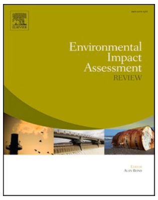
Environmental Impact Assessment Review 97 (2022) 106867

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar



A systematic review on sustainability assessment of electric vehicles: Knowledge gaps and future perspectives

Nuri C. Onat [a], Murat Kucukvar [b,*]

[a] Qatar Transportation and Traffic Safety Center, College of Engineering, Qatar University, Doha, Qatar
[b] Industrial and Systems Engineering, College of Engineering, Qatar University, Doha, Qatar

A R T I C L E I N F O

Keywords:
Life cycle assessment
Life cycle sustainability assessment
Review
Emerging technologies
Electric vehicles
Sustainable transportation

A B S T R A C T

Electric mobility is emerging all around the world to minimize environmental impacts, reduce dependency on petroleum, and diversify energy sources for transportation. Any emerging technology comes with uncertainties in terms of its environmental, economic, and social impacts on the global society, and history has shown that some technological changes have led also to great societal transformation thus shaping our future as humanity. Understanding, perceiving, and anticipating the potential changes are essential to managing as well as internalizing maximum benefits out of these technological advancements for a sustainable global community. In the literature, life cycle assessment approaches are mainly used to assess the potential environmental impacts of electric vehicles. Considering the potential impacts of emerging transportation technologies, traditional life cycle assessment is not sufficient to analyze economic and social impacts, ripple, side, or rebound effects, macro-economic impacts, and global-supply chain related impacts. In response to these knowledge gaps, traditional environmental life cycle assessment approaches are evolving into new more integrated, and broader approaches (e.g., life cycle sustainability assessment). This research aims to reveal research gaps in the sustainability assessment of electric vehicles and provide an outlook of the current state of knowledge, perspectives on research gaps, and potential ways for the adoption of integrated life-cycle modeling approaches. We conducted a comprehensive literature review focusing on sustainability assessment studies for emerging electric vehicle technologies for the period between 2009 and 2020 using the Scopus database. A total of 138 life cycle assessment studies focusing on electric and autonomous (electric) vehicles are analyzed. The reviewed studies are classified and analyzed based on sustainability indicators, life cycle approaches, life cycle phases, data sources and regions, and vehicle technology and class. We also compared the global warming potential of battery electric vehicles of different class sizes. According to the literature review, five major knowledge gaps are identified; 1) lack of socio-economic assessment, 2) lack of integrated modeling approaches and macro-level assessment; 3) limited consideration of end-of-life management and circular economy applications, 4) underrepresented developing world; 5) underrepresented emerging technologies. The findings of this review can help researchers worldwide to overview the state-of-art and state-of-practice in the field of sustainability assessment of emerging technologies and electric vehicles.

1. Introduction

Electric mobility is emerging all around the world with the goals of minimizing environmental impacts, reducing dependency on petroleum, and diversification of energy sources for transportation. In the literature, Life Cycle Assessment (LCA) is mainly used to assess the potential environmental impacts of electric mobility. Using LCA models, researchers worldwide revealed these potential impacts as well as important challenges associated with electric vehicle technologies. LCA is typically applied in four steps: First, goal and scope definition; where objectives and system boundary are determined, Second, inventory analysis; in which inputs and outputs data for each process in the life cycle are compiled, Third, impact assessment; where impacts and emissions are quantified, Fourth, results from interpretation; where the inventory and impact assessment results are explained to answer the goals of the study (Hellweg, 2014). The main goal of LCA is to assess and enhance the environmental performance of the studied system. It can determine the key drivers of the entire system-related impacts, and

---

* Corresponding author.
E-mail address: mkucukvar@qu.edu.qa (M. Kucukvar).

https://doi.org/10.1016/j.eiar.2022.106867
Received 6 August 2021; Received in revised form 24 July 2022; Accepted 25 July 2022
Available online 2 August 2022
0195-9255/© 2022 Elsevier Inc. All rights reserved.

hence it allows identifying the largest impact reduction potential. LCA is applied to support environmentally informed decisions in policymaking, product development, and consumer choices. It can identify the environmental hotspots in complex supply chains (Kucukvar et al., 2019). LCA is a powerful decision-support tool for developing and implementing policies toward optimizing environmental performance and hence achieving sustainable consumption and production (Hellweg, 2014).

LCA has been evolving since it was initially developed in the 1970s. LCA has been transformed into a Life Cycle Sustainability Assessment (LCSA) framework in which the scope of LCA has been broadened from environmental impacts only to covering all other dimensions of sustainability such as economy and society. In the LCSA framework, there are also improvements in encompassing mechanisms (feedbacks, complex interdependencies, ripple effects, involvement of stakeholders, etc.) (Guinée et al., 2011; Onat et al., 2017a). A brief history of LCA and its transformation into LCSA are provided in the Supplementary information (SI) file available on the journal's website.

1.1. Application of life cycle assessment approaches to emerging technologies

Considering the growing concern about the prospective *environmental impacts* resulting from emerging technologies, the assessment at the early stages of technology development is highly required. The early-stage assessment for new technologies can assist in setting the targets for technology development, influence the design, and ensure that innovative environmental goals are accomplished (Bergerson et al., 2020). LCA result of emerging technologies is used to track progress throughout the funding cycle. While the LCA of emerging vehicle technologies is similar to that of the existing technologies, there are additional LCA-related challenges with the emerging technologies, such as lack of data, uncertainty for technology, and market factors that can affect its deployment (Bergerson et al., 2020). Many studies in the literature applied the LCA for emerging technologies at an early stage, coupling them with additional analysis and identifying the challenges. For example, Sharp and Miller, and Cooper et al. (Cooper and Gutowski, 2018; Sharp and Miller, 2016) used a combination of LCA and diffusion of innovations approaches to better represent the implementation of the emerging vehicles. In other work, Arvidsson et al. (Arvidsson et al., 2017) performed a review of LCA of emerging technologies in the areas of energy, biomaterials, and nanomaterials, along with providing recommendations on the use of predictive scenarios and scenarios ranges. In another recent contribution, (Moni et al., 2019) argued that current LCA approaches require methodological advances for evaluating emerging technologies. The authors made recommendations about techniques that can be used in combination with LCA at the early stages of emerging technology development.

Bonilla-alicea et al. (2020) applied LCA to investigate the future technological developments and the respective environmental impacts of bicycle docking and bike-sharing technologies. Wolff and Fries (2020) used a combination of LCA and optimization algorithms to evaluate the environmental impacts of multiple new technologies including hybrid or battery electric vehicles, electrified roads, liquefied natural gas (LNG), and hydrogen for long-haul transportation. Also, the authors investigated the optimal solution that would provide the best compromise between carbon reduction and costs. Due to the increasing role of lithium-ion batteries in the emerging vehicle industry, Ambrose, (Ambrose, 2020a; Ambrose, 2020b) investigated the environmental impacts that could result from the use of lithium. Shimizu et al. (2020) used LCA with a regional energy simulation model to evaluate the region-specific based impacts of new technologies considering a wide set of environmental and social indicators. Sen et al. (2020) employed both hybrid input-output and LCSA techniques to quantify the impact of connected and autonomous heavy-duty trucks considering 20 macro-level environmental and economic indicators.

1.2. Motivation

Using LCA models, researchers worldwide revealed the potential impacts as well as important challenges associated with electric vehicle technologies. In this study, a systematic literature review is conducted with the following motivations:

1) To present a comprehensive review of LCA studies on emerging electric vehicle technologies globally.
2) To classify and analyze reviewed studies based on sustainability indicators, LCA approaches, life cycle phases, data sources and regions, and vehicle technology and class.
3) To reveal current knowledge gaps, challenges, and future perspectives to contribute to the state-of-art and state-of-practice in the field of LCA of e-mobility.
4) And finally, to provide new insights for researchers and LCA practitioners by comparing the results of past LCA studies and revealing critical knowledge gaps in environmental, economic, and social LCA of emerging electric vehicle technologies in terms of method, system boundary, indicator, and system-based decision support models.

2. Method of literature review

The review followed the 3-stage protocol for the comprehensive assessment. *Stage 1* was tailored to identify the database and define the review scope, objectives, and protocol for a structured review of the literature. The keywords along with the inclusion and exclusion criterion were defined. The literature search aims to classify the studies and analyze them to identify knowledge gaps in the literature. By identifying the knowledge gaps, we highlight major challenges and future directions for the sustainability assessment of electric mobility.

In Stage 2, we performed the literature review in three filtering steps. First, the Scopus database is utilized for the literature review using the keywords ("Sustainability assessment" OR "Life cycle assessment" AND "Electric vehicles" OR "autonomous vehicles"). The search is performed in the title, abstract, or keywords for the period between 2009 and 2020. The search was performed on 17 April 2020. The initial search resulted in a total number of 308 papers (Step 1). These studies include original research articles, conference proceedings, review papers, and editorials (letters to editors). The full list of these studies is given in Table S1 in Supplementary Information (SI2) file 2, available on the journal's website. In the second filtering step (Step 2), the abstracts of each journal articles were then 'eye balled' to match the keyword selections. The eye-balling techniques, filtered out the articles that were a letter to editors, systematic reviews (review papers), and commentaries on journal articles within the research theme and ruled out disparities to initialize the categorization of the articles. This paper is predominantly focusing on the life cycle impacts of electric vehicles. Therefore, we excluded the LCA-based studies solely focus on one aspect such as vehicle parts (e.g., composite body, converters, traction motors, electrodes, energy storage systems, etc.). The filtration resulted in 150 journal articles, which are presented in Table S2 in the SI2 file. Then, in Step 3, we removed the duplicates (where the same study was captured from different sources), which resulted in 138 studies to be analyzed further. Then, studies are formatted and listed using, a row number, article title, authors, and year of publication.

Stage 2 continues in conducting a review of the selected articles where each study was then grouped under multiple categories for analysis purposes. We classified the studies based on the following aspects:

- **Indicator Selection:** This classification serves to analyze whether the study includes certain indicator categories representing the environment, economy, or society. This classification allows for analyzing the coverage of the literature in terms of sustainability indicator quantification and analysis.

- **Life Cycle-based Approaches:** This classification aims to cover life cycle-based approaches utilized to analyze the sustainability impacts of electric vehicles. Each approach has its advantage and disadvantage. Therefore, a combination of multiple life cycle-based approaches is likely to provide a more comprehensive and robust approach. By classifying the studies in terms of the life cycle-based approaches, we could identify the most common methods, whether there are integrated LCA approaches sufficiently adopted or not, to overcome methodological challenges. Life cycle-based approaches include process-based LCA (P-LCA), input-output-based LCA (IO-LCA), multi-region input-output-based LCA (MRIO-LCA), hybrid LCA, and decision support extensions (e.g. system dynamics, forecasting, scenario analysis, uncertainty analysis, etc.) (Kucukvar et al., 2019; Kucukvar et al., 2018; Kucukvar et al., 2017;Kucukvar et al., 2016). Classification of life cycle-based approaches is a very important aspect as it provides significant information about knowledge gaps such as consideration of economy-wide impacts (product, regional/national, or global), ripple or rebound effect, stakeholder involvement, and deeper mechanisms (interconnection mechanisms, scenario analysis, uncertainty/sensitivity analysis).
- **Analysis Scope/ Life Cycle Phases:** This classification aims to reveal the life-cycle phases included in the LCA studies. Life cycle phases include manufacturing (vehicle and battery manufacturing), operation (fuel/electricity generation, maintenance, and repair), and end-of-life phases (disposal, recycling, etc.). To allow a proper comparison, we must understand the scope of the LCA studies. For instance, it is not fair to compare a well-to-wheel (WTW) analysis (operation phase) to a full LCA study encompassing all life-cycle phases. Hence, the scope of the evaluated studies must be classified, and healthy comparisons can be performed. While the selection of scope depends on the goal of the assessment, it is usually healthier and more elegant to include full phases in a proper LCA study. This classification also allows us to gain insights into the literature regarding the selection of full LCA or WTW analysis.
- **Life Cycle Inventories:** There are multiple databases available in the literature. This classification allows us to see the most common life cycle inventory adopted in the scientific community. This classification might be useful to understand the divergence in the results when comparing LCA studies with the same scope and same vehicle size. Also, consideration of regional and spatial characteristics plays a crucial role in the results of LCA studies. While data are abundant in some regions, there are no or few databases covering certain parts of the world. As United Nations' Sustainable Development Goals (SDGs) dictate, the coverage of regions (countries) is an important aspect to consider for providing a holistic understanding of the issues around the world. Classification of countries in the literature can spotlight the underrepresented regions, thus, requiring further attention to develop national LCA databases to contribute to the sustainable development of these regions.
- **Vehicle Types and Size:** This classification allows us to provide more fair comparisons when analyzing results derived from literature. It is not fair to compare a sedan size vehicle with a sport utility vehicle (SUV) as their value proposition is different despite having the same utility (functional unit- distance driven). We also classify vehicle technologies investigated in the literature. Classification of vehicle engine technologies includes internal combustion engine vehicles, hybrid, plug-in hybrid, full battery electric vehicles, and others (fuel cell, hydrogen). We also included the level of autonomy as one of the vehicle technology factors as a vehicle can be autonomous regardless of the engine technology classification.

In Stage 3, the analysis and synthesis of the reviewed studies were conducted, and the manuscript is written with insights from both structurally analyzed references and additional supporting literature to elaborate the findings aligned to the research theme in a better way for the audience of the manuscript. With additional references in Stage 3, the total number of references used in this study was raised to over 150 literature pieces. Fig. 1 summarizes the literature review process.

In addition to literature classification and analysis, comparable studies (based on scope, vehicle type, etc.) are filtered. LCA results for the environmental impact category of Global Warming Potential (GWP) are compared for the same vehicle types. This analysis aims to provide a comparison between GWP derived from different studies for various vehicle types.

3. Results

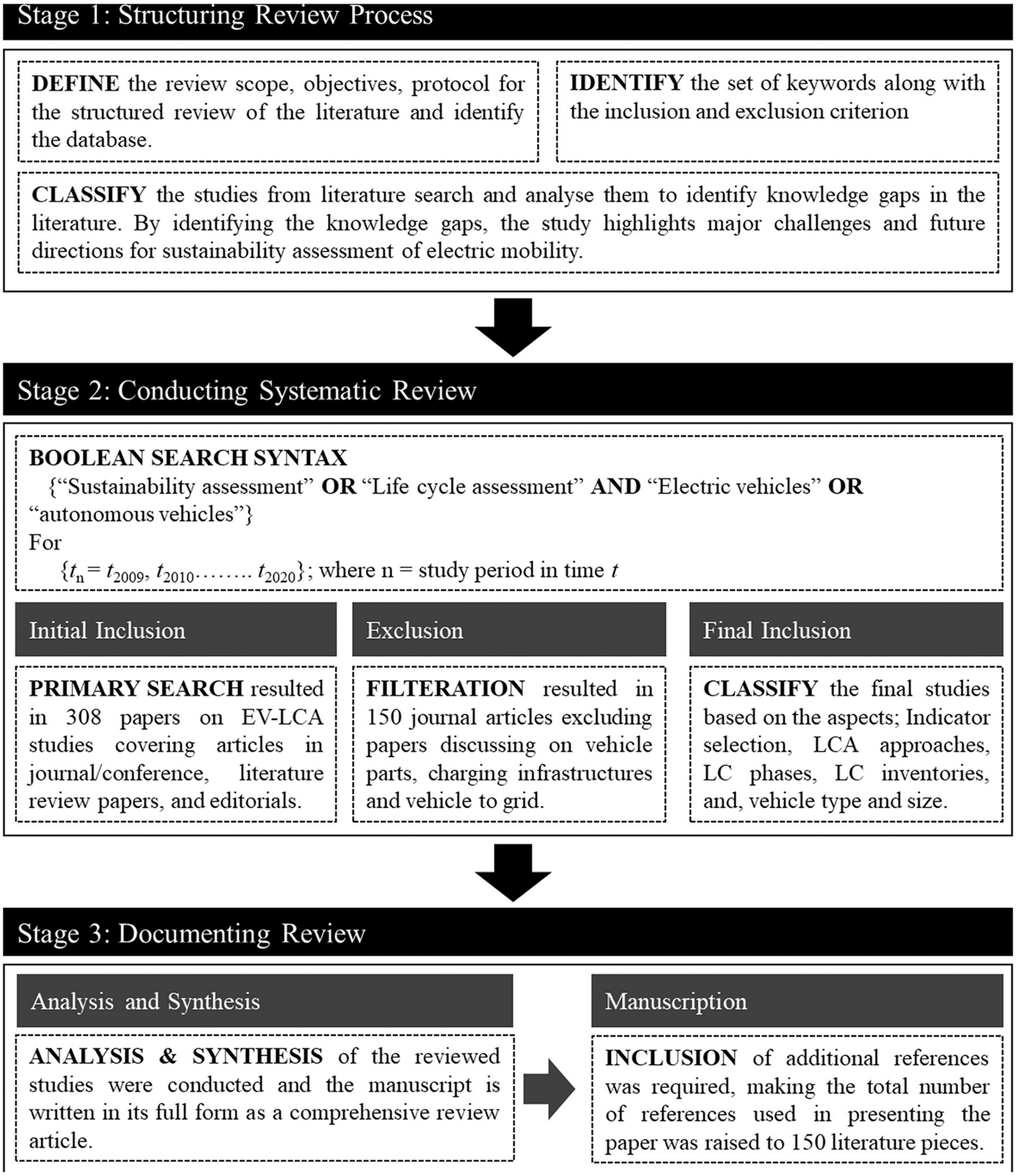
3.1. Analysis of indicators: consideration of social, economic, and environmental indicators

Ideally, a sustainability assessment approach should encompass both environmental, social, and economic dimensions. In this section, we analyzed the indicators representing sustainability in the studies. The sustainability impacts are divided into two main sub-categories as environmental and socio-economic impacts. Although many studies in the literature have applied life cycle-based methods to analyze the environmental impacts of alternative vehicle technologies, only a handful of studies consider the socio-economic aspects of these vehicle technologies. If we exclude studies applying life cycle cost analysis, which is a common approach to calculate life cycle cost (LCC), the percentage of macro-level socio-economic indicators is as low as 2% (please see Fig. 2 (a). This is an important finding showing that socio-economic aspects were often overlooked in the literature. Fig. 2. (a) shows the breakdown of the socioeconomic indicators considered. LCC and human health (end-point-indicator in traditional environmental LCA) are the most studied aspects. A full list of these studies is presented in Table S3 in the SI2 file, where each indicator and corresponding study can be found.

While LCC (economic) and human health (social) indicators have paramount importance, other economic and social indicators should be considered. The literature's main economic indicator focus is LCC, which is a product-level indicator. Most of the studies could not capture macro-level socio-economic impacts such as employment generation, compensations, contributions to gross domestic product (GDP), tax generation, injuries, human development index, and child labor with a few exceptions: (Aboushaqrah et al., 2021; Onat et al., 2019; Onat et al., 2016; Onat et al., 2014; Reuter, 2016; Wang et al., 2019). A full list of these studies and the assessed socio-economic indicators in the entire literature can be found in Table S3 in the SI2 file.

Fig. 2 (b) shows the detailed breakdown of environmental indicators covered in the literature. Among the environmental impact indicators, a great majority of studies focused on GWP with a 91% share, while resource depletion (58.7%) and eutrophication (44.2%) are also among the top indicators considered in the literature. Water withdrawal and water consumption were reported by less than 10% of the reviewed studies. Similarly, ecosystem quality and energy demand impacts were reported by around 5%.

While reducing GHG emissions is the major motivation for the adoption of electric vehicles, the side effects which are expected with deep-sea mining and li-ion battery production were overlooked. For example, switching from conventional vehicles to battery electric vehicles can reduce the dependency on oil and shift it to electricity generation where sources of energy are more diversified. However, electric vehicle batteries are produced from rare earth elements (REEs) which require deep extraction involving removal of overburden, mining, milling, crushing, grinding, separation or concentration. Also, due to the lack of diversity in the supply of REEs, they can be extracted from secondary sources such as waste streams and industry byproducts (Gaustad et al., 2020). REEs are a group of 17 elements: namely lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, scandium, yttrium. Furthermore, the production of



Stage 1: Structuring Review Process

DEFINE the review scope, objectives, protocol for the structured review of the literature and identify the database.

IDENTIFY the set of keywords along with the inclusion and exclusion criterion

CLASSIFY the studies from literature search and analyse them to identify knowledge gaps in the literature. By identifying the knowledge gaps, the study highlights major challenges and future directions for sustainability assessment of electric mobility.

Stage 2: Conducting Systematic Review

BOOLEAN SEARCH SYNTAX
{“Sustainability assessment” **OR** “Life cycle assessment” **AND** “Electric vehicles” **OR** “autonomous vehicles”}
For
$\{t_n = t_{2009}, t_{2010} \ldots\ldots\ t_{2020}\}$; where n = study period in time t

Initial Inclusion

PRIMARY SEARCH resulted in 308 papers on EV-LCA studies covering articles in journal/conference, literature review papers, and editorials.

Exclusion

FILTERATION resulted in 150 journal articles excluding papers discussing on vehicle parts, charging infrastructures and vehicle to grid.

Final Inclusion

CLASSIFY the final studies based on the aspects; Indicator selection, LCA approaches, LC phases, LC inventories, and, vehicle type and size.

Stage 3: Documenting Review

Analysis and Synthesis

ANALYSIS & SYNTHESIS of the reviewed studies were conducted and the manuscript is written in its full form as a comprehensive review article.

Manuscription

INCLUSION of additional references was required, making the total number of references used in presenting the paper was raised to 150 literature pieces.

Fig. 1. A systematic review processes.

REEs is heavily dominated by China. They are of considerable economic importance and are used in a wide range of technological applications. On the other hand, REEs produce geopolitical risks including ecosystem destruction human health, and species-related risks (Vonnahme et al., 2020; Zepf, 2016). Incorporating such risk into the LCSA framework complements and extends the current assessment. Gemechu et al. (Gemechu et al., 2017) applied a geopolitical supply risk indicator to metals used in electric vehicles and the results were compared with a conventional LCA of the same resources. According to the author’s results, aluminum, copper, and steel are the main elements that cause high environmental impacts, whereas neodymium and magnesium generate relatively higher risks when rare earth metals are considered. If batteries are not designed with careful consideration of their end-of-life management, the dependency will be just shifted from one non-renewable source (petroleum) to others (rare earth metals), which is an important aspect to further study for the green revolution in the world.

3.2. Analysis of methodologies: life cycle thinking approaches

Fig. 3 presents the LCA methodologies used in evaluating the sustainability impacts of alternative vehicle technologies in the literature. P-LCA is the most widely applied approach with 92%. While hybrid-LCA and input-output LCA represent only 6.5% and 1.4% of the studies applied, respectively. MRIO-LCA (2.9%), which is an advanced version of single region input-output analysis found in only 1.4% of the studies. While P-LCA can quantify the impacts of a certain process for an object, it does not take into consideration the other supply chain components due to the decisions taken subjectively on the inclusion and exclusion of processes (cut-off criteria) which leads to an underestimation of the impacts (Suh et al., 2004). Due to some limitations of P-LCA, six studies

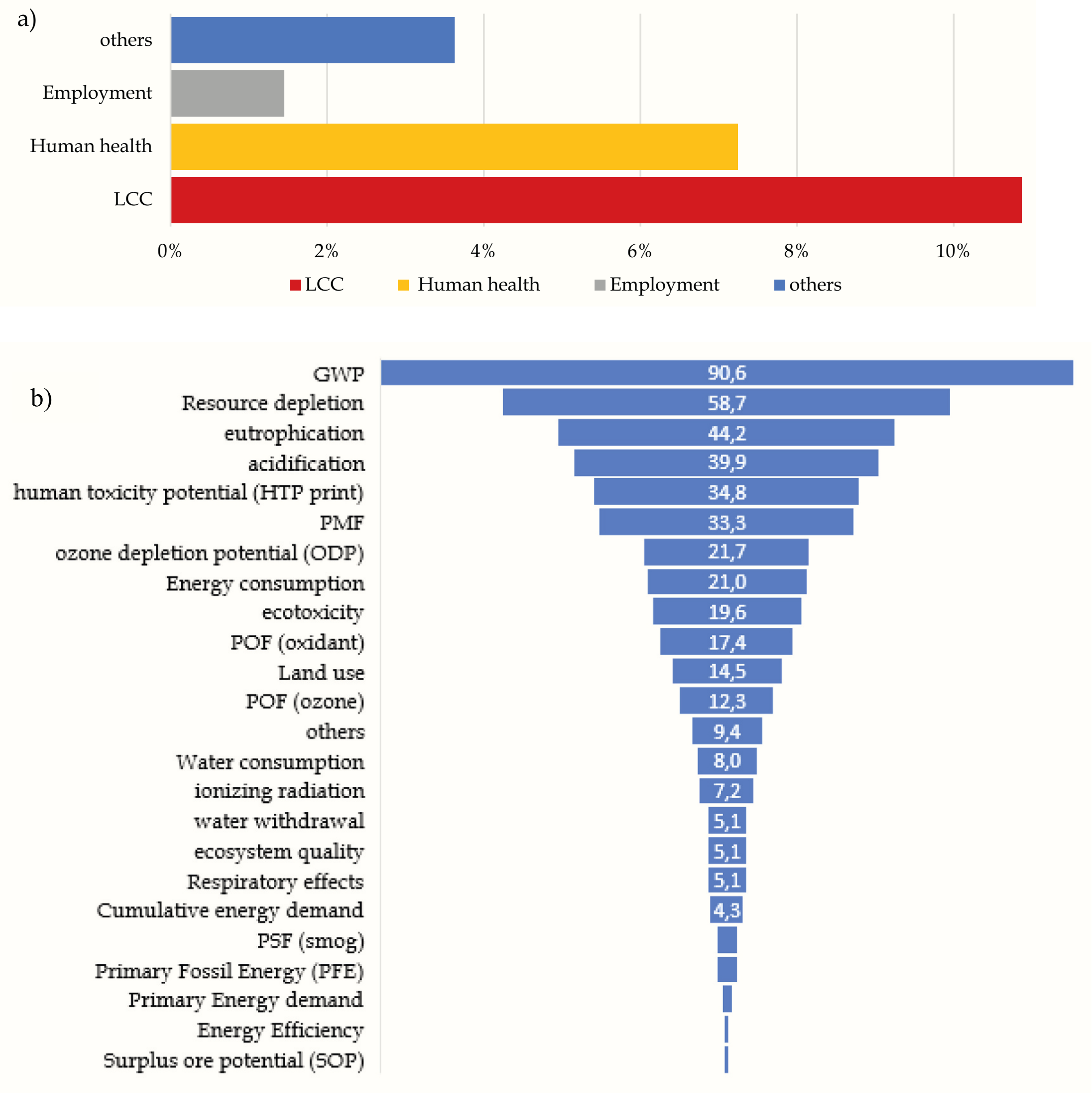


Fig. 2. Literature analysis of sustainability indicator categories by percentage (%). a) socio-economic impacts, b) environmental impacts.

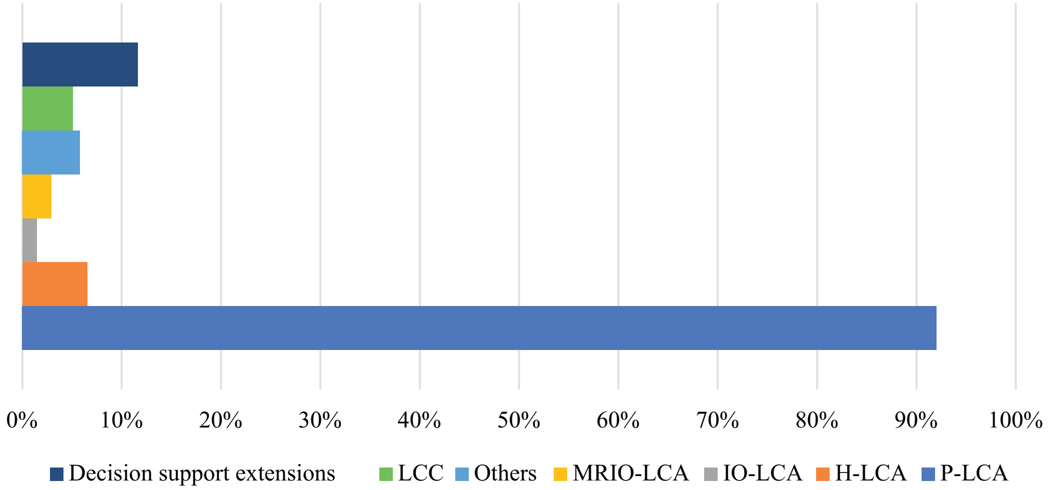


Fig. 3. Percentage of studies by type of life-cycle assessment approach and decision support extensions.

utilized IO-LCA as it can track the overall impacts across the entire supply chain. However, because not all processes can be defined using IO-LCA due to aggregated structure of sectors within an economy, nine studies used H-LCA which is a combination of P-LCA and IO-LCA to evaluate the impacts of a specific process and the overall supply chain related-impacts. Because IO-LCA can quantify the impacts for a single region only, many papers in the literature used MRIO-LCA for its capability to capture macro-level impacts throughout the global supply chains. To provide a more comprehensive sustainability assessment, the inclusion of macro-level impacts is crucial and MRIO-based hybrid LCA approaches can serve best to fill this knowledge gap found in the literature.

In addition, we looked at in more detail which studies adopted a decision support extension such as multi-criteria decision making (MCDM), system dynamics modeling, forecasting, scenario analysis, simulation, etc. We found that around 11% of studies supported the life-cycle approaches with decision-support extension, which are crucial to extending the interpretation of results with further in-depth mechanisms and they are very helpful to communicate results with different disciplines. For example, MCDM approaches can be adopted to solve decision-making problems in which a set of alternatives and criteria of conflicting objectives (e.g. maximize economic and social benefits, minimize the environmental impacts). Such approaches can help to provide compromised solutions when multiple conflicting objectives exist, which is the case for almost all sustainability problems. Also, simulation approaches such as system dynamic modeling are useful to investigate dynamic relationships and interconnections between sustainability indicators, ripple effects, side effects, and rebound effects, which serve to obtain consequential LCA results. Other approaches such as material flow analysis, techno-economic analysis, cost-effectiveness analysis, and process-based social LCA are used in around 6% of the total reviewed papers. Considering that there are studies that adopted more than one life-cycle approach (e.g., both LCC and P-LCA), the sum of the percentage value in Fig. 3 exceeds 100%.

Technological transitions require thinking in systems, consideration of interconnections among different systems, and potential consequential impacts of the emerging technologies. Considering the potential impacts of emerging transportation technology, traditional LCA is not sufficient to analyze economic and social impacts, ripple, side, or rebound effects, macro-economic impacts, and global-supply chain related impacts. In this regard, integration of decision support tools approaches with lifecycle thinking approaches proposes a comprehensive approach where triple bottom line impacts (social, economic, and environmental) can be investigated altogether, encompass broader impacts at the national or even global level, and can reveal mechanisms, interconnections among important factors affecting decisions. Therefore, the adoption of decision support tools is vital to explore trade-offs, inform sustainable development policies, initiatives, and decisions, and can provide insights at early design stages and later for managing and regulating new emerging transportation systems (Mendoza Beltran et al., 2020; Onat et al., 2017a). LCSA framework can be very useful for the integration of life cycle-based approaches with various decision support approaches to broaden the scope and deepen the mechanism and sustainability assessments (Valdivia et al., 2021).

3.3. Analysis of scope: life cycle phases

Typically, LCA studies have addressed the manufacturing, operation, maintenance and repair, and end-of-life phases. The manufacturing phase includes vehicle and battery components production, from raw material extraction to delivery of manufactured vehicles to the end-user. The operation phase covers all the impacts associated with driving vehicles, including supply chain-related impacts from fuel production and delivery and direct impacts such as tailpipe emissions. The maintenance and repair (M&R) are also parts of the operation phase. The end-of-life phase covers the disposal and recycling processes of vehicles at the end of a useful lifetime. In Fig. 4, the percentage of studies by life-cycle phase coverage is presented. Among the life-cycle phases, the operation phase was the most studied, and 83% of the papers considered fuel generation which refers to WTW analysis. The manufacturing phase is the second-largest life-cycle phase considered and around 68% of studies covered vehicle production and 63% of the studies included battery production. According to the existing literature, battery production and maintenance & repair of vehicles are responsible for a lower amount of total environmental impacts in comparison to the operation phase. The end-of-life phase was the least studied phase with less than 20% and only 11% of papers included recycling. As a common finding, the end-of-life phase has a negligible impact in terms of the considered environmental impact categories such as GWP compared to the fuel and vehicle cycle. However, one notable insight is that the end-of-life phase can introduce different indirect impacts in form of material scarcity, and ecosystem destruction due to the need for extracting materials required for manufacturing batteries. While WTW analysis (operation phase) is the widely accepted life-cycle phase for policy development and the most studied phase, it can misguide policymakers since further parts of the scope are not revealed.

From Fig. 4., it is apparent that the end-of-life phase is not studied sufficiently. Considering recent crises in the automobile industry related to a shortage of semiconductor chips, automobile spare parts due to increasing raw materials prices, and a shortage of lithium used for electric vehicle batteries, it will be crucial to consider the reuse, recycling, and remanufacturing in the end-of-life management and Section 4 presents a detailed discussion about the importance of circular economy in electric vehicles' life cycle management.

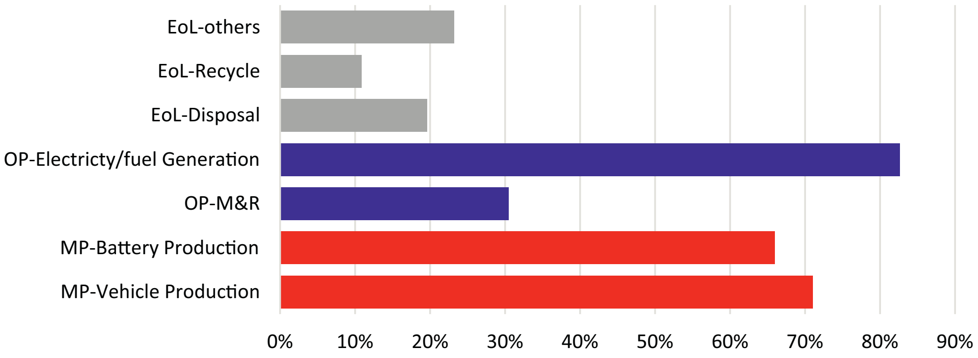


Fig. 4. Percentage of studies by life-cycle phase coverage.

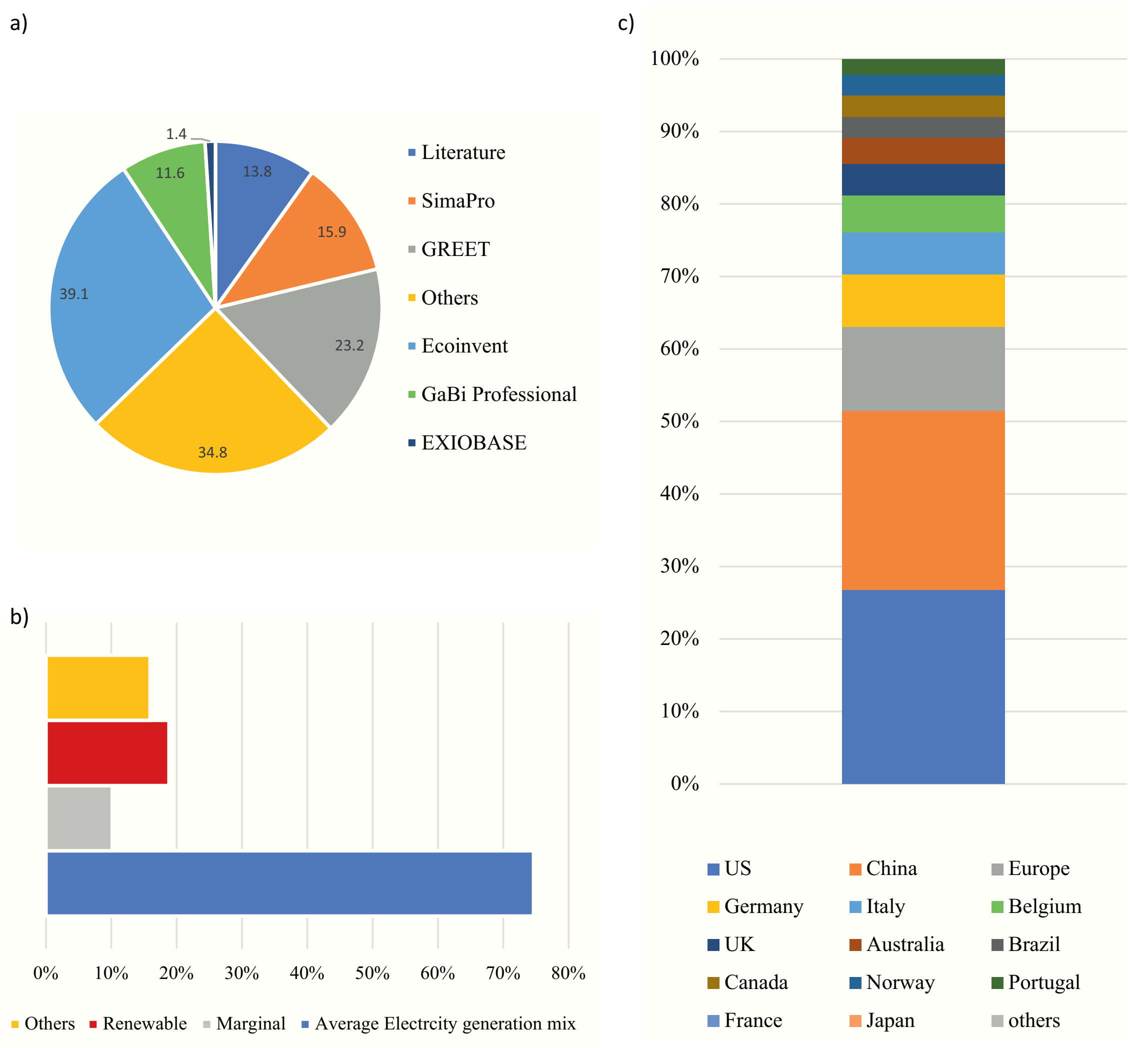


Fig. 5. Percentage of studies a) by life cycle inventory/database, b) by type of electricity generation mix, c) by analyzed country.

3.4. *Analysis of data sources, regional and spatial considerations: life cycle inventories*

Fig. 5 (a) shows the percentage of studies using various life-cycle inventories as the data source to conduct their LCA. Studies utilized several well-known databases such as Ecoinvent (39%), The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model (23%), SimaPro (16%), GaBi professional (12%), and EXIOBASE (2%). On the other hand, 13% of the studies used secondary data from previous studies in the literature. Other data sources such as eGRID, national accounts, Open LCA (databases provided by GreenDelta), World Input-Output Database, etc. are also utilized in the studies. The studies sometimes relied on multiple data sources and therefore, the sum exceed 100% in Fig. 5 (a). The complete list of data sources and the corresponding studies are presented in Table S3 in the SI2 file. An explanation of the main databases is presented in Section 2 in the SI file.

The selection of data source is one of the reasons for the divergence in indicator selection, scope, and eventually in the results. While some studies in the literature point out this divergence in results stemming from a selection of life cycle inventories (Ekvall and Weidema, 2004; Kalverkamp et al., 2020; Miller and Theis, 2006), in this review, the source of divergences in results cannot be proportionally measured. This is mainly because the studies have too many parameters/variables (such as a source of electricity generation, the vehicle specifications, regional differences in prices, etc.) (Egede et al., 2015). However, It can be highlighted that development of region-specific datasets and life cycle inventories has paramount importance to increase the quality and accuracy of the results. Establishing comprehensive region and process-specific datasets requires a considerable amount of time and effort. Therefore, developing regions are not sufficiently studied and these studies are more likely to rely on assumptions, thus reducing the quality of outputs.

Fig. 5 (b) shows the percentages of studies by types of the electricity generation mix. The average electricity generation mix is the percentage of electricity generation sources (coal, natural gas, wind, solar, etc.) in a region on average during a year. Mostly, the average electricity generation mix gives a holistic picture of characteristics (emission intensity, reliability, technology, social impacts such as employment per output of electricity, etc.) associated with the electricity generation mix in the region of interest (country, city, etc.). Therefore, the average electricity generation mix is usually used for national planning and government reports. In life cycle inventories, the data are presented in form of emissions by electricity generation source (e.g. emissions per kWh of electricity generation by a type of coal power plant in a certain country or region), and the average electricity generation mixes are used to calculate the average impacts (e.g. GHG emissions per kWh electricity generation) by taking a weighted average of each energy source (coal, natural gas, nuclear, solar, wind, etc.). In countries where electricity is mostly imported from other countries (neighbor countries), using average electricity generation mixes can be misguiding (Tamayao et al., 2015; Weber et al., 2010). Also, taking imported and exported electricity amounts is a complex process and usually accessing such data is challenging (Buyle et al., 2019; Qu et al., 2018). On the other hand, the marginal electricity mix scenario is generally estimated to cover for impacts from different generation costs, and demand trends over a day and a season. Due to the need for instantaneously meeting the electricity demand, electricity power generation operators utilize different generation sources to ensure grid stability. For example, while nuclear power and hydroelectric power plants usually provide a steady supply to meet a base electricity load demand, some fossil fuels-based power plants such as natural gas or coal power plants supply some portion of the baseload and mostly peak demand above the baseload. Therefore, marginal electricity mixes are dirtier in terms of emission intensity and can significantly change the results of LCA. Marginal generation mix depends on both temporal and spatial variations. The importance of consideration of different electricity generation mixes for conducting LCA of electric vehicles has been highlighted in several studies (Faria et al., 2013; Moro and Lonza, 2018; Onat et al., 2017b; Woo et al., 2017).

Due to concerns related to using average electricity generation mix scenarios, some studies put more emphasis on acquiring electricity trade data, while some other studies focused on marginal electricity generation scenarios (Please see Table S3 in the SI2 file for a full list of these studies). Most of the studies (74.6%) performed the life cycle analysis based on the average electricity generation mix scenarios of the region they investigated. It is followed by renewable and marginal electricity mixes with 19% and 10%, respectively. In 16% of the studies, the electricity generation mix is not specified (indicated as others in Fig. 5b). It is worth mentioning that the average electricity mix might not be representative for estimating impacts associated with electricity generation and hence focusing on it might be misleading as it assumes constant emissions over time. Therefore, using different mixes in the assessment such as marginal and renewable-based electricity mixes would make the analysis more meaningful and representative, and useful for policy development. The concept of marginal electricity mix is intended to account for impacts from different generation sources to instantaneously meet the electricity demand for securing the grid stability. Renewable energy-based power generation is typically used in the analysis to mitigate the environmental impacts and especially greenhouse gas (GHG) emissions.

The results showed that the LCA of alternative vehicles is mostly studied in developed countries (see Fig. 5c). Nearly 27% of the studies investigate alternative vehicles in the USA. The second most studied country is China (25%), followed by Germany (7%), Italy (6%), Belgium (5%), and the UK (4%), respectively. Some studies cover all European member states and these account for 12% of the total. While very few studies provide analysis for Brazil, Canada, Norway, Portugal, France, and Japan, adding up to 2–3%. Only 1% of the studies analyzed refer to the Czech Republic, Denmark, Iceland, Mexico, Estonia, Greece, Iran, Lithuania, Malaysia, Poland, Singapore, India, South Africa, Algeria, Spain, Sweden, Switzerland, and Scandinavia. These results showed that the developing regions (except China) are underrepresented in the literature. This might be since life cycle inventories mostly provide process-level data for developed regions (please see Section 3.4.). Considering that LCA of alternative fuel vehicles aims to minimize environmental impacts that are mostly at the global level, the underrepresentation of developing regions such as India and other major countries from Asia, the Middle East, Russia, and African states is an obstacle to setting sustainable development goals encompassing all the globe that is destined to fight the Climate Change together.

3.5. *Analysis of vehicle types: a navigation for comparison and understanding of the technologies*

Fig. 6 shows the percentage of studies focusing on different vehicle types. The vehicle type classification can allow readers/researchers to compare different studies focusing on different technologies. By utilizing the filtering feature in the SI2 file available on the journal's website, the readers can navigate and compare studies with similar scope. For example, a comparison between same class vehicle types (SUV to SUV, sedan to sedan) with the same scope (consideration of same life cycle phase components) can provide insights about findings of different papers from different regions, or papers using different databases or tools (e.g., SimaPro, Ecoinvent, GREET, etc.).

The classification of alternative fuel vehicles under three main subcategories: vehicle class, technology type, and level of autonomy. In the first classification category (vehicle class), vehicles are commonly classified into sedans, sport utility vehicles (SUVs), buses, trucks, and others. The majority (70.3%) of the studies analyzed the sedan vehicle class, followed by trucks with 7.2%, and buses and SUVs with 5.1% and 3.6%, respectively, while other types of vehicles including taxis, bicycles, motorcycles, tractors, shared vehicles, and vehicles used for transferring goods accounted for 19.6% of the total. This is an expected outcome since most of the vehicles on road are sedan class. However, one notable vehicle class that requires further attention is emerging compact mobile devices that are not found in the literature. Compact personal mobility devices are expected to grow, and they are expected to have lower environmental impacts per kilometer travel compared to regular sedan vehicles that are often underutilized (having one passenger only). In other words, compact personal mobility devices might meet the short-distance travel demand and reduce the environmental impacts by replacing the short trips that are made by sedan or SUV class types of vehicles. However, It is unknown that they might introduce the travel demand due to rebound effects (improved fuel efficiency, etc.). Hence, further research is needed about more compact travel/mobility devices.

In the second sub-classification category (technology type), three

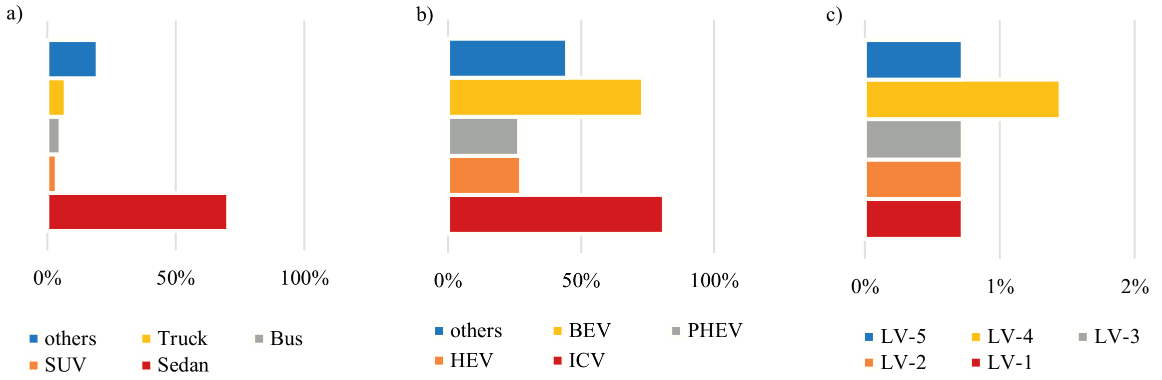


Fig. 6. Literature analysis of existing studies of the sustainability impacts of vehicles categorized by a) vehicle class b) vehicle technology type c) level of autonomy.

types of electric vehicles are commonly compared to Internal Combustion Engine Vehicles (ICEV): Full Battery Electric Vehicle (BEV), Hybrid Electric Vehicle (HEV), and Plug-in Hybrid Electric Vehicle (PHEV). ICEVs are powered by fossil fuels and have engines where the combustion of fuels takes place. On the other hand, BEVs use motors instead of internal combustion engines which are powered by batteries that are charged using the electricity grid. The HEVs combine the internal combustion engine systems with the electric motors. PHEVs run on electricity generated by batteries until they are nearly depleted, and then the changeover to the use of an internal combustion engine automatically takes place. It is observed that (please see Fig. 6 (b)), 81.2% of the reviewed studies analyzed ICV technology as a basis for comparison. BEV are commonly found in comparisons, with 73.8% of the total, followed by HEV and PHEV with 27.5% and 26.8%, respectively, while other technologies including hydrogen fuel cell vehicle (HFCV), biodiesel/ biofuel, compressed natural gas and their variations, liquefied natural gas vehicles, account for nearly 45%. The findings show that there is a diversity in consideration of different technology types for engines and fuel types. While the literature provides a diverse technology type, the comparison among less studied vehicle types such as trucks, SUVs, etc. is challenging, mainly due to significant variations in studies' scope.

The literature review clearly shows that autonomous electric vehicles were not studied from a life-cycle perspective sufficiently. Only a handful of studies (2%) analyzed autonomous electric vehicles and studied their environmental impacts. We classified these studies based on the level of autonomy. Levels of driving automation are defined as follows: Level 0: zero autonomy, where the driver is in charge of all driving tasks, Level 1: driver assistance, in which most of the driving functions are performed by the driver, Level 2: partial automation, in which some functions are automated while the driver remains responsible to take control of the vehicle at all times, Level 3: conditional automation, where most of the functions are automated but still the driver is required to control the vehicle at all times however not as with previous levels, Level 4: high automation, in which the vehicle is capable to carry out all functions under certain conditions and driver interaction is optional, Level 5: full automation, where the vehicle is capable to carry out all functions under all circumstances and zero driver interaction is required. Our analysis shows that only two papers addressed the level of vehicle autonomy, one analyzed all levels of autonomy while the other analyzed the impacts of vehicles of level 4 of autonomy.

3.6. A comparison of results for GWP

Using the filtering in the tables presented in the SI2 file available on the journal's website, we provided a comparison for the GWP impact category to show the divergence in results for the comparative studies. To provide a comparable result, we selected the same vehicle class

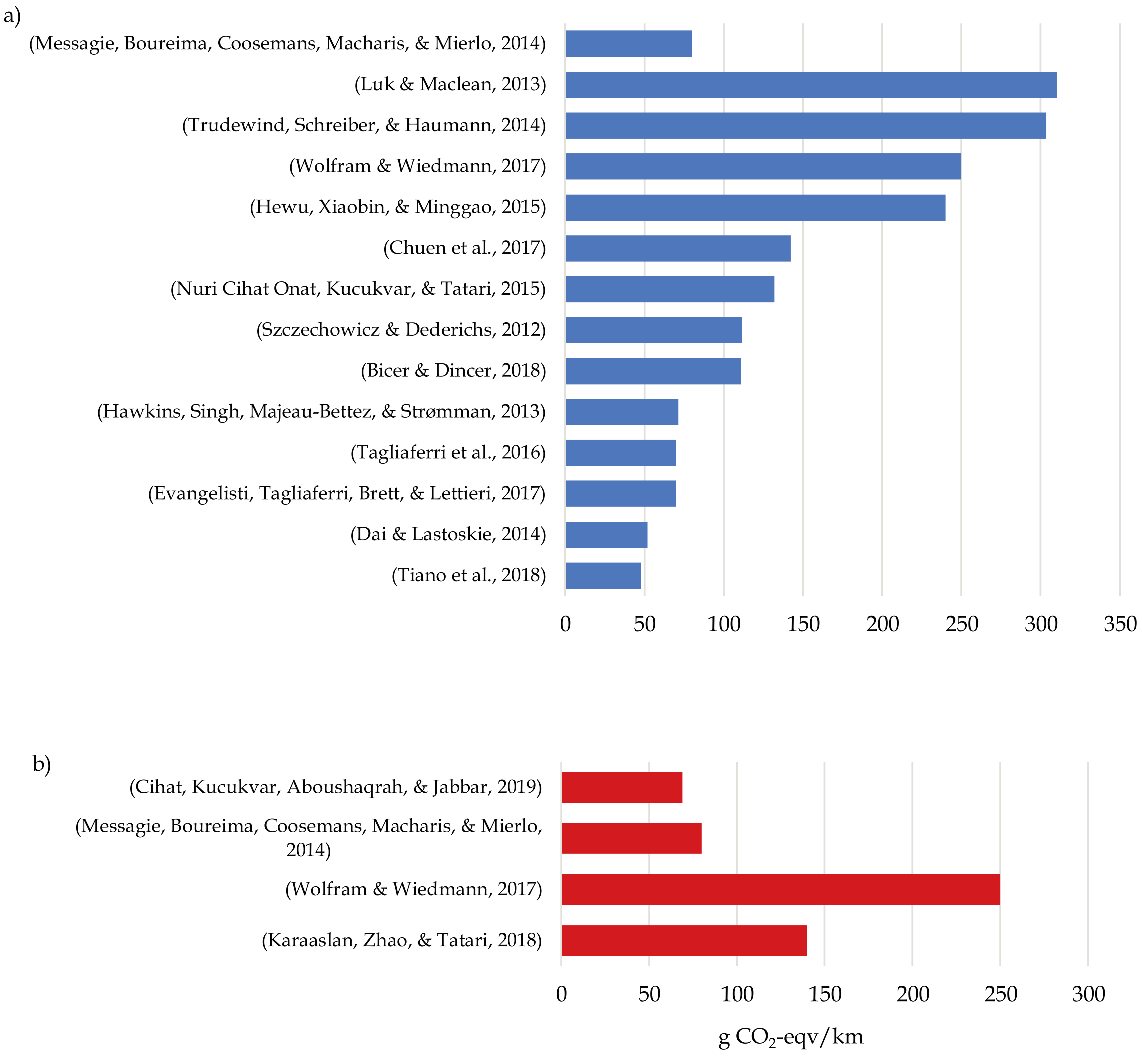


Fig. 7. Comparison of greenhouse gas emissions from operation life cycle phase (g CO_2-eq) a) Sedan b) SUV.

(Sedan or SUV) and selected studies that cover the same life cycle phases and subphases (Manufacturing, WTT, TTW, maintenance and repair, recycling, etc.). We synthesized the GWP impact results from the existing studies in the literature for full battery electric vehicles (BEV) of different classes including sedans, SUVs, buses, trucks, and other vehicle types. A comparison of results for GWP is conducted across studies for sedan and SUV vehicle classes of BEV from the vehicle operation. The same comparison for other vehicle classes including buses and trucks could not be performed because existing studies diverge significantly in terms of scope and inclusion of life-cycle phases. Similarly, the GWP results for BEV vehicle classes could not be compared from a full life cycle perspective as some studies present the findings for some certain life cycle phases only while excluding the rest, and some provide the results for some phases while mentioning them explicitly in the study that all phases are quantified, and some papers do not provide results by phase, however, they only show total results. Thus, phase-by-phase comparison for such studies was not possible. Also, as per the current literature, some papers evaluated the GWP for a set of countries or a set of scenarios (e.g., electricity generation mix, periods, etc.). It's worth mentioning that the comparison for other impact categories is not possible to be performed as the inclusion of social and economic indicators in the vehicle impact assessment is not sufficiently addressed in the literature.

Fig. 7a compares the GWP resulting from the vehicle operation phase per kilometer for Sedan-BEV across the existing studies in the literature. A variation in the GWP results is shown in Fig. 7 for Sedan-BEV between the studies ranging from 48 g/km to 310 g/km. This variation is likely to stem from the differences in the electricity generation mix and life cycle inventories (database). The Ecoinvent and the GREET are the most common data sources used in the LCA of transportation literature. Some studies (Bicer and Dincer, 2018; Hewu et al., 2015; Luk and Maclean, 2013; Onat et al., 2015; Tiano et al., 2018) conducted the LCA using the impact factors obtained from the GREET model. Others (Bicer and Dincer, 2018; Dai and Lastoskie, 2014; Onn et al., 2017; Szczechowicz and Dederichs, 2012; Tagliaferri et al., 2016; Trudewind et al., 2014; Wolfram and Wiedmann, 2017) have extracted the LCA dataset from Ecoinvent database and Evangelisti et al. (2017) and Trudewind et al., (2014) calculated the life cycle impacts using the upstream impact factors extracted from the GaBi professional. Furthermore, it is found that the SimaPro tool has been used by Hawkins et al., (Hawkins et al., 2013); Onn et al. (2017).

GWP impacts of the operation phase are dominant for Sedan- BEVs in areas where the electricity mix is mainly based on fossil fuels, however for low-impact electricity mixes the contribution of the use phase may be significantly reduced. Specifically, in studies (Hewu et al., 2015; Luk and Maclean, 2013; Onn et al., 2017; Szczechowicz and Dederichs, 2012; Trudewind et al., 2014; Wolfram and Wiedmann, 2017), the average regional electricity mix mainly based on fossil fuels is used. In studies (Dai and Lastoskie, 2014; Onat et al., 2019), the electricity mix is exclusively generated from natural gas. On the other hand, in studies (Hawkins et al., 2013; Messagie et al., 2014; Tagliaferri et al., 2016; Tiano et al., 2018) average regional electricity mix is mainly based on renewable sources. In studies, (by Bicer and Dincer, 2018; Evangelisti et al., 2017) electricity mix is exclusively generated from renewable sources.

The comparison of GWP impact results per kilometer across the studies for SUV-BEV during the vehicle operation phase is presented in Fig. 7b. The results vary between 69 g/km to 250 g/km for SUV-BEV in this phase due to different electricity mix and data sources used in the analysis. (Wolfram and Wiedmann, 2017) has used a dataset of the Ecoinvent database, while (Messagie et al., 2014) and (Onat et al., 2019) used data analysis of the Eco score and EXIOBASE databases respectively. (Karaaslan et al., 2018; Wolfram and Wiedmann, 2017) considered nationwide electricity generation mix in the analysis that is of high carbon intensity. On the other hand, (Onat et al., 2019) used electricity that is generated that is solely generated from natural gas, while (Messagie et al., 2014) considered the average regional electricity mix based on renewables.

The root reasons for the divergence in results should be well-understood, as the parameters influencing the overall environmental life-cycle performance of these vehicles highly depend on the electricity generation mix, the emission, and characterization factors derived from life-cycle inventories, and life cycle impact assessment methods. This comparison can also serve as a benchmark for new analysis in the literature as we provided the data sources (LCA inventories and LCIA methods), electricity generation mix assumptions, type of vehicles, region/country that studies performed for, and all other classification categories provided in this paper. The detailed tables containing all this information are provided in the SI2 file available on the journal's website.

4. Discussions: addressing the knowledge gaps, future perspectives, and outlook

According to the literature review, five major knowledge gaps are identified and grouped under five main categories and explained as follows:

1) ***Lack of socio-economic assessment:*** A proper comprehensive sustainability assessment should include social and economic aspects in addition to environmental aspects that have been extensively studied with traditional LCA approaches. Socio-economic aspects of emerging technologies or services are very critical and should be considered an extension of traditional environmental LCA. Social indicators such as employment, human health, equity, injuries, etc. can be considered extensions of LCA studies. United Nations Environment Development Program's life cycle initiative provides detailed guidelines for social LCA of products, which can be adapted to advance the social sustainability assessment of electric vehicle technologies using the right tools, methods, and indicators as well as considering stakeholders from industry, policymakers, and business. Especially, social LCA of autonomous electric cars, buses, trucks, and other types of innovative public transportation technologies will be critical to understanding the societal aspects of next-generation transportation in terms of the contribution to a knowledge-based economy, employability, safety, and health & well-being.
2) ***Lack of integrated modeling approaches and macro-level assessment***: One of the most important knowledge gaps is identified as the use of decision support methods and approaches integrated with LCA. Only 11% of the studies extended the LCA results with decision support tools such as scenario development, multi-criteria decision making, multi-objective optimization, system dynamics, forecasting, etc. The use of integrated assessment/modeling approaches is crucially important to interpret, clarify, and articulate the interconnected system of goals and to assess and inform key policies, for their impact on sustainable development goals. Integrated modeling approaches, especially multi-criteria decision support approaches, system dynamics modeling, and scenario development should be one of the main priorities to enhance the interpretation and use of LCA results. Sustainable transportation is at the heart of the United Nations Sustainable Development Goals (SDGs) and It is linked to many SDGs such as climate action (SDG 13), water (SDG 14), good health, and well-being (SDG 3), and sustainable cities and communities (SDG 11). Using system-based dynamic modeling approaches can also help to reveal the relationship between e-mobility and sustainable development and understand the complex dynamic relationships between life cycle impacts of electric vehicle technologies and social, economic, and environmental pillars of sustainable development.

   While P-LCA models are useful and can provide detailed process-level improvement opportunities, they are not fully capable of capturing economy-wide and supply-chain-based regional and global impacts. As discussed in Sacchi et al. (2022), using LCI databases such as Ecoinvent, it is only possible to produce some aggregated life cycle results for some supply chain components instead of providing a complete region or technology-specific analysis. However, using global multiregional databases such as Eora (Lenzen et al., 2013), EXIOBASE (Stadler et al., 2018), World Input-output Database (Timmer et al., 2012), and Global Trade Analysis Project (GTAP) (Peters et al., 2011), it can be possible to create input-output hybrid LCSA models, in which global life cycle sustainability impacts of e-mobility can be estimated by employing a value chain-based approach considering the technology-specific parameters (Onat et al., 2019). Therefore, to be able to answer macro-level questions, develop technology-specific policies supporting United Nations SDGs, and effectively link and measure our decisions about emerging mobility technologies to SDGs, researchers should consider hybridization of LCA models using global multiregional input-output databases.

3) ***Limited inclusion of End-of-life phase and management strategies:*** A limited number of studies (23.2%) considered the end-of-life phase. Only very few studies developed a sustainability analysis for vehicles for disposal (19.6%) and recycling (10.9%) life cycle phases. While the end-of-life phase has 5% of the total environmental life cycle impacts of alternative vehicle technologies (Schmidt et al., 2004), it might introduce different risks and dependencies due to the use of rare-earth metals in batteries. End of rare earth metals which are used in battery technologies poses different risks such as ecosystem destruction due to deep-sea mining and dependency on a new set of non-renewable sources (rare earth metals) (Vonnahme et al., 2020). Recycling rare earth metals preserve important opportunities for the industry (Ferron and Henry, 2015). Hence, LCA can play an important role in end-of-life management strategies and can pave the way for less use of rare earth metal extraction, and indirectly minimize the dependency by providing opportunities for close loop systems for end-of-life management (Kucukvar et al., 2021; Al-Hamrani et al., 2021). A hybrid LCA-based material flow and footprint analysis can also provide important insights for hotspots of rare mineral and metallic product use in the value chains of electric vehicles. Furthermore, the role of circular economy business models should be integrated into a full LCA of electric vehicles by considering the reuse, recycle, and remanufacturing principles of a circular economy. Shifting from a linear economy to a circular economy will provide vital benefits for the long-term sustainability of e-mobility in the world and therefore the authors suggest that net benefits of circular economy business models for end-of-life management of electric vehicles should be estimated by using advanced life cycle environmental, economic, and social impact assessment models using regional and multinational LCA methods.
4) ***Underrepresented developing world:*** Developed countries are predominantly analyzed, while there are very few studies from developing countries except China. Considering that the developing world is more vulnerable to Global Climate Change as well as economic shocks, studies targeting the developing world should be supported by international funding organizations to enhance sustainable development in developing parts of the world. It is important to estimate the life cycle impacts of e-mobility in the developing world by using region and sector-specific data. Ecoinvent database recently released version 3.8 which can provide sufficient detail of life cycle inventory data for developing countries and recently advanced high country and sector resolution multinational MRIO databases such as EXIOBASE and Eora can also be integrated with environmental and socioeconomic accounting matrices of sectors of developing nations to build a hybrid life cycle sustainability assessment model for electric vehicles.
5) ***Unrepresented emerging technologies:*** Autonomous electric vehicles and compact electric mobility (compact electric vehicles/compact personal mobility devices) are not sufficiently studied from a life-cycle perspective. Only a few studies were found focusing on autonomous electric vehicles. While this might due to low dissemination or development of life-cycle inventories or methodologies to properly assess autonomous vehicles, the LCSA framework can be very useful for assessing the sustainability impacts of these unrepresented emerging electric mobility technologies. Especially, autonomous vehicles might introduce rebound effects and thus, there should be advanced methodological mechanisms (system dynamics simulation, agent-based modeling, AI-supported decision support platforms) integrated into LCA approaches to capture consequential results of adopting autonomous electric vehicles. The future of electric mobility is very likely to be autonomous and more compact (smaller size of mobility devices/vehicles), and therefore, researchers should investigate the potential impacts of these emerging technologies to inform policymaking, automakers, and the public about sustainability impacts of these technologies.

5. Conclusions and recommendations

This paper conducts a literature review on LCA for emerging vehicle technologies. 138 studies found focusing on the life cycle impacts the assessment of electric or autonomous electric vehicles. We investigated various aspects as follows; 1) Analysis of Indicators: consideration of social, economic, and environmental indicators, 2) Analysis of Methodologies: Life cycle thinking approaches, 3) Analysis of Scope: Life cycle phases, 4) Analysis of Data sources, regional and spatial considerations: Life Cycle Inventories, 5) Analysis of Vehicle Types: A navigation for comparison. A comparative result analysis for the GWP category across the literature showed significant variations among the LCA studies due to divergence in scope, life-cycle inventories, and source of electricity generation. The GWP results for Sedan and SUV vehicle classes across current studies during the vehicle operation phase vary between 48 and 310 g/km and 69–250 g/km respectively, in which such variation is heavily dependent on the electricity mix for charging and type of database. The GWP results reported for other vehicle classes including buses and trucks during the operation phase were not possible due to incomparable differences in life cycle phase considerations.

According to our comprehensive analysis, there is a strong need for advancing the current state-of-the-art of current electric vehicle's life cycle sustainability assessment by 1) integrating social and economic aspects into environmental LCA and considering various stakeholders, 2) by integrating system-based decision-making methods such as system dynamics, agent-based modeling, and multi-criteria decision making with LCA results of electric vehicles, 3) by shifting from a linear economy to circular economy models for end-of-life management of batteries, 4) by broadening system boundary from the region to globe using hybrid LCA models, and by better coverage of developing countries, 5) by consideration of compact electricity mobility devices and unrepresented/uncertain impacts of autonomous electric vehicles. These aspects remain important gaps to be addressed by LCA practitioners. We believe that the findings of this review can help researchers worldwide to overview the state-of-art and state-of-practice in the field of LCA of emerging technologies and electric vehicles.

Authorship contribution statement

Nuri Cihat Onat: Research Design, Conceptualization, Methodology, formal analysis, Writing - review & editing, Writing - original draft, Project administration. Murat Kucukvar: Data curation, validation, Writing – original draft, Writing - review & editing, visualization, software

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This paper is an output of a project supported within the scope of the Qatar National Research Fund (QNRF), grant number NPRP13S-0203-200235. The authors acknowledge and appreciate QNRF for the generous continuous support for electric vehicle research at Qatar University.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2022.106867.

References

Aboushaqrah, N.N.M., Onat, N.C., Kucukvar, M., Hamouda, A.M.S., Kusakci, A.O., Ayvaz, B., 2021. Selection of alternative fuel taxis: a hybridized approach of life cycle sustainability assessment and multi-criteria decision making with neutrosophic sets, pp. 1–14. https://doi.org/10.1080/15568318.2021.1943075.

Al-Hamrani, A., Kim, D., Kucukvar, M., Onat, N.C., 2021. Circular economy application for a Green Stadium construction towards sustainable FIFA world cup Qatar 2022TM. Environ. Impact Assess. Rev. 87, 106543.

Ambrose, H., 2020a. Understanding the future of lithium Part 1, resource model, pp. 80–89. https://doi.org/10.1111/jiec.12949.

Ambrose, H., 2020b. Understanding the future of lithium Part 2, temporally and spatially resolved life-cycle assessment modeling, pp. 90–100. https://doi.org/10.1111/jiec.12942.

Arvidsson, R., Tillman, A.-M., Sand'en, B.A., Janssen, M., Nordel, A., Kushnir, D., Molander, S., 2017. Environmental Assessment of Emerging Technologies Recommendations for Prospective LCA, p. 22. https://doi.org/10.1111/jiec.12690.

Bergerson, J.A., Brandt, A., Cresko, J., Carbajales-Dale, M., MacLean, H.L., Matthews, H. S., McCoy, S., McManus, M., Miller, S.A., Morrow, W.R., Posen, I.D., Seager, T., Skone, T., Sleep, S., 2020. Life cycle assessment of emerging technologies: evaluation techniques at different stages of market and technical maturity. J. Ind. Ecol. 24, 11–25. https://doi.org/10.1111/jiec.12954.

Bicer, Y., Dincer, I., 2018. Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles. Resour. Conserv. Recycl. 132, 141–157. https://doi.org/10.1016/J.RESCONREC.2018.01.036.

Bonilla-alicea, R.J., Telenko, C., Watson, B.C., Shen, Z., Tamayo, L., 2020. Life Cycle Assessment to Quantify the Impact of Technology Improvements in Bike-Sharing Systems, pp. 138–148. https://doi.org/10.1111/jiec.12860.

Buyle, M., Anthonissen, J., Van den Bergh, W., Braet, J., Audenaert, A., 2019. Analysis of the Belgian electricity mix used in environmental life cycle assessment studies: how reliable is the ecoinvent 3.1 mix? Energy Effic. 12, 1105–1121. https://doi.org/10.1007/S12053-018-9724-7/TABLES/6.

Cooper, D.R., Gutowski, T.G., 2018. Prospective Environmental Analyses of Emerging Technology: A Critique, a Proposed Methodology, and a Case Study on Incremental Sheet Forming [WWW Document].

Dai, Q., Lastoskie, C.M., 2014. Life Cycle Assessment of Natural Gas-Powered Personal Mobility Options. https://doi.org/10.1021/ef5009874.

Egede, P., Dettmer, T., Herrmann, C., Kara, S., 2015. Life cycle assessment of electric vehicles – a framework to consider influencing factors. Procedia CIRP 29, 233–238. https://doi.org/10.1016/J.PROCIR.2015.02.185.

Ekvall, T., Weidema, B.P., 2004. System boundaries and input data in consequential life cycle inventory analysis. Int. J. Life Cycle Assess. 93 (9), 161–171. https://doi.org/10.1007/BF02994190.

Evangelisti, S., Tagliaferri, C., Brett, D.J.L., Lettieri, P., 2017. Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles. J. Clean. Prod. 142, 4339–4355. https://doi.org/10.1016/j.jclepro.2016.11.159.

Faria, R., Marques, P., Moura, P., Freire, F., Delgado, J., De Almeida, A.T., 2013. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. Renew. Sust. Energ. Rev. 24, 271–287. https://doi.org/10.1016/j.rser.2013.03.063.

Ferron, C.J., Henry, P., 2015. A review of the recycling of rare earth metals. Can. Metall. Q. 54, 388–394. https://doi.org/10.1179/1879139515Y.0000000023.

Gaustad, G., Williams, E., Leader, A., 2020. Rare Earth Metals from Secondary Sources: Review of Potential Supply from Waste and Byproducts [WWW Document].

Gemechu, E.D., Sonnemann, G., Young, S.B., 2017. Geopolitical-related supply risk assessment as a complement to environmental impact assessment: the case of electric vehicles. Int. J. Life Cycle Assess. 22, 31–39. https://doi.org/10.1007/s11367-015-0917-4.

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life cycle assessment: past, present, and future. Environ. Sci. Technol. 45, 90–96. https://doi.org/10.1021/es101316v.

Hawkins, T.R., Singh, B., Majeau-Bettez, G., Strømman, A.H., 2013. Comparative environmental life cycle assessment of conventional and electric vehicles. J. Ind. Ecol. 17, 53–64. https://doi.org/10.1111/j.1530-9290.2012.00532.x.

Hellweg, S., Milà i Canals, L., 2014. Emerging approaches, challenges and opportunities in life cycle assessment. Science 344, 1109–1113. https://doi.org/10.1126/science.1248361.

Hewu, W., Xiaobin, Z., Minggao, O., 2015. Energy and environmental life-cycle assessment of passenger car electrification based on Beijing driving patterns, 58, pp. 659–668. https://doi.org/10.1007/s11431-015-5786-3.

Kalverkamp, M., Helmers, E., Pehlken, A., 2020. Impacts of life cycle inventory databases on life cycle assessments: a review by means of a drivetrain case study. J. Clean. Prod. 269, 121329 https://doi.org/10.1016/J.JCLEPRO.2020.121329.

Karaaslan, E., Zhao, Y., Tatari, O., 2018. Comparative life cycle assessment of sport utility vehicles with different fuel options. Int. J. Life Cycle Assess. 23, 333–347. https://doi.org/10.1007/s11367-017-1315-x.

Kucukvar, M., Cansev, B., Egilmez, G., Onat, N.C., Samadi, H., 2016. Energy-climate-manufacturing nexus: new insights from the regional and global supply chains of manufacturing industries. Appl. Energy 184, 889–904.

Kucukvar, M., Haider, M.A., Onat, N.C., 2017. Exploring the material footprints of national electricity production scenarios until 2050: the case for Turkey and UK. Resour. Conserv. Recycl. 125, 251–263.

Kucukvar, M., Onat, N.C., Haider, M.A., 2018. Material dependence of national energy development plans: the case for Turkey and United Kingdom. J. Clean. Prod. 200, 490–500.

Kucukvar, M., Onat, N.C., Abdella, G.M., Tatari, O., 2019. Assessing regional and global environmental footprints and value added of the largest food producers in the world. Resour. Conserv. Recycl. 144, 187–197.

Kucukvar, M., Kutty, A.A., Al-Hamrani, A., Kim, D., Nofal, N., Onat, N.C., Al-Nahhal, W., 2021. How circular design can contribute to social sustainability and legacy of the FIFA world cup Qatar 2022™? The case of innovative shipping container stadium. Environ. Impact Assess. Rev. 91, 106665.

Lenzen, M., Moran, D., Kanemoto, K., Geschke, A., 2013. Building EORA: a global multi-region input–output database at high country and sector resolution. Econ. Syst. Res. 25, 20–49. https://doi.org/10.1080/09535314.2013.769938.

Luk, J.M., Maclean, H.L., 2013. Ethanol or Bioelectricity? Life Cycle Assessment of Lignocellulosic Bioenergy Use in Light-Duty Vehicles. https://doi.org/10.1021/es4006459.

Mendoza Beltran, A., Cox, B., Mutel, C., van Vuuren, D.P., Font Vivanco, D., Deetman, S., Edelenbosch, O.Y., Guinée, J., Tukker, A., 2020. When the background matters: using scenarios from integrated assessment models in prospective life cycle assessment. J. Ind. Ecol. 24, 64–79. https://doi.org/10.1111/JIEC.12825.

Messagie, M., Boureima, F.-S., Coosemans, T., Macharis, C., Mierlo, J., 2014. A range-based vehicle life cycle assessment incorporating variability in the environmental assessment of different vehicle technologies and fuels. Energies 7, 1467–1482. https://doi.org/10.3390/en7031467.

Miller, S.A., Theis, T.L., 2006. Comparison of life-cycle inventory databases: a case study using soybean production. J. Ind. Ecol. 10, 133–147. https://doi.org/10.1162/108819806775545358.

Moni, S.M., Mahmud, R., Carbajales-Dale, M., High, K., 2019. Life Cycle Assessment of Emerging Technologies: A Review [WWW Document].

Moro, A., Lonza, L., 2018. Electricity carbon intensity in European member states: impacts on GHG emissions of electric vehicles. Transp. Res. Part D Transp. Environ. 64, 5–14. https://doi.org/10.1016/J.TRD.2017.07.012.

Onat, N.C., Kucukvar, M., Tatari, O., 2014. Towards life cycle sustainability assessment of alternative passenger vehicles. Sustainability 6, 9305–9342. https://doi.org/10.3390/su6129305.

Onat, N.C., Kucukvar, M., Tatari, O., 2015. Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States. Appl. Energy 150, 36–49. https://doi.org/10.1016/j.apenergy.2015.04.001.

Onat, N.C., Kucukvar, M., Tatari, O., Egilmez, G., 2016. Integration of system dynamics approach toward deepening and broadening the life cycle sustainability assessment framework: a case for electric vehicles. Int. J. Life Cycle Assess. 21 https://doi.org/10.1007/s11367-016-1070-4.

Onat, N.C., Kucukvar, M., Halog, A., Cloutier, S., 2017a. Systems thinking for life cycle sustainability assessment: a review of recent developments, applications, and future perspectives. Sustain 9, 706. https://doi.org/10.3390/SU9050706.

Onat, N.C., Noori, M., Kucukvar, M., Zhao, Y., Tatari, O., Chester, M., 2017b. Exploring the suitability of electric vehicles in the United States. Energy 121, 631–642.

Onat, N.C., Kucukvar, M., Aboushaqrah, N.N.M., Jabbar, R., 2019. How sustainable is electric mobility? A comprehensive sustainability assessment approach for the case of Qatar. Appl. Energy 250, 461–477. https://doi.org/10.1016/J.APENERGY.2019.05.076.

Onn, C.C., Chai, C., Abd Rashid, A.F., Karim, M.R., Yusoff, S., 2017. Vehicle electrification in a developing country: status and issue, from a well-to-wheel perspective. Transp. Res. Part D Transp. Environ. 50, 192–201. https://doi.org/10.1016/j.trd.2016.11.005.

Peters, G.P., Andrew, R., Lennox, J., 2011. Constructing an environmentally-extended multi-regional input-output Table using the GTAP database. Econ. Syst. Res. 23, 131–152. https://doi.org/10.1080/09535314.2011.563234.

Qu, S., Li, Y., Liang, S., Yuan, J., Xu, M., 2018. Virtual CO2 emission flows in the global electricity trade network. Environ. Sci. Technol. 52, 6666–6675. https://doi.org/10.1021/ACS.EST.7B05191/SUPPL_FILE/ES7B05191_SI_001.PDF.

Reuter, B., 2016. Assessment of sustainability issues for the selection of materials and technologies during product design: a case study of lithium-ion batteries for electric vehicles. Int. J. Interact. Des. Manuf. 10, 217–227. https://doi.org/10.1007/s12008-016-0329-0.

Sacchi, R., Bauer, C., Cox, B., Mutel, C., 2022. When, where and how can the electrification of passenger cars reduce greenhouse gas emissions? Renew. Sust. Energ. Rev. 162, 112475.

Schmidt, W.-P., Dahlqvist, E., Finkbeiner, M., Krinke, S., Lazzari, S., Oschmann, D., Pichon, S., Thiel, C., 2004. Life cycle assessment of lightweight and end-of-life scenarios for generic compact class passenger vehicles. Int. J. Life Cycle Assess. 9, 405–416. https://doi.org/10.1007/BF02979084.

Sen, B., Onat, N.C., Tatari, O., 2020. Life Cycle Sustainability Assessment of Autonomous Heavy-Duty Trucks, pp. 149–164. https://doi.org/10.1111/jiec.12964.

Sharp, B.E., Miller, S.A., 2016. Potential for Integrating Diffusion of Innovation Principles into Life Cycle Assessment of Emerging Technologies [WWW Document].

Shimizu, T., Ihara, M., Kikuchi, Y., 2020. A Region-Specific Environmental Analysis of Technology Implementation of Hydrogen Energy in Japan Based on Life Cycle Assessment, pp. 217–233. https://doi.org/10.1111/jiec.12973.

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J.H., Theurl, M.C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., de Koning, A., Tukker, A., 2018. EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables. J. Ind. Ecol. 22, 502–515. https://doi.org/10.1111/jiec.12715.

Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., Norris, G., 2004. System boundary selection in life-cycle inventories using hybrid approaches. Environ. Sci. Technol. 38, 657–664. https://doi.org/10.1021/es0263745.

Szczechowicz, E., Dederichs, T., 2012. Regional Assessment of Local Emissions of Electric Vehicles Using Traffic Simulations for a Use Case in Germany, pp. 1131–1141. https://doi.org/10.1007/s11367-012-0425-8.

Tagliaferri, C., Evangelisti, S., Acconcia, F., Domenech, T., Ekins, P., Barletta, D., Lettieri, P., Industriale, I., Salerno, U., Giovanni, V., Ii, P., Fisciano, I., 2016. Life cycle assessment of future electric and hybrid vehicles: a cradle-to-grave systems engineering approach, 2, pp. 298–309.

Tamayao, M.-A.M., Michalek, J.J., Hendrickson, C., Azevedo, I.M.L., 2015. Regional variability and uncertainty of electric vehicle life cycle CO 2 emissions across the United States. Environ. Sci. Technol. 49, 8844–8855. https://doi.org/10.1021/acs.est.5b00815.

Tiano, F.A., Rizzo, G., De Feo, G., Landolfi, S., 2018. Converting a Conv Ntional Car into a Hybrid Solar Vehicle: A LCA Approach.

Timmer, M., Erumban, A.A., Gouma, R., Los, B., Temurshoev, U., de Vries, G.J., Arto, I., Genty, V.A.A., Neuwahl, F., Francois, J., 2012. The World Input-Output Database (WIOD): Contents, Sources and Methods. Institue for International and Development Economics.

Trudewind, C.A., Schreiber, A., Haumann, D., 2014. Photocatalytic methanol and methane production using captured CO2 from coal power plants. Part II e Well-to-Wheel analysis on fuels for passenger transportation services. J. Clean. Prod. 70, 38–49. https://doi.org/10.1016/j.jclepro.2014.02.024.

Valdivia, S., Backes, J.G., Traverso, M., Sonnemann, G., Cucurachi, S., Guinée, J.B., Schaubroeck, T., Finkbeiner, M., Leroy-Parmentier, N., Ugaya, C., Peña, C., Zamagni, A., Inaba, A., Amaral, M., Berger, M., Dvarioniene, J., Vakhitova, T., Benoit-Norris, C., Prox, M., Foolmaun, R., Goedkoop, M., 2021. Principles for the application of life cycle sustainability assessment. Int. J. Life Cycle Assess. 26, 1900–1905. https://doi.org/10.1007/S11367-021-01958-2/FIGURES/1.

Vonnahme, T.R., Molari, M., Janssen, F., Wenzhöfer, F., Haeckel, M., Titschack, J., Boetius, A., 2020. Effects of a deep-sea mining experiment on seafloor microbial communities and functions after 26 years. Sci. Adv. 6, eaaz5922. https://doi.org/10.1126/sciadv.aaz5922.

Wang, Y., Zhou, G., Li, T., Wei, X., 2019. Comprehensive evaluation of the sustainable development of battery electric vehicles in China. Sustain 11, 5635. https://doi.org/10.3390/SU11205635.

Weber, C.L., Jiaramillo, P., Marriott, J., Samaras, C., 2010. Life cycle assessment and grid electricity: what do we know and what can we know? Environ. Sci. Technol. 44, 1895–1901. https://doi.org/10.1021/es9017909.

Wolff, S., Fries, M., 2020. Technoecological Analysis of Energy Carriers for Long-Haul Transportation, pp. 165–177. https://doi.org/10.1111/jiec.12937.

Wolfram, P., Wiedmann, T., 2017. Electrifying Australian transport: hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity. Appl. Energy 206, 531–540. https://doi.org/10.1016/J.APENERGY.2017.08.219.

Woo, J.R., Choi, H., Ahn, J., 2017. Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: a global perspective. Transp. Res. Part D Transp. Environ. 51, 340–350. https://doi.org/10.1016/J.TRD.2017.01.005.

Zepf, V., 2016. Chapter 1 - An Overview of the Usefulness and Strategic Value of Rare Earth Metals [WWW Document].