traditional laboratory tests. PEMS (Portable Emissions Measurement Systems) are devices that allow for the measurement of emissions from vehicles during real road driving. The introduction of these tests aims to reduce discrepancies between results obtained under laboratory conditions and actual on-road emissions. This ensures that manufacturers must guarantee compliance with emission standards even in varying conditions, such as different speeds, changes in terrain gradients, and varying vehicle loads.

Technological innovations are a direct response to the growing need to reduce the environmental impact of transportation and to meet increasingly stringent emission regulations. In the future, further tightening of regulations and the introduction of even more advanced technological solutions to further reduce exhaust emissions and pollutants can be expected.

Table 1 presents global greenhouse gas (GHG) emissions by sector for the period of 1990–2023, showing changes relative to 1990 and 2005. The data analysis reveals that the transport sector recorded the third-highest increase in emissions, with a 78% rise compared to 1990 and a 26% rise compared to 2005. Only the power industry and industrial combustion and processes sectors showed larger increases. These results highlight the significant contribution of transport to the global rise in GHG emissions, underscoring the challenges of decarbonizing this sector. Tables 1 and 2 were developed based on data from the Joint Research Centre [11].

Table 2 illustrates GHG emissions across sectors in the EU-27 from 1990 to 2023 [10]. Unlike other sectors in the EU, transport is the only sector to have recorded an increase in emissions over the period, with a 19% rise relative to 1990. This increase indicates that despite efforts within the EU's climate policy framework, the transport sector remains a substantial source of emissions. Compared to 2005, transport emissions decreased by 6%, which may reflect the initial impact of implemented strategies, though their effectiveness remains limited in achieving reductions relative to 1990 levels.

Table 1. Global greenhouse gas emissions by sector for the period 1990–2023.

Sector	2023 vs. 1990	2023 vs. 2005
Power Industry	+96%	+36%
Industrial Combustion and Processes	+91%	+41%
Buildings	+1%	+3%
Transport	+78%	+26%
Fuel Exploitation	+48%	+23%
Agriculture	+20%	+15%
Waste	+56%	+37%
All sectors	+62%	+28%

Table 2. EU-27 greenhouse gas emissions by sector for the period 1990–2023.

Sector	2023 vs. 1990	2023 vs. 2005
Power Industry	−51%	−50%
Industrial Combustion and Processes	−42%	−30%
Buildings	−37%	−31%
Transport	+19%	−6%
Fuel Exploitation	−46%	−27%
Agriculture	−27%	−6%
Waste	−35%	−26%
All sectors	−34%	−29%

The interpretation of these results highlights the urgent need to intensify efforts in the transport sector, especially at the global level, to achieve ambitious climate targets. While the EU has made substantial progress, with significant emission reductions in other sectors, transport remains a critical area requiring further action. The EU's strides toward decarbonization demonstrate the potential effectiveness of targeted policies and technological advancements, setting an example that underscores the necessity for similar commitments worldwide. On the global scale, stronger initiatives in technological innovation, energy efficiency, and policy implementation are essential to address transport emissions effectively and support comprehensive climate action.

In this context, the EN 16258 [12] standard, developed by the European Committee for Standardization (CEN), is also important for accurately measuring and reporting energy consumption and greenhouse gas emissions in transport. It provides a comprehensive methodology for assessing emissions at various stages of a vehicle's life cycle, enabling detailed environmental analysis. This is particularly significant for Battery Electric Vehicles (BEVs), as it accounts for emissions not only during operation but throughout the entire life cycle, including battery production and the energy source, allowing for more precise comparisons between electric, hybrid, and conventional vehicles. Integrating the EN 16258 standard with carbon footprint calculation methodologies, such as Life Cycle Assessment (LCA) or GHG protocols, is a valuable addition to existing environmental assessment tools, enabling result harmonization and improving the quality of reporting in line with ESG guidelines.

Research, such as the study by Skrúcaný et al. (2019) [13], highlights the environmental impact of implementing electric vehicles in Central European countries assessed within the EN 16258 framework. This study points to the variability in greenhouse gas (GHG) emissions associated with electricity production, dependent on the energy mix and efficiency of power generation in individual countries. By applying the well-to-wheel (WtW) approach, the authors demonstrated that the ecological benefits of using electric vehicles are highly dependent on the energy source used for charging. For instance, in Austria, where renewable energy sources dominate, WtW GHG emissions for electric vehicles are significantly lower, ranging from 19.74 to 29.47 gCO_2e/km. In contrast, in Poland, where the energy mix is predominantly coal-based, emissions can reach between 114.31 and

170.66 gCO_2e/km. These findings emphasize the necessity of full life cycle analysis (LCA) when assessing the sustainability of electromobility.

These insights underscore the critical need for countries to transition toward cleaner energy sources and adopt comprehensive Life Cycle Assessments to truly harness the environmental benefits of electric vehicles.

3. Methodology for Calculating the Carbon Footprint in the Transport Sector

The growing emphasis on reducing greenhouse gas (GHG) emissions worldwide underscores the importance of accurate measurement and management of the carbon footprint across various sectors, including transport. Transport is a significant source of GHG emissions, and the development of effective methodologies for calculating the carbon footprint is crucial for monitoring and minimizing its environmental impact. This chapter presents an analysis of available methodologies for calculating the carbon footprint in the transport sector, highlighting their principles, applications, and relevance to achieving decarbonization goals. The choice of methodology in the transport sector is determined by the life cycle of emission sources, from fuel extraction to their final use in vehicles. Table 3 provides an overview of methods and standards for calculating the carbon footprint of organizations and products that can be applied in the transport sector, taking into account their characteristics and areas of application.

Table 3. Methods and Standards for Calculating the Carbon Footprint of Organizations and Products Applicable in the Transport Sector.

Method/Standard	Description
PAS 2050	PAS 2050 is a standard developed by the British Standards Institution. It focuses on calculating the carbon footprint of products and services. This standard considers the product life cycle from raw material acquisition, through production, distribution, and usage, to disposal [14].
IPCC Method—Intergovernmental Panel on Climate Change	The IPCC method is used to calculate the carbon footprint, particularly for products and technologies [15].
GHG Protocol	The GHG Protocol concerns the assessment and monitoring of the carbon footprint. It serves for ESG reporting for sustainable development within organizations. According to the GHG Protocol, greenhouse gas emissions are divided into three scopes [16].
LCA Method—Life Cycle Assessment	The LCA framework allows for the calculation of CF by applying different LCIA (life cycle impact assessment) methods, taking into account the impact categories [17,18].
WtW—Well-to-Wheel	The WtW method is dedicated solely to the assessment of transportation fuels. In vehicle assessment, it only considers categories related to energy consumption and greenhouse gas emissions associated with the fuel life cycle [19].
ISO 14067:2018	ISO 14067:2018 defines terms related to the carbon footprint and guidelines for quantitatively determining the carbon footprint of a product. This international standard concerns the calculation of product carbon footprints [20].
ISO 14064-1:2018	ISO 14064-1:2018 provides guidelines for reporting greenhouse gas emissions at the organizational level to enable the quantification and reporting of emissions for planning, reporting, and management purposes [21].

The first and most widely used method for calculating the carbon footprint (CF) is the Publicly Available Specification 2050 (PAS 2050) [22] developed by the British Standards Institute. This specification was created to standardize the methods of calculating greenhouse gas emissions over the life cycle of products and services. PAS 2050 is utilized by BSI to update quantitative assessments of greenhouse gas emissions across product and service life cycles in line with the latest technological advances and accumulated experience [23]. As it enables the measurement of the environmental impact of products and services throughout their life cycle, PAS 2050 serves as the foundation for preparing reliable reports necessary for companies to achieve greenhouse gas emission reductions over the product life cycle.

Currently, one of the most widely adopted carbon footprint calculation methods is the IPCC method, which serves as a useful tool for calculating the carbon footprint, particularly at the product and technology level. Developed by the Intergovernmental Panel on Climate Change (IPCC), this method considers not only CO_2 emissions but also emissions of other greenhouse gases. If only CO_2 emissions are included in the analysis, the results are presented in units of kg CO_2. However, when other greenhouse gases are included, the results are expressed in kg CO_2eq, which represents the mass of CO_2 equivalents. These equivalents are calculated by multiplying the actual mass of the gas by its global warming potential (GWP), allowing for the global warming effects of different greenhouse gases to be comparable and additive. The recently published sixth IPCC report provides an updated reference on global warming conditions [15].

The most important document for carbon footprint assessment and monitoring, particularly for organizations, is currently the Greenhouse Gas Protocol (GHG Protocol). The GHG Protocol is used for greenhouse gas emissions reporting and is the result of a collaboration between the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). The GHG Protocol includes the following components: The GHG Protocol Corporate Accounting and Reporting Standard, The Scope 2 Guidance, and The Corporate Value Chain (Scope 3) Accounting and Reporting Standard. Under CF reporting according to the GHG Protocol, six greenhouse gases are considered.

According to the GHG Protocol, CF reporting should be based on the following principles: relevance to users, completeness, consistency, transparency, and accuracy. The GHG Protocol divides the organization's carbon footprint into three scopes:

- Scope 1—encompasses direct emissions from sources owned and controlled by the organization, including emissions related to refrigerant leakage from air conditioning equipment used by the organization;
- Scope 2—includes indirect emissions associated with the organization's purchased electricity, heat, steam, and cooling. These are emissions generated outside the organization;
- Scope 3—similar to Scope 2, includes indirect emissions occurring outside the organization, but excludes those covered in Scope 2. These emissions are associated with purchased raw materials, services, or products, as well as emissions related to leased assets, the use of products manufactured by the organization, waste management, and employee business travel. Scope 3 includes 15 specific categories of emissions.

The introduction of mandatory carbon footprint analyses across all three scopes is essential for managing the carbon footprint throughout the entire value chain of an organization, including in the transport sector.

The Life Cycle Assessment (LCA) methodology enables an evaluation of the potential environmental impact throughout the entire life cycle, starting from the extraction of raw materials, through the utilization phase, to the final disposal. LCA allows for the comparison of environmental aspects of both various products and technological solutions, facilitating the selection of products or solutions with the lowest environmental impact over their entire life cycle. Life Cycle Assessment is governed by international standards related to environmental management systems ISO 14040 [17] and ISO 14044 [18].

In the automotive industry, environmental assessment methods that account for the fuel life cycle (WtW, Well-to-Wheel) are applied, where two phases are analyzed:

- WtT, Well-to-Tank—in this phase, environmental burdens associated with the extraction of raw materials for fuel production are considered. It also accounts for fuel production, as well as its transportation and storage;
- TtW, Tank-to-Wheel—in this phase, environmental burdens associated with the utilization of fuel in vehicles are considered, including refueling and fuel combustion during vehicle operation.

Compared to LCA, the WtW method in vehicle assessments considers only impact categories related to energy consumption and greenhouse gas emissions associated with the fuel life cycle. In the LCA, materials used in the vehicle production process and many other stages of the vehicle life cycle are also considered, along with environmental impact categories.

The methodology for carbon footprint assessment is also presented in other ISO standards. Guidelines and requirements related to the design, development, management, reporting, and verification associated with a company's GHG inventory are contained in ISO 14064 [21], which consists of three parts. Meanwhile, the CF calculation proposal is presented in ISO 14067 [20]. This standard includes requirements and guidelines for the quantification and communication of the product's carbon footprint. Similar to PAS 2050, ISO 14067:2018 [20] focuses on the entire life cycle of a product. However, this standard provides more detailed guidelines regarding individual stages of calculations and measurement methodologies. Unlike PAS 2050, this standard was developed by an international team, with members representing various countries around the world. It was created due to the necessity of establishing clear, consistent, and universal principles for determining the carbon footprint, as well as defining guidelines for reporting and making the results of these calculations widely accessible. According to ISO 14067, the carbon footprint calculation process—similar to PAS 2050—should consider the life cycle concept. Therefore, greenhouse gas emissions not only from direct business activities but also indirect emissions are included in the analyses. In ISO 14067, greenhouse gas emissions are grouped into three levels:

- Scope 1—emissions from greenhouse gas sources owned or controlled by the company (direct emissions);
- Scope 2—greenhouse gas emissions from the production of electricity, heat, or steam consumed by the company (indirect energy-related greenhouse gas emissions);
- Scope 3—emissions other than indirect energy-related greenhouse gas emissions that result from the company's activities but occur in facilities owned or controlled by other companies.

This means that calculations take into account not only direct emissions within the organization but also those occurring within the supply chain, making the data analysis process time consuming, labor intensive, and requiring specialized expert knowledge. The CF analysis includes the following scopes:

- From cradle to grave—considering all stages from raw material extraction to disposal;
- From cradle to gate—where the stages from raw material extraction to the delivery of the finished product to the customer are calculated, including the transport process to the customer.

Table 4 describes the links between the family ISO 14060 standards for organization and product carbon footprint analysis. The ISO 14060 series of standards provides a set of guidelines ensuring a consistent approach to the quantification, monitoring, reporting, and verification of greenhouse gas (GHG) emissions. These standards are aimed at supporting sustainable development and the transition to a low-carbon economy, offering both environmental and organizational benefits. Implementing the ISO 14060 standards enables companies to manage emissions effectively by precisely determining their levels, which facilitates more informed strategic planning. Consequently, companies can systematically monitor their emissions, analyze their sources and environmental impact, and report progress accurately. These standards also support the achievement of environmental goals, helping companies to prepare for future legal and societal requirements related to GHG management, while enhancing their credibility with stakeholders and consumers.

Table 4. An overview of the family ISO 14060 standards for organization and product carbon footprint analysis.

Standard	Description
ISO 14064-1 [21]	Design and develop GHG inventories for organizations. Output: GHG inventory and report.
ISO 14064-2 [24]	Quantify, monitor, and report emission reduction and removal enhancement. Output: GHG project documentation and reports.
ISO 14067 [20]	Develop CFP per functional or declared unit. Output: CFP study report.
ISO 14064-3 [25]	Provides guidance for the verification and validation of GHG statements.
ISO 14065 [26]	Specifies requirements for validation and verification bodies.

4. Carbon Footprint Analysis of Electric Vehicles—Review of Methods and Determinants

The analysis of the carbon footprint of electric vehicles (EVs) is a vital aspect of contemporary research on sustainable transportation. In the face of growing demand for environmentally friendly vehicles and global commitments to reduce greenhouse gas emissions, EVs are gaining popularity as an alternative to conventional combustion vehicles. Despite their potential to reduce carbon dioxide (CO_2) emissions during the usage phase, a comprehensive assessment of the carbon footprint of EVs requires consideration of the entire life cycle of these vehicles, from production and raw material acquisition through usage to recycling and disposal.

In scientific literature, there are various methodologies for analyzing the carbon footprint of EVs, differing in approach and scope of analysis. The choice of methodology affects the obtained results, which can vary significantly depending on research assumptions and defined system boundaries. These differences also arise from considering diverse determinants, such as regional energy sources (renewable or conventional) used for vehicle charging, charging infrastructure, and the recycling possibilities for components, including batteries.

This chapter will discuss the classification of methods used for analyzing the carbon footprint of electric vehicles and present the key determinants that have a significant impact on the final assessment results.

4.1. A Review of Studies Related to the Carbon Footprint Analysis of Electric Vehicles

Table 5 provides an overview of 24 studies related to the analysis of greenhouse gas (GHG) emissions associated with various types of vehicles, including electric vehicles (Battery Electric Vehicles—BEV), hybrids (Hybrid Electric Vehicles—HEV), internal combustion engine vehicles (Internal Combustion Engine Vehicles—ICEV), plug-in hybrids (Plug-in Hybrid Electric Vehicles—PHEV), and fuel cell vehicles (Fuel Cell Electric Vehicles—FCEV). The overview includes passenger cars, buses, vans, and trucks. A wide range of methodological approaches has been considered, aiming to estimate the total environmental impact of these vehicles throughout their entire life cycle. These studies highlight the growing interest not only in passenger vehicles but also in public and freight transport, which play a crucial role in reducing global emissions and striving toward sustainable transportation.

Each author conducted carbon footprint analyses within the context of specific local conditions and based on unique methodological assumptions that could significantly impact the obtained results. Local conditions included, among others, the characteristics of the energy mix, the availability and type of electric vehicle charging infrastructure, local emission standards, and environmental regulations. For example, in regions where electricity mainly comes from renewable sources, such as in some Scandinavian countries, the impact of electric vehicles on GHG emissions will be significantly lower than in countries that rely on fossil fuels for their energy, such as China. In China, the majority of electricity production still comes from fossil fuels, primarily coal, which significantly increases the carbon footprint of electric vehicles. Gao L. et al. (2012) [27] emphasize that the greatest impact on GHG emissions for ICEVs, HEVs, and PHEVs comes from vehicle operation, whereas for BEVs and FCEVs, energy supply plays a crucial role. Additionally, Lie K.

W. et al. (2021) [28] stated that the carbon footprint of a bus fleet was reduced by 37% through the introduction of biofuel and electric buses. They also noted that an additional 52% reduction could be achieved with full electrification using the Nordic energy mix, highlighting the significant environmental benefits of using renewable energy sources for vehicle charging.

Considering vehicle brands, popular models such as the Toyota Corolla, Toyota Prius, Nissan Leaf, VW Golf, and Tesla Model 3 are analyzed. It is important to note, however, that not all authors include specific vehicle brands in their studies, often focusing on general technological categories instead. These models come from various manufacturers, indicating that the research aims to represent a broad cross-section of the automotive market and technological diversity. The analyses are conducted in the context of different regions, enabling the assessment of the impact of local energy conditions and regulations on the outcomes of studies related to vehicle emissions and life cycle analyses.

The type of vehicle plays a significant role in carbon footprint analyses, as different categories of vehicles have varying impacts on GHG emissions. Passenger cars are the most frequently analyzed, with 17 articles dedicated to these vehicles, due to their widespread use and substantial share in greenhouse gas emissions. Buses, both electric and combustion-powered, are a crucial part of public transport systems, especially in cities, making their environmental impact an important research topic—reflected in six publications. Trucks and vans, essential for logistics and deliveries, are characterized by a high carbon footprint due to their heavy fuel consumption. This has also been an area of intensive study, although only one article has been dedicated to each of these vehicle types.

Table 5. Review of the literature related to carbon footprint analysis from electric passenger cars, buses, trucks and vans.

N°	Authors	Vehicle Type	Vehicle Models	Propulsion Type	Functional Unit	Assessment Methods	Region
1	Gao L. et al. (2012) [27]	Passenger cars	Toyota Corolla, Nissan Leaf, GM Volt, Toyota Prius, Toyota Prius Plug-in, Honda Clarity	ICEV, BEV, HEV, PHEV, FCEV	160,000 miles	CML2001	China
2	Hawkins T. R. et al. (2012) [29]	Passenger cars	Mercedes A-Class, Nissan Leaf	ICEV, BEV	1 km	GREET	European Union
3	Cooney G. et al. (2013) [30]	Buses	-	ICEV, BEV	1 vehicle-kilometer over a 12-year lifetime.	IMPACT2002	USA
4	Girardi P. et al. (2015) [31]	Passenger cars	Volkswagen Golf, Volkswagen e-Golf	ICEV, BEV	150,000 km	IPCC	Italy
5	Onat N. C. et al. (2015) [32]	Passenger cars	Toyota Corolla, Nissan Leaf, Toyota Prius, Toyota Prius-Plug in, Chevrolet Volt	ICEV, BEV, HEV, PHEV	1 km	GREET	USA
6	Tagliaferri C. et al. (2016) [33]	Passenger cars	Toyota Yaris, Nissan Leaf, Toyota Yaris Hybrid, Toyota Prius, Toyota Prius Plug-in	ICEV, BEV, HEV	1 km	CML 2001	European Union

Table 5. *Cont.*

N°	Authors	Vehicle Type	Vehicle Models	Propulsion Type	Functional Unit	Assessment Methods	Region
7	Zhao Y. et al. (2016) [34]	Delivery trucks	Freightliner P700, Freightliner P70H, Grumman Olson, Navistar E-Star Class 3, Smith Newton Class 5	ICEV, HEV, CNG, BEV	Vehicle Miles of Travel	Hybrid LCA	USA
9	Qiao Q. et al. (2017) [35]	Passenger cars	Mercedes S400, Mercedes S400 Hybrid	ICEV, BEV	Per vehicle	GREET	China
8	Mierlo J.V. et al. (2017) [36]	Passenger cars	Volkswagen Golf, Fiat Punto, Nissan Leaf, Opel Ampera, Toyota Prius	ICEV, BEV, HEV, PHEV	1 km	ReCiPe	Belgium
10	Harris A. et al. (2018) [37]	Buses	-	BEV, ICEV	1 km	EIO-LCA	UK
11	Rosenfeld D. C. et al. (2019) [38]	Passenger cars	-	ICEV, BEV, PHEV, HEV, FCEV	1 pkm	CML 2001	European Union
12	Jursova S. et al. (2019) [9]	Passenger cars	-	ICEV, BEV	100 km	IPCC2013	Czech Republic
13	Qiao Q. et al. (2019) [39]	Passenger cars	BAIC EC-Series	ICEV, BEV	150,000 km	GREET	China
14	Bekel K. and Pauliuk S. (2019) [40]	Passenger cars	Volkswagen e-Golf, Toyota Mirai	BEV, FCEV	1 km	ReCiPe	Germany
15	Chang C. et al. (2019) [41]	Buses	-	ICEV, LNG, LPG, FCEV, PEV	1 pkm	LCA ISO/TS 14067:2013 and PAS2050	Taiwan
16	Petrauskienė K. et al. (2020) [42]	Passenger cars	Fiat Tipo, Nissan Leaf	ICEV, BEV	1 km	ReCiPe	Lithuania
17	Wong E. Y. C. et al. (2020) [43]	Passenger cars	Tesla Model 3, Toyota Mirai, Hyundai ix35, Honda Clarity Fuel Cell, Mercedes GLC F-Cell	FCEV, BEV	1 km	GREET	Various countries
18	Candelaresi D. et al. (2021) [44]	Passenger cars	-	FCEV, H2-ICE, HEV H2-IC,E CNG, HEV CNG, Hythane, H2-Gasoline	1 km	GREET	Global
19	Pipitone E. et al. (2021) [45]	Passenger cars	A selection of example models from the 15 given: Volkswagen Polo, Peugeot e-208, Renault Clio Hybrid	ICEV, BEV, HEV	150,000 km	ReCiPe, GREET	EU
20	Yang L. et al. (2021) [46]	Passenger cars	Toyota Corolla, Nissan Leaf, Toyota Corolla Plug-in	ICEV, BEV, PHEV	150,000 km	GREET	China

Table 5. *Cont.*

N°	Authors	Vehicle Type	Vehicle Models	Propulsion Type	Functional Unit	Assessment Methods	Region
21	Lie K. W. et al. (2021) [28]	Buses	Volvo 7900 Electric	BEV, HEV, PHEV	1 pkm	Input–output based (IO-LCA)	Norway
22	Garcia A. et al. (2021) [47]	Buses	MAN Lion's City, Volvo 7900 Hybrid, BYD 12 m Electric	ICEV, BEV, HEV	1 pkm	GREET	Spain
23	Ellingsen L. et al. (2022) [48]	Buses	-	BEV, ICEV	1 km	CML-IA	Norway
24	Farzaneh F. and Jung S. (2023) [49]	Van	Ford Transit, Ford E-Transit, Mercedes Sprinter 2500, Lightning ZEV3	ICEV, BEV	1 km	Own algorytm with CF coef.	USA

Methodological assumptions also played a crucial role in the study results, as they included various approaches to defining system boundaries, functional units, and the life cycle stages of vehicles considered in the analyses. Based on the literature review presented in Table 5, the most commonly used functional unit in Life Cycle Assessment (LCA) for passenger vehicles is kilometers traveled or 100 km. For buses, which carry a larger number of passengers, the unit 1 pkm (passenger-kilometer) is used, reflecting the distance traveled by a single passenger. This approach allows for a more accurate estimation of environmental impact by taking into account the efficiency of transporting a higher number of people. For trucks, various functional units are used depending on the research purpose, often incorporating both cargo weight and distance traveled.

The most frequently used method was GREET, applied in nine articles. The ReCiPe and CML2001 methods were each used in four studies. Other methods include IPCC, IMPACT2002, LCA ISO/TS 14067:2018, and PAS 2050. Each method has specific assumptions and approaches to Life Cycle Assessment, which affect the results obtained and their applicability in different regions.

Studies on vehicle carbon footprint analysis have been conducted in various regions, taking into account their specific environmental, regulatory, and energy-related conditions. In China and the USA, countries with high emission levels and intensive use of combustion vehicles, these studies are often driven by the need to reduce emissions in response to the growing number of vehicles and their impact on air quality and public health. In contrast, in the European Union, where detailed regulations on emission reduction and sustainable development are in place, many studies focus on the electrification of transport and its impact on GHG emissions. Europe, in particular, emphasizes the implementation of low-emission transport technologies, which support the objectives of the European Green Deal.

4.2. Determinants for Assessing the Carbon Footprint of Electric Vehicles Considering the Whole Life Cycle of the Vehicle

Tables 6 and 7 provide a detailed overview of the determinants of the carbon footprint for electric vehicles and the main results of GHG emission analyses. The division of the tables into two parts—separately for passenger vehicles and for trucks, buses, and vans—reflects differences in the usage characteristics, function, and environmental impact of these vehicles.

Table 6 provides a detailed overview of the results of studies on the carbon footprint of electric passenger vehicles, focusing on the main determinants of greenhouse gas emissions and the system boundaries considered in the analyses. The findings of these studies emphasize that the most important factor affecting the total carbon footprint of BEVs is the vehicle's use phase, specifically emissions related to battery charging, which depend on the energy sources used to generate electricity.

The charging phase during vehicle use has the greatest impact on the carbon footprint of BEVs, as emissions are directly tied to the energy mix of the given region. Some studies (e.g., Girardi P. et al., 2015 [31]) indicate that even with a relatively high share of fossil fuels in the energy mix, BEVs can still generate a lower carbon footprint than ICEVs.

The production of Battery Electric Vehicles (BEVs), particularly the battery manufacturing process, has a significant impact on total greenhouse gas emissions. Production processes, such as the extraction and processing of metals (e.g., lithium, nickel, cobalt), are emission-intensive and place a burden on the environment. For instance, in the study by Qiao Q. et al. (2017) [35], it was shown that the production of electric vehicles with NCM (nickel-cobalt-manganese) batteries generates approximately 14.6 tons of CO_2, which is 59% higher than that for ICEVs. This higher footprint is mainly due to the energy-intensive processes involved in mining and refining these metals. Additionally, as battery capacity increases to extend the vehicle's range, the demand for raw materials and energy during production rises, further elevating emissions. Reducing these emissions would require both advancements in battery recycling to reuse critical metals and a shift toward renewable energy sources in the manufacturing process.

Most studies in the table include a full life cycle analysis of the vehicle, which allows for consideration of all stages—from production through use to end-of-life disposal. Additionally, seven publications focus on the well-to-wheel approach, highlighting the importance of analyzing the entire fuel life cycle.

Table 7 describes the determinants of the carbon footprint and the main results of greenhouse gas emission analyses for commercial vehicles, such as trucks, buses, and vans. For these vehicles, the main factors influencing total emissions differ from passenger vehicles due to their specific usage characteristics and higher environmental load.

For buses, particularly electric ones, the charging phase and electricity sources are crucial for the total carbon footprint. For instance, in the study by Harris A. et al. (2018) [37], it was shown that electric buses can reduce greenhouse gas emissions by 10–58% compared to traditional diesel buses, depending on the energy mix of the region. Regions with a higher share of renewable energy in their grid see the greatest reductions, as the emissions from electricity generation are significantly lower. However, the life cycle costs for electric buses can be significantly higher due to the expensive battery production and infrastructure requirements, which becomes an important economic factor in assessing their sustainability and feasibility for large-scale adoption.

Table 6. Determinants of the carbon footprint assessment of electric passenger vehicles.

N°	Authors	Propulsion Type	Analysis Results	Carbon Footprint Determinants	System Boundary
1	Gao L. et al. (2012) [27]	ICEV, BEV, HEV, PHEV, FCEV	Electric vehicles (EVs), hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs) enable a reduction in energy consumption and emissions throughout their entire life cycle.	The greatest impact on GHG emissions for ICEVs, HEVs, and PHEVs comes from vehicle operation, while for BEVs and FCEVs, fuel supply plays a significant role.	Well-to-wheel, Cradle to grave
2	Hawkins T. R. et al. (2012) [29]	ICEV, BEV	BEVs reduce GWP by 20–24% compared to gasoline (ICEVs) and by 10–14% compared to diesel ICEVs, assuming a vehicle lifetime of 150,000 km.	Use phase directly through fuel combustion or indirectly during electricity production.	Cradle to grave

Table 6. *Cont.*

N°	Authors	Propulsion Type	Analysis Results	Carbon Footprint Determinants	System Boundary
3	Girardi P. et al. (2015) [31]	ICEV, BEV	Although electricity in Italy comes from fossil fuels, BEVs are able to reduce GHG.	Battery manufacturing for BEVs is a major contributor to their GHG emissions.	Cradle to grave
4	Onat N. C. et al. (2015) [32]	ICEV, BEV, HEV, PHEV	In a scenario based on the average energy mix, EVs are the least carbon-intensive vehicle option in 24 states, while HEVs are the most energy-efficient in 45 states.	The operation phase had the greatest impact on GHG emissions among all vehicles studied.	Cradle to grave
5	Tagliaferri C. et al. (2016) [33]	ICEV, BEV, HEV	The ICEVs' use phase greenhouse gas emissions are 50% higher than those of BEVs.	Use phase, exploitation of precious metals and production of chemical used in the battery manufacturing phase.	Cradle to grave
6	Qiao Q. et al. (2017) [35]	ICEV, BEV	CO_2 emissions from vehicle production for an EV with an NCM battery are around 14.6 tons, which is 59% higher than the 9.2 tons for an ICEV. For an EV with an LFP battery, emissions are slightly higher at 14.7 tons, marking a 60% increase compared to an ICEV.	CO_2 emissions from active material production are the most influential variable for both LFP and NCM batteries.	Cradle to grave
7	Mierlo J.V. et al. (2017) [36]	BEV, HEV, PHEV, EREV	As the level of electrification increases—from hybrids (HEVs) to plug-in hybrids (PHEVs), extended-range electric vehicles (EREVs), and fully electric vehicles (BEVs)—the life cycle CO_2 emissions of these vehicles systematically decrease.	Manufacturing for electric vehicles. For PHEV, the mining of nuclear, coal, and fossil fuels in the fuel supply chains.	Cradle to grave
8	Rosenfeld D. C. et al. (2019) [38]	ICEV, BEV, PHEV, HEV, FCEV	The production process of FCEVs and EVs can have a GWP as high as 50%, but over a 200,000 km lifetime, their GWP is 45% lower for EVs and 35% lower for FCEVs compared to ICEVs.	For HEVs and gasoline ICEVs, the use phase has the highest GHG impact; for FCEVs, it's fuel production, and for PHEVs, vehicle production dominates.	Well-to-wheel
9	Jursova S. et al. (2019) [9]	ICEV, BEV	The value of carbon footprints of electric vehicles in the Czech Republic is expected to decrease between 2015 and 2050. Electric vehicle charging from mixed electricity sources in the Czech Republic resulted in reductions in carbon footprints and increases in water footprints.	Electricity for BEV.	Cradle to grave

Table 6. *Cont.*

N°	Authors	Propulsion Type	Analysis Results	Carbon Footprint Determinants	System Boundary
10	Qiao. et al. (2019) [39]	ICEV, BEV	In 2015, an EV's life cycle GHG emissions were about 41.0 t CO_2eq, 18% lower than an ICEV. This is expected to drop to 34.1 t CO_2eq by 2020 due to lower GHG emissions from electricity.	The largest impact on GHG emissions for EVs comes from the electricity generation phase (WtW).	Well-to-wheel, Cradle to grave
11	Bekel K. and Pauliuk S. (2019) [40]	ICEV, BEV, FCEV	BEVs achieve lower GWP than FCEVs (e.g., BEV: 1.40E−01 kg CO_2-eq/km, FCEV: 1.68E−01 kg CO_2-eq/km)	Fuel supply infrastructure for BEV and FCEV.	Well-to-wheel, Cradle to grave
12	Petrauskienė K. et al. (2020) [42]	ICEV, BEV	In 2015, BEVs powered by the existing electricity mix produced 26% more GHG emissions than gasoline ICEVs and 47% more than diesel ICEVs.	Use phase for BEV.	Well-to-wheel, Cradle to grave
13	Wong E. Y. C. et al. (2020) [43]	ICEV, FCEV, BEV	The most carbon-intensive method is hydrogen produced from distributed grid electricity, while the least carbon-intensive method is hydrogen from central biomass with liquid truck delivery and gaseous dispensing. Centralized wind electrolysis also offers low emissions, making it a more sustainable option compared to grid electricity.	Fuel consumption phase for ICEV.	Well-to-wheel
14	Candelaresi D. et al. (2021) [44]	FCEV, H2-ICE, HEV H2-IC,E CNG, HEV CNG, Hythane, H2-Gasoline	Hydrogen-powered vehicles contribute the most to the decarbonization process, but vehicle infrastructure was highlighted as the primary source of environmental impact.	For hydrogen-powered vehicles, the vehicle infrastructure had the greatest impact.	Well-to-wheel
15	Pipitone E. et al. (2021) [45]	ICEV, BEV, HEV	Throughout its life cycle, a BEV generates about 60% of global warming emissions compared to an equivalent ICEV, but its acidifying and particulate matter emissions are twice as high.	For ICEVs and HEVs, the use phase has the highest GHG impact due to fuel combustion. For BEVs, production, especially battery manufacturing, dominates GHG emissions.	Cradle to grave
16	Yang L. et al. (2021) [46]	ICEV, BEV, PHEV	Compared to internal combustion engine vehicles (ICEVs), battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) have the potential to reduce CO_2 emissions.	Fuel production for ICEV and PHEV. Electricity generation for BEV.	Cradle to grave

Table 7. Determinants of carbon footprint assessment of electric buses, trucks and vans.

N°	Authors	Propulsion Type	Analysis Results	Carbon Footprint Determinants	System Boundary
1	Cooney G. et al. (2013) [30]	ICEV, BEV	The study shows that the use phase, involving diesel combustion for conventional buses and electricity production for electric buses, dominates most impact categories, while battery production significantly contributes to global warming, carcinogenic emissions, ozone depletion, and ecotoxicity.	Use phase for ICEV and electricity for BEV.	Cradle to grave
2	Zhao Y. et al. (2016) [34]	ICEV, HEV, CNG, BEV	Based on the national average electricity mix, battery electric trucks generate more GHG emissions over their life cycle than other trucks, despite having no tailpipe emissions. Among diesel, hybrid, CNG, and electric vehicles, hybrid trucks produce the least GHG emissions.	Fuel Consumption for BEV.	Well-to-wheel
3	Harris A. et al. (2018) [37]	BEV, ICEV	In a scenario involving battery electric buses, there is an 80% likelihood that life cycle greenhouse gas (GHG) emissions decrease by 10–58% when compared to traditional diesel buses. Nonetheless, life cycle costs are projected to be 129–247% higher.	GHG emission is dependent on the electricity generation source.	Cradle to grave
4	Chang C. et al. (2019) [41]	ICEV, LNG, LPG, FCEV, PHEV	Replacing diesel buses with LNG increases the carbon footprint by 16%, while using liquefied petroleum gas reduces it by 13%. Hydrogen fuel cell buses cut the carbon footprint by 47%, and plug-in electric buses by 31%. Only hydrogen and plug-in electric buses align with greenhouse gas reduction goals. Switching all Taiwan's city buses to hydrogen fuel could reduce emissions by 227,832 tons CO_2e annually.	Fuel manufacturing stage for FCEV and PHEV. Bus service stage for ICEV, LNG buses and LPG buses.	Cradle to grave
5	Lie K. W. et al. (2021) [28]	BEV, HEV, PHEV	The carbon footprint of a bus fleet was reduced by 37% through the introduction of biofuel and electric buses. An additional 52% reduction can be achieved with full electrification using the Nordic charging energy mix.	GHG emission is dependent on the electricity generation source.	Well-to-wheel
6	Garcia A. et al. (2021) [47]	ICEV, BEV, HEV	Hybrid buses reduce CO_2 emissions by 40%, while electric buses achieve a 60% reduction, both measured per passenger-kilometer traveled.	TtW (tank-to-wheel) phase for ICEV and HEV. WtT (well-to-tank) phase for BEV.	Cradle to grave

Table 7. *Cont.*

N°	Authors	Propulsion Type	Analysis Results	Carbon Footprint Determinants	System Boundary
7	Ellingsen L. et al. (2022) [48]	BEV, ICEV	The plug-in bus with a 400 kWh lithium iron phosphate (LFP) battery exhibits the highest impact across all categories, including the bus itself, battery, maintenance, battery replacement, electricity, and end-of-life stages. Extending the BEV lifespan from 10 to 20 years alters both environmental performances.	The highest emissions are for buses with large batteries (lithium iron phosphate 400 kWh), and the phases with the highest emissions are the use and replacement of batteries, especially with extended life cycles.	Cradle to grave
8	Farzaneh F. and Jung S. (2023) [49]	ICEV, BEV	The analysis for vans shows that electrification in Florida reduces the carbon footprint per vehicle by 22.6%. For EVs, raw material production is the major emitter, while for ICEVs, it's the operation phase. A lifespan sensitivity study found that with a 350,000 km lifespan, EVs become 48.1% more efficient compared to ICEVs.	Raw material to virgin input for BEV.	Cradle to grave

Trucks also generate significant emissions, especially during the use phase, where fuel consumption is the main source of emissions. The study by Zhao Y. et al. (2016) [34] found that electric trucks, despite having no tailpipe emissions, may have a higher total carbon footprint than their combustion counterparts due to the high carbon footprint associated with battery production and electricity generation in some energy mixes.

For vans, as highlighted in the study by Farzaneh F. and Jung S. (2023) [49], emission analysis showed that electrification in the state of Florida reduces the carbon footprint per vehicle by 22.6%. This reduction is influenced by Florida's evolving energy mix, which includes an increasing portion of renewables, helping to decrease emissions from electricity generation used for vehicle charging. In electric vehicles, the greatest impact on emissions comes from the production of raw materials for batteries, particularly due to the mining and processing of metals like lithium, nickel, and cobalt, which are both resource- and energy-intensive. Meanwhile, in combustion vehicles, the dominant emission phase is the use phase, where continuous burning of fossil fuels contributes directly to CO_2 and other greenhouse gas emissions. This difference underscores the potential benefits of transitioning to electric vans, especially in regions that continue to expand their renewable energy infrastructure.

The battery recycling process plays a crucial role in reducing the carbon footprint (CF) at the end of the life cycle of electric vehicles (EVs). According to Li et al. (2022) [50], the choice of recycling method significantly impacts the overall CF. Hydrometallurgical processes, with lower energy demands, offer significant environmental benefits over pyrometallurgical methods, which produce higher emissions due to high-temperature requirements. Efficient recycling methods, such as hydrometallurgy, can greatly reduce the overall CF of EVs and enhance sustainability.

Shah and Kaka (2022) [51] highlight that alternative battery technologies, such as sodium-ion and redox flow (RF) batteries, can further lower the carbon footprint due to their more sustainable production and resource availability. Combining innovative battery technologies with advanced recycling methods can substantially reduce the CF of EVs throughout their life cycle.

5. Conclusions

This study presents an overview of methodologies for carbon footprint assessment, including a review of concepts, methods, and standards based on the life cycle approach. The review highlights that various carbon footprint assessment methods have been developed to date, making it challenging to standardize the results obtained by different methods. Currently, from the perspective of ESG reporting guidelines, also in the transport sector, the primary method for carbon footprint assessment is the GHG Protocol.

In many countries, alternative fuels are being introduced to mitigate climate change impacts. This study reviews literature on the life cycle carbon footprint of various electric vehicles, showing that the primary factor influencing the carbon footprint of electric vehicles is the production of electricity used to charge vehicle batteries. In countries where renewable energy sources make up a significant share of electricity, the environmental impact of electric vehicles is substantially lower. In such countries, the carbon footprint determinant for electric vehicles is the production of the battery and the vehicle itself. Battery production, particularly for larger vehicles including buses and trucks, generates considerable CO_2 emissions due to the energy-intensive processes of extracting and processing metals, making the production phase a critical stage for these vehicles.

For commercial vehicles, such as buses, different functional units, such as "passenger-kilometer" or "kilometer", are used to accurately estimate their environmental impact based on their specific functions. Despite ecological benefits, the life cycle costs of electric vehicles can be higher than those of combustion vehicles, which necessitates a cost-benefit analysis in assessing their sustainability.

This review highlights the need to consider the full life cycle and usage specifics when assessing the actual environmental impact, indicating the necessity of standardized analytical methods in the transport sector. Based on the conducted review, it is suggested that, to achieve full environmental benefits, efforts should focus on decarbonizing the energy sector, including increasing the share of renewable energy sources used for charging electric vehicles. Based on the analysis conducted by Burchart-Korol et al. (2018) [52], it can be stated that the source of electricity used for charging electric vehicles has a crucial impact on their total greenhouse gas (GHG) emissions. The study showed that in Poland, where 84.76% of electricity in 2015 came from fossil fuels, the carbon footprint of electric vehicles was significantly higher than in regions using renewable energy sources. These results indicate that decarbonizing the energy sector and increasing the share of renewable energy sources are essential to achieving the full environmental benefits of electric vehicle usage. By transitioning to renewable energy sources, such as wind or solar power, it is possible to significantly reduce CO_2 emissions associated with the operation of electric vehicles. Therefore, changing the energy mix towards renewable sources can be one of the most effective ways to lower the carbon footprint of electric transport.

There are also solutions that can reduce energy consumption in electric vehicles, such as vehicle lightweighting and strategies for optimizing energy management on board the vehicle. Sandrini et al. (2023) [53] analyzed the impact of lightweighting on energy consumption and found that reducing the vehicle's mass significantly improves energy efficiency, particularly in the context of limiting energy consumption in electric vehicles. Candela et al. (2024) [54] emphasized that using lighter materials and structures reduces the overall carbon footprint of vehicles by lowering energy consumption during the operational phase.

Moreover, the application of regenerative braking strategies can significantly enhance energy recovery, contributing to more efficient energy management in vehicles. Sandrini et al. (2023) [55] presented a regenerative braking logic which, when properly implemented, allows for up to 30% energy recovery during the WLTC driving cycle compared to a vehicle without this system, while also increasing vehicle stability during braking, which is crucial for safety.

The carbon footprint (CF) of fuel station infrastructure for conventional vehicles and charging stations for electric vehicles (EVs) is an essential element of life cycle analysis. Beloev et al. (2017) [56] demonstrated that the use of photovoltaic parks at fuel stations can reduce CO_2 emissions by up to 37%, depending on the scenario adopted. Similarly, as shown in the study by Faisal et al. (2024) [57], the use of renewable energy systems, such as photovoltaic or hybrid installations, to power EV charging stations can reduce the carbon footprint by 89.8%.

Integrating renewable energy sources into charging station infrastructure not only significantly minimizes environmental impact but also lowers operational costs, making this solution more economically viable in the long term. Findings highlight the necessity for further investment in sustainable energy technologies to reduce emissions associated with energy infrastructure. Increasing the share of clean energy sources and improving charging infrastructure will be crucial for promoting transport electrification and achieving decarbonization goals in the transport sector, bringing both environmental and economic benefits.

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