Clean Technologies and Environmental Policy (2024) 26:1631–1642
https://doi.org/10.1007/s10098-023-02588-y

ORIGINAL PAPER

Sustainability accounting for greenhouse gas emissions measurement using the GREET LCA model: practical review of automotive ESG reporting

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Received: 28 February 2023 / Accepted: 12 July 2023 / Published online: 4 August 2023

Abstract
The production and personal use of passenger vehicles contribute significantly to greenhouse gas (GHG) emissions, making personal transport a major contributor. In response to increasing pressure from regulators and consumers to lower emissions, original equipment manufacturers (OEMs) have introduced alternative powertrains, such as battery electric vehicles (BEVs). To assess the economic and environmental feasibility of BEVs, OEMs conduct various life cycle assessment (LCA) approaches as part of their internal management practices. However, the public presentation of their results is often ambiguous and of unverifiable quality. This study conducts a review of sustainability impact reporting using the GREET model, which is based on the total vehicle life cycle. The paper provides a summary of the input data requirements for validating emissions from both the fuel and vehicle cycles as part of the proposed model. The availability of the model components was tested against actual public corporate environmental, social and governance reporting disclosures of the largest global automotive OEMs, indicating a deficit in the public presentation of essential sustainability information. The implications of the research suggest that LCA models could benefit sustainability accounting by incorporating proper tagging during accounting practices and taking advantage of digital accounting and reporting practices such as the extensible business reporting language (XBRL). By further developing the model, sustainability reporting can benefit from its structure and workflow, thus ensuring improved information validity for stakeholders.

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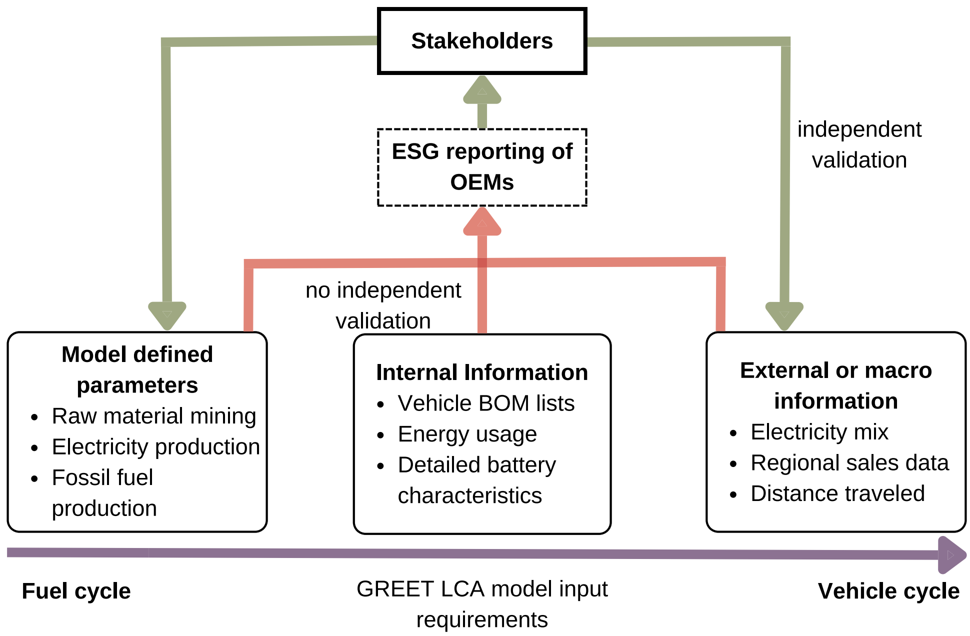
Graphical abstract



Keywords Sustainability accounting · ESG reporting · Life cycle assessment · GREET · Battery electric vehicles · Automotive

Introduction

As environmental sustainability becomes an increasingly important part of our lives, mobility and transport are on the verge of a radical change in the technologies currently used. Daily transport, whether personal or commercial, is largely based on passenger cars and light commercial vehicles, which produce 12% of the EU's total CO_2 emissions, exacerbating the climate impact of the most widely emitted greenhouse gas (GHG) (European Commission 2021a). To reduce emissions, alternative powertrains are being brought to market to replace the internal combustion engine vehicles (ICEVs) used today (Slowik and Lutsey 2016). The main alternative powertrains to ICE are plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and, more recently, hydrogen fuel cell vehicles (HFCVs), which have both important advantages and disadvantages from a sustainability perspective (Ball et al. 2021). The introduction of alternative powertrains brings with it a paradigm shift in the fuel consumption of vehicles—although the alternative powertrain vehicles themselves do not produce harmful greenhouse gases, the underlying energy mix and production processes remain major sources of harmful emissions (Pipitone et al. 2021). To accurately compute and compare total emission impact, the production and use phases of new vehicles should be differentiated as a theoretical consideration. The environmental impact can be measured for the two significant phases in the case of different vehicle models using full life cycle assessment (LCA) methods (Ball et al. 2021).

LCA is a methodology that focuses on calculating emissions throughout the total life cycle of a given object. The range of objects that have been studied in the previous LCA studies has varied from food products to buildings to motor vehicles (De Benedetto and Klemeš 2009). The LCA methodology in several previous contributions regarding vehicles differentiated the production and use phases (Puig-Samper Naranjo et al. 2021; Wong et al. 2021). The first stage involves calculating the total emissions of the fuels used from production to use, while the second stage calculates the total emissions of the vehicles considered, from the extraction of the various raw materials (mostly metals) used in their production to the end of the average life of the vehicle (Pero et al. 2019). LCA should, therefore, reflect real gross emissions data that, for accurate representation, require a large amount of internal corporate data about the vehicles and the exact emissions data of the technologies used. Original equipment manufacturers (OEMs) must provide their gross emission data and prove that the emissions from their production processes are within legal limits (European Commission 2021b).

The accurate sustainability reporting for emissions from production processes and vehicle emissions must be supported by trustworthy data sources. So far, no comparative research has been done on the technical underpinnings of the audited emission disclosures and the analysis of underlying methodological features. If the reported information is not internally generated by OEMs (Scopes 1 and 2) or not supervised and validated on the supply chain (Scope 3), it can only be considered an assumption. In the absence of reliable and clean data, external parties cannot validate sustainability information as part of decision-making (Tóth et al. 2022). There is, therefore, a strong need to review the exact data requirements of the LCA models involved and compare them with the quality and quantity of data published by OEMs.

The current paper collected data on the best-selling BEV models in 2021 to systematically review the reported complementary information to GHG emission performance. As this indicator is primarily a function of the number of vehicles produced and sold by car manufacturers, a qualitative content analysis was carried out to review the input data required by the technical structure of the Greenhouse gases, Regulated Emissions and Energy use in Technologies (GREET) model (Wang et al. 2022). Through the model input criteria and default assessment process, the manufacturing and use phase emissions of passenger cars can be accurately simulated for both the upstream and downstream activities (Wang and Cheng 2018). The novelty of the paper, therefore, can be attributed to its use of a widely used LCA modeling technique for the purpose of sustainability accounting, which contributes to the previous studies on sustainable manufacturing initiatives (i.e., Bhanot et al. 2016) by increasing the transparency and comparability of corporate reporting for CO_2 emissions. To do so, the research provides a content analysis of the current emission data provided by the selected OEMs, as well as their current LCA methodologies implemented. Furthermore, a possible pathway for improvement in terms of disclosing quality information was explored concerning the environmental effect of BEV production. The structure of the paper follows a review of the relevant literature, the presentation of the research methodology, results on the input data criteria of the GREET model and the analysis of corporate ESG reports, followed by discussion and conclusions.

Literature review

The use of LCA in the case of alternate powertrain vehicles is broad and varies greatly in terms of its methodological approach. Previous contributions were reviewed with the aim to determine the data needs of an LCA model, to be subsequently used with collected corporate data during the analysis. Scientific and business sources were reviewed in the cross section of LCA (and related synonyms, e.g., life cycle analysis, lifetime emissions and well-to-wheel emissions), and results were limited to a variety of commercial ground vehicle categories (e.g., passenger cars, personal vehicles, automobiles and SUVs).

Use of LCA models for assessing emission impact of BEV manufacturing

In many cases, studies conducting LCA did not use previously developed frameworks or software to conduct such an analysis. Instead, own models were being used aimed at computing the gross life cycle emissions of a selected product or production process (Hawkins et al. 2013; Girardi et al. 2015; Bauer et al. 2015; Puig-Samper Naranjo et al. 2021). For BEVs, life cycle emissions have often been compared with other powertrains, in particular PHEVs, and assessed considering the effects of indirect emissions. The varying results in terms of reported emission differences under specified conditions are presented in Table 1.

The scope of some of the papers was limited by the geographical location of the analyses or by the specific focus of the LCA models. For the European region, most of the studies concluded that the lifetime emissions of a PHEV are higher than those of a BEV, based on the European energy generation mix (Puig-Samper Naranjo et al. 2021; Alonso-Villar et al. 2022). However, BEVs have a higher human toxicity potential, i.e., their life cycle operation emits the highest amount of potentially toxic substances into our environment, mainly related to battery production and the vehicles' decomposition phases. In addition to human toxicity, the life cycle carbon emissions of BEVs, despite their zero-emission drivetrain, are highly dependent on the energy mix. For example, in Norway, a BEV can operate with more favorable emissions, while in Poland, a PHEV and even an ICEV have better lifetime emissions than a BEV, because about 70% of Poland's electricity generation is based on coal-fired power plants (Pipitone et al. 2021). Similar results were obtained in China by Yu et al. (2018), wherein the traditional ICEV exhibited superior gross emission outcomes and lower global warming potential (GWP) compared to BEVs.

Some contributions used commercially available LCA software such as GaBi (Herrmann and Moltesen 2015; Kalverkamp et al. 2020), which was developed and distributed worldwide by Sphera (formerly Thinkstep or PE). Its software tools include a user interface for modeling the product system, a database of life cycle unit processes, an impact assessment database with data supporting several life cycle impact assessment methodologies and a calculator that combines figures from the databases according to the modeling of the product system in the user interface (Herrmann and Moltesen 2015).

Table 1 Main findings of alternate passenger vehicle LCA studies by incorporated methodologies (own editing)

Methodology	Main findings	References
Drivetrain emission comparisons by geographic area	The life cycle emission is mostly dependent on the energy mix of the location	
Europe	PHEVs or ICEVs have higher emissions than BEVs	Perez-Neira et al. (2020), Pipitone et al. (2021), Chanaron (2007), Puig-Samper Naranjo et al. (2021), Alonso-Villar et al. (2022), Bauer et al. (2015)
Asia	BEVs have higher emissions than PHEVs or ICEVs	Sim and Sim (2017), Wang et al. (2015), Hwang et al. (2013), Yu et al. (2018)
America	PHEVs or ICEVs have higher emissions than BEVs	Tamayao et al. (2015), Dunn et al. (2015)
Fuel production analyses	The production of batteries causes emission increase regardless of location, while electric generation's pollution is highly dependent on location	Hwang et al. (2013), Evangelisti et al. (2017), Elgowainy et al. (2013)
Fuel type-based comparison	Importing ethanol from the US, China lowers emissions; BEV battery production leads to significantly higher emissions	Ding et al. (2013), Agostini et al. (2021)
Other LCA studies	Optimizing processes, improving emission databases and reducing vehicle mass are key in emission lowering	Delogu et al. (2016), Del Pero et al. (2017), Dhingra and Das (2014)

A widely used open-source alternative for automotive LCA case study methodologies was found to be the GREET model, developed by the US Argonne National Laboratory (Wang et al. 2022). The implementation of Ahmed et al. (2023) computed emission data for BEVs using different electric generation mixes, which illustrated the flexibility of the model from the aspect of the two life cycle phases; while Wong et al. (2021) used the model to compare the total LCA results of different powertrains in passenger vehicles. In comparison, GREET was found to offer greater transparency compared to GaBi and was freely accessible to all users, aligning with the research's objective of ensuring transparency within this domain. However, it is important to note a significant limitation highlighted in the studies conducted by Yu et al. (2018) and Ambrose et al. (2020), which pertains to the limited availability of data regarding vehicle mileage and battery characteristics. The absence of these crucial elements, combined with the lack of internal corporate information, raises questions about the accuracy of the LCA calculations. Consequently, this underscores the need for enhancements in LCA reporting practices and the disclosure of gross emission data, as elaborated in the subsequent section.

Reporting for drivetrain-specific emission elements

The reporting of drivetrain-specific emission elements is a key step in reaching transparent and accurate ESG reporting practices. In recent years, reporting on sustainability elements has evolved significantly as the International Accounting Standards Board (IASB) has issued an Exposure Draft of proposed amendments to International Financial Reporting Standards (IFRSs) (IFRS Foundation 2022). The amendments are intended to improve the consistency and comparability of the accounting for service concession arrangements, with respect to the recognition of construction obligations and the timing of revenue recognition. OEMs have incorporated these, and the general concept of GHG reduction, into their business models; BMW AG (2022) claimed that reducing CO_2 emissions is a key factor in formulating its strategy. Similarly, Audi AG (2022) declared the introduction of net-zero emission passenger cars as an important element of its carbon neutrality strategy. Hyundai Motor (2022), on the other hand, placed greater emphasis on the production of hydrogen fuel cell vehicles, alongside its prominent BEV sales results. Although the BEVs and HFCVs have "net-zero" emissions during their service life, the indirect emissions associated with them may lead to worse life cycle emissions than those of traditional ICEVs (Pipitone et al. 2021). At the same time, the reporting practices of the OEMs are not always convergent with the previously mentioned principles and declarations, showing that there should be a unified system for emission reporting.

In the case of BEVs, it is important to consider the emissions associated with the production and use of the vehicles. For example, emissions of toxic materials during battery production can account for around 23–34% of the total harmful emissions over the life cycle of a BEV (Ellingsen et al. 2016). The emissions to be considered during the use phase, even in the case of net-zero CO_2 emission vehicles (as claimed by manufacturers), the indirect emissions from the generation of the electricity used to charge the vehicles, larger or smaller amounts of emissions are indirectly associated with the use phase of BEVs.

Although energy consumption and thus CO_2 emissions are significantly influenced by driving strategies (Pusztai et al. 2022), the amount of emissions depends mainly on the electricity generation mix of the geographical location where the vehicle is used (Woo et al. 2017). For OEMs to report transparently and accurately their gross Scope 3 emissions, the inclusion of LCA in their reports and calculations would be a highly important element. In the current practice, LCA methodologies in reports are already present, but the limited amount of public data and methodologies does not allow the level of transparency anticipated by stakeholders.

As for regulations on LCA calculations, the corporate use of LCA and accounting for GHGs are connected to the United Nations Sustainable Development Goals 13 ("Take urgent action to combat climate change and its impacts") and its fifth target of promoting mechanisms to raise capacity for planning and management. The goal aims at achieving more transparent corporate social responsibility, however, does not define the technical requirements to do so (United Nations 2015). Similarly, the ISO 14001 and 14040/44 standards contain the definition of the objective and scope of LCA, and the conditions for the use of value choices and optional elements, but only as guidelines (Panagiotakopoulos et al. 2015). There also exist permitted corporate practices that influence accounting disclosures, such as carbon offsets that allow products and production processes to be classified as net-zero for accounting purposes by the voluntary purchase of CO_2 emission-negating certificates (Koronka et al. 2022), which do not reflect reality in terms of GHG emissions. In the following chapter, the research methodology is elaborated in depth.

Methodology

The research methodology was developed in several steps in accordance with the research objectives. The GREET model was identified as an appropriate, open-source and comprehensive methodological grounding for the sustainability accounting evaluation based on the findings of the literature review. To ensure an unbiased LCA methodology, the GREET model was preferred, as it is an independent model (e.g., in the role of carbon offsets) that has no links to any car manufacturer. The analysis of the GREET model was carried out in Sect. "Main data requirements of the GREET LCA model," where the required data input categories were described qualitatively to simplify the understanding of the model, of which the parameters are illustrated in Fig. 1. The GREET 1 fuel cycle and the GREET 2 vehicle cycle, which are the two components of the model, were analyzed based on the MS Excel spreadsheet variant of the model, obtained from the developer institution, the Argonne National Laboratory (Wang et al. 2022).

Subsequently, selection criteria for data collection were developed for the sustainability reports. The sample of global automotive brands that manufacture and sell BEV models was selected based on the companies with the 10 highest BEV sales (by unit) in 2021 (Statista 2023), and their annual ESG (integrated or sustainability) reports were retrieved from official sources. The sustainability reports of six companies that had public information on LCA methodology in their reports were further analyzed. The reason to do so was that sustainability reports and

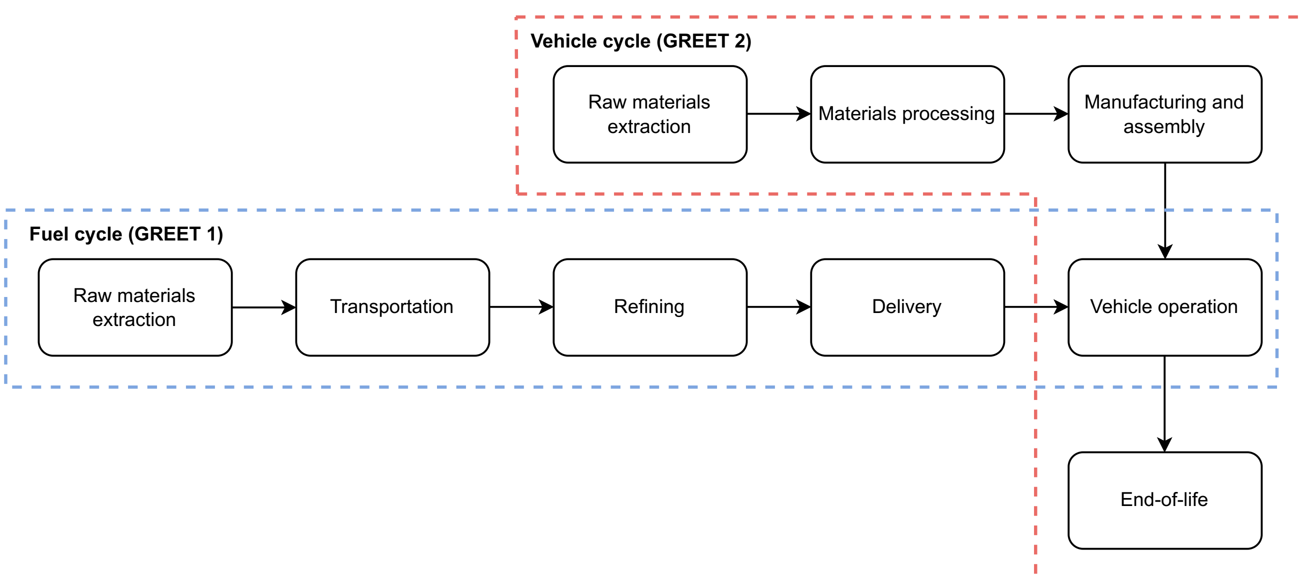


Fig. 1 The two cycles of the GREET model (based on Ahmed et al. 2023)

their complementary material (appendices and external references) are the main channels of communication between companies and their stakeholders (European Commission 2022). Table 2 presents the sample of companies and their main information.

The LCA methodologies applied by the companies and potentially involved third-party providers were reviewed in order to gain insight into possible methodological differences in company practice in Sect. "Applied LCA emission models by BEV manufacturing companies." In Sect. "Comparison of data provided with the data needs of the model," the content of the overall ESG reports was compared with the previously reviewed user-defined input data requirements of the GREET model. This comparison was carried out by reviewing the actual textual data (report content) from a qualitative aspect. The identification of input variables was conducted using a systematic qualitative examination that involved the utilization of screening tables encompassing relevant indicators and keyword searches performed within the textual sections of the documents. This structured approach ensured a comprehensive evaluation of the reports, enabling the identification and assessment of the presence or absence of the specified input variables. After obtaining information on the status of reporting, the main conclusions were drawn on the working method of LCA models and their role in the current regulation of sustainability reporting.

Results

The results section comprises three subsections, each presenting different analyses. The first subsection provides a summary of the GREET model, which is presented in two tables that analyze the categories of the two cycles of the GREET model and their input data requirements. The second subsection involves an analysis of the sustainability reports of a sample of BEV manufacturing OEMs. The LCA methodologies implemented by the companies were examined, and the findings were presented in a summary table that showed the methodologies, the standards applied and the sources used by the OEMs to present the analyses. In the third subsection, a qualitative content analysis was conducted to compare the data requirements of the GREET model against the companies' sustainability reports. The results of the comparison were summarized in a table.

Main data requirements of the GREET LCA model

Tables 3 and 4 demonstrate a review of the main user input parameters to both the fuel cycle and vehicle cycle model components from a user perspective. The purpose of this contribution was to collect and systemize the input categories of the model to reduce its complexity. The input variables were categorized into model-defined parameters and user-defined parameters, with a brief description provided for each input category to facilitate accurate LCA analysis.

The GREET 1 model component provides a complete well-to-pump analysis of the emissions of various fuels used in transport, including electricity generation, natural gas fuels and different types of petroleum-based fuels such as diesel and petrol. The GREET 1 takes into account the type of vehicle used in the simulation and allows customization of not only the parameters of different fuels but also the locations of the extraction and fuel production processes, as well as process losses due to production storage or fuel. The model also includes feedstock-related emissions for plant-based fuels such as ethanol or rapeseed oil. The GREET 1 comprises nineteen main input categories, which are primarily user selection from default dropdown lists or fully model-defined parameters, as presented in Table 3.

Almost all different fuel pathway parameters in the model are provided with default assumptions which can be

Table 2 Sample of automotive OEMs (own editing, based on OEM 2021 annual reports)

Rank	OEM	Sold BEV units, 2021	Disclosed CO_2 emission/vehicle (gCO_2 e/km)	Disclosure of LCA model used	References
1	Tesla Motor Co	936,222	101.25	Available	Tesla (2022)
2	BYD Auto Co	320,810	Not available	Not available	BYD (2022)
3	SGWA (SAIC-GM-Wuling Automobile)	456,123	Not available	Not available	Statista 2023
4	Volkswagen AG	427,946	147	Available	Volkswagen (2022)
5	BMW AG	103,854	115.9	Available	BMW (2022)
6	SAIC Motor	226,963	Not available	Not available	Statista 2023
7	Volvo Group	189,115	Not available	Not available	Volvo (2022)
8	Hyundai Motor Co	141,000	109.7	Available	Hyundai (2022)
9	Mercedes-Benz AG	90,082	115	Available	Mercedes (2022)
10	Audi AG	85,379	122	Available	Audi (2022)

Table 3 GREET 1—Fuel cycle model component's model-defined input parameters (own editing)

Ref	Model-defined input categories	Description
G1/3	Petroleum-based fuels	Definition of fuel production and characteristics in detail: plant design; source area; type of raw fuel; composition and type of fuel product
G1/4	Natural gas to compressed natural gas (CNG), liquefied natural gas (LNG) and liquefied petroleum gas (LPG)	
G1/5	Natural gas, biomass and coal to methanol (MeOH), dimethyl ether (DME), Fischer–Tropsch diesel (FTD) and Fischer–Tropsch naphtha (FTN)	
G1/6	Hydrogen production	
G1/7	Assumptions regarding boil-off effects of LNG and liquid H2	
G1/13	Default key assumptions for well-to-pump activities (GREET 1 reference)	Definition of energy efficiency
G1/14	Fuel economy and emission rates of baseline vehicles: gasoline-equivalent MPG and grams/mile emissions	Listed emission data sorted by GHGs
G1/15	Fuel economy and emission changes by alternative-fueled vehicles and advanced vehicle technologies	
G1/16	Fuel economy, electricity consumption and operational all-electric range vs. rated all-electric range of grid-connected PHEVs	
G1/17	Fuel economy, payload and emissions (grams/mile) of baseline heavy-duty vehicles and relative changes by alternative-fueled heavy-duty vehicles and advanced vehicle technologies	

Table 4 GREET 2—Vehicle cycle model component's user-defined input parameters (own editing)

Ref	User-defined input categories	Description
G2/2	Specification of total vehicle weight, pounds	Providing the weight of batteries (in pounds)
G2/3	Vehicle battery and fluids weight, pounds per vehicle	Providing the weight of vehicle fluids (in pounds)
G2/4	Key input parameters for vehicle components: body, powertrain system, transmission, etc.	Providing the weight of vehicle parts (in pounds) and the specification of other parts (e.g., battery capacity in kW, etc.)
G2/5	Key input parameters for batteries	Providing detailed data about the batteries and selecting the alternative drivetrain type (PHEV, BEV, etc.)
G2/6	Key input parameters for fluids	Providing detailed data about the composition of the used fluid
G2/7	Default key assumptions for vehicle assembly	Emission data of assembly and disposal
G2/8	Lifetime VMT of a vehicle, miles	Providing the assumed lifetime VMT in miles
G2/9	Ratios of fuel economy of chosen conventional vehicles relative to their baseline vehicles	Ratios provided by GREET
G2/10	Ratios of fuel economy of lightweight material vehicles relative to their conventional material vehicles counterpart	

modified by the user to achieve a more accurate simulation. Specific measured data can be used to provide accurate model-defined alternatives for missing elements. User input can overwrite all model-defined parameters except those imported from the GREET 2 model component, which is not explicitly controlled by the user. For example, the energy mix of the simulated area can be manually specified, or a specific region previously calculated by the model can be selected for energy mix generation.

In addition to the life cycle emissions of the fuel used, the GREET 2 model component, as presented in Table 4, includes the steps to simulate the vehicle cycle. Parameters imported into GREET 1 are included in this part of the model. The GREET 2 model component has ten main inputs with model-defined parameters, but internal company data are also required to simulate life cycle emissions accurately for a specific vehicle or vehicle category. Table 4 presents user-defined parameters that are crucial for achieving company-specific LCA results.

The data requirements for the vehicle cycle are largely associated with the bill of materials (BOM) lists of the vehicles, which outline the particular materials and processes utilized in the construction of the simulated vehicles. Consequently, it can be inferred that a fully precise LCA calculation cannot be carried out without knowledge of the precise composition of the vehicles.

Applied LCA emission models by BEV manufacturing companies

In this section, the LCA methodologies employed by OEMs to quantify carbon emissions in the production of BEVs are presented. This information is essential for deriving conclusions from the LCA comparison of OEMs based on the data provided in ESG reports since variations in methodologies can result in disparities. Table 5 provides an overview of the various LCA methodologies, standards and third-party providers disclosed by the OEMs.

Tesla and BMW have both used outsourcing to complete an LCA of their models; in the case of both manufacturers, the party providing the LCA analysis was Sphera, a German company that performs LCA and various environmental or sustainability-related analyses for corporate clients. The companies under consideration have claimed to utilize the GaBi LCA methodology, in conjunction with Sphera's database. However, the report lacks information concerning the calculation process and, in the case of BMW, the definition of the simulated vehicle model. This issue is particularly pronounced in the four additional LCA reports that were analyzed. Volkswagen, for instance, has outsourced this section of the report to TÜV Nord CERT GmbH, a German company, which employed a distinct methodology and database compared to BMW and Tesla. TÜV Nord relied on a database created by Volkswagen to perform their calculations. Mercedes-Benz, on the other hand, employed a different LCA methodology, based on ESSENZ, and relied on its database to calculate the lifetime emissions of a specific model. A specific methodology used by Hyundai Motor was not included in their report, nor was one mentioned as the basis for their calculations. It was stated by the company that their own methods and databases were used, based on the Environmental Product Declaration of the Ministry of Environment of South Korea. Among the six analyzed enterprises, the least data connected to their LCA calculations was provided by Audi. An estimated amount of cradle-to-grave emissions was presented in their report, and it was stated by the company that a methodology to conclude LCAs is presently being developed.

It can be inferred that the LCA calculations of all the companies examined were based on the fundamental principles of two ISO standards, namely, ISO 14040 and ISO 14044. Although these ISO standards provided a framework and concepts for calculating LCA emissions, they did not furnish exact and unified methodologies that would enable a comprehensive and comparable analysis of the firms' LCA results with quantitative methods. Tesla also noted that a discrepancy of about 5% in the outcomes could be anticipated when using two different LCA methods. This highlights the necessity of mandating companies to utilize the same methodologies and implement the same steps when calculating LCA emission figures. The section contended, cited and substantiated that sustainability reports cannot be compared without a common methodology, while the subsequent section examined whether the present reporting of the companies fulfills the data requirements of this common methodology.

Comparison of data provided with the data needs of the model

After the input needs of the two cycles of the GREET model and the company sustainability reports were analyzed, it was deemed reasonable to compare the results of the GREET model analysis with the data that were provided by the reports. The data in the sustainability reports were analyzed systematically and manually, with a search conducted through all the reports following the categories that were defined and examined in GREET 2 in the preceding section. The input categories required by the model component were analyzed, consisting of a total of 26 variables. Each variable contains information that included in the company reports would enhance the verifiability of the full emission impact of vehicle production. The presence of each variable was determined as a proportion of the total variables in all categories and is presented in Table 6, which provides a

Table 5 LCA methodology of the analyzed automotive OEMs (own editing, based on OEM 2021 annual reports)

OEM	LCA method	Standard	Third-party provider	Database	Source
Tesla Motor Co	GaBi DfX software	ISO 14040 and 14044	Sphera	GaBi	Tesla (2022)
Volkswagen AG	Own ISO-based LCA methodology	ISO 14040 and 14044	TÜV NORD CERT GmbH	Own database (LEAD)	Volkswagen (2022)
BMW AG	GaBi	ISO 14040 and 14044	Sphera	GaBi	BMW (2022)
Hyundai Motor Co	Own national standard-based methodology	ISO 14040 and 14044	–	Own database (not specified)	Hyundai (2022)
Mercedes-Benz AG	ESSENZ	ISO 14040 and 14044	–	Own database (not specified)	Mercedes (2022)
Audi AG	Under development	–	–	–	Audi (2022)

comparison between the required and the actual content in the OEM reports.

The analysis of sustainability reports from prominent automotive companies reveals variations in the coverage of input variables pertaining to the total life cycle emissions of BEV manufacturing. Mercedes-Benz seems to have provided the highest-scoring information in its sustainability reports, covering six out of the 26 examined variables. Mercedes distinguished itself by providing comprehensive data on key variables such as total vehicle weight (G2/2), vehicle components (G2/4), battery type (G2/5) and cathode material (G2/5). Tesla demonstrated a commitment to transparency by disclosing information on lifetime vehicle miles traveled (VMT) (G2/8). BMW focused on vehicle weight (G2/4), while Audi's report lacked certain details in this category. Remarkably, Hyundai and Volkswagen showed some data gaps, with limited information on the evaluated input variables. Additionally, the extended version of Table 6 is provided in Table S1 of the Supplementary Material.

In some instances, emission data were declared by producers in terms of tons or grams of CO_2 per mile (in the case of automobiles) or the amount of CO_2 per production phase. However, it should be noted that these values only represent end results, and the model necessitates energy consumption details for each production stage to determine accurate emission values. Additionally, if available, the average CO_2 emissions per kilometer of BEV models were also reported, serving as one of the primary indicators of GHG emissions. A common issue is the lack of specification or justification regarding whether the reported CO_2 emissions are Scope 2 or Scope 3. Thus, reporting requirements should be strengthened to ensure that companies report in a standardized manner, covering all significant elements of Scope 3. Current EU legislation mandates that the average fleet emission of CO_2 per kilometer should be 95 g/km or less from 2025 (European Commission 2019).

Discussion

Insights were gained from the results regarding the challenges faced by OEMs in reporting GHG emissions across their supply chains. The IFRS S2 Basis for Conclusions BC3 and BC110 emphasizes the importance of consistent, complete, comparable and verifiable reporting of climate-related risks by entities, which helps stakeholders to understand the risks and emissions associated with each entity (ISSB 2022). Reporting of Scope 3 emissions is not yet mandatory, but IFRS S2 21. (a) (vi) requires entities to disclose their gross greenhouse gas emissions for the reporting period in accordance with the GHG Protocol Corporate Standard, classified as Scope 1, Scope 2 or Scope 3 emissions. The operational methodology of the GREET model facilitates the calculation of Scope 3 emissions (ISSB 2022), especially in the model input variables exploring the list of vehicle components (G2/4) and vehicle-specific assembly assumptions (G2/7).

In relation to this issue, the expansion of obligatory disclosures and the provision of comprehensive guidance to reporting entities regarding the calculation procedures would significantly enhance stakeholders' capacity to evaluate the reliability and accuracy of total emissions. By ensuring that filers provide detailed information and follow standardized calculation methodologies, the transparency and credibility of the disclosed emission figures can be improved. This, in turn, enables stakeholders to make informed assessments and evaluations based on a more robust foundation of data and methodology. In the future, section 21 (a) (vi) (4) of the IFRS S2 climate-related disclosures will require OEMs to disclose their Scope 3 emissions (ISSB 2022). The voluntary inclusion of detailed information on the input variables related to the total life cycle emissions of BEV manufacturing by OEMs holds potential benefits for external stakeholders. The inclusion of such information allows external parties to independently validate the methodology employed in LCA calculations. It is worth noting that certain OEMs, such as BYD Auto Co and SGWA, have not provided extensive

Table 6 Content analysis of sustainability reports, based on GREET 2 input variables (own editing, based on OEM 2021 annual reports)

Ref	Reported input variables requiring internal data	Tesla Motor Co	Volkswagen AG	BMW AG	Hyundai Motor Co	Mercedes-Benz AG	Audi AG
G2/2	Total vehicle weight	0/1	0/1	1/1	0/1	1/1	0/1
G2/3	Battery and fluid weights	0/1	0/1	0/1	0/1	0/1	0/1
G2/4	Input parameters for vehicle components	0/5	0/5	2/5	1/5	2/5	1/5
G2/5	Detailed battery characteristics	3/7	1/7	2/7	1/7	2/7	2/7
G2/6	Parameters for fluid	0/1	0/1	0/1	0/1	1/1	1/1
G2/7	Vehicle-specific assembly assumptions	0/10	0/10	0/10	0/10	0/10	0/10
G2/8	Lifetime vehicle miles traveled (VMT) of vehicles	1/1	0/1	0/1	0/1	0/1	0/1
	Total	4/26	1/26	5/26	2/26	6/26	4/26

information on the LCA methodology utilized for emissions calculations. These companies could enhance industry-wide comparability and transparency by adopting widely accepted models, such as the GREET model, during their initial implementation stages.

The current state of sustainability reporting among global automotive OEMs producing BEVs is not fully standardized, as evidenced by empirical research. Implementation of the GREET model or any open-source LCA model in corporate reporting would render reported quantitative data more verifiable and easier to analyze from a regulatory standpoint (Pizzi et al. 2022). LCA studies have demonstrated that not only the methodologies but also the implemented databases can have a significant impact on the results of such studies (Yin et al. 2019). The applications of the GREET model would not only ensure transparency but also allow for the comparison of different solutions provided by producers in response to the challenges of e-mobility transformation (Soukhov and Mohamed 2022). In response to stakeholders' need to validate OEM-reported data, a Recommended Potential Global General Model was proposed to enhance the GREET model, similar to the framework of Shad et al. (2019). To develop an architecture that meets the requirements of transparent sustainability reporting, environmental information management systems could be used as an automated source of environmental data (e.g., material flows) and tagged via the extensible business reporting language (XBRL) framework (Solsbach et al. 2009). The validation process and transparent reporting are of interest not only to company stakeholders and regulatory bodies such as IASB but also to the manufacturers themselves, who rely heavily on stakeholder investment; lack of transparency or inability to validate reported data could significantly impact their internal financing.

Conclusions

The objective of the research was to analyze discrepancies and missing elements in the sustainability reporting of large automotive companies in the context of the transition to BEVs. Another objective was to identify an open-source, scientifically developed LCA methodology or model that could be incorporated into a possible model framework for corporate sustainability reporting, ensuring transparent and insightful corporate reporting of sustainability data and emissions associated with their activities and the post-sale life of products.

In the results section, summary tables were presented for two cycles of the GREET model, which were analyzed based on their respective input categories. Additionally, a table was included which summarized the final results of the analysis of the LCA content of ESG reports, detailing the methodologies and standards employed. Further results outlined the reported information on input requirements and level of detail concerning OEMs. It should be noted that the validity of these results is contingent upon the OEMs disclosing the source data for analysis, which encompasses BOM lists, raw materials, supply chain composition, raw material sources, regional sales data as well as vehicle component and battery details.

If such data were publicly available, standardized LCA methodologies such as the GREET model under review could be made mandatory in corporate reporting, promoting a harmonized sustainability measurement and reporting system. However, unless a common, technologically and methodologically synchronized LCA methodology is adopted by OEMs, it is unlikely to achieve this in the near future. In the future, simulations of several vehicle models based on data obtained from company reports complemented by model-defined default LCA parameters of the GREET model could allow for more accurate and standardized comparisons of the gross emissions of OEMs.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10098-023-02588-y.

Author contributions All authors contributed to the study's conception and design. Material preparation, data collection and analysis were performed by Péter Molnár and Alex Suta. The first draft of the manuscript was written by Péter Molnár and Árpád Tóth, and Alex Suta commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding The research was supported by the European Union within the framework of the National Laboratory for Artificial Intelligence (RRF-2.3.1-21-2022-00004).

Data availability Enquiries about data availability should be directed to the authors.

Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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