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Review

Beyond Tailpipe Emissions: Life Cycle Assessment Unravels Battery's Carbon Footprint in Electric Vehicles

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Abstract: While electric vehicles (EVs) offer lower life cycle greenhouse gas emissions in some regions, the concern over the greenhouse gas emissions generated during battery production is often debated. This literature review examines the true environmental trade-offs between conventional lithium-ion batteries (LIBs) and emerging technologies such as solid-state batteries (SSBs) and sodium-ion batteries (SIBs). It emphasizes the carbon-intensive nature of LIB manufacturing and explores how alternative technologies can enhance efficiency while reducing the carbon footprint. We have used a keyword search technique to review articles related to batteries and their environmental performances. The study results reveal that the greenhouse gas (GHG) emissions of battery production alone range from 10 to 394 kgCO_2 eq./kWh. We identified that lithium manganese cobalt oxide and lithium nickel cobalt aluminum oxide batteries, despite their high energy density, exhibit higher GHGs (20–394 kgCO_2 eq./kWh) because of the cobalt and nickel production. Lithium iron phosphate (34–246 kgCO_2 eq./kWh) and sodium-ion (40–70 kgCO_2 eq./kWh) batteries showed lower environmental impacts because of the abundant feedstock, emerging as a sustainable choice, especially when high energy density is not essential. This review also concludes that the GHGs of battery production are highly dependent on the regional grid carbon intensity. Batteries produced in China, for example, have higher GHGs than those produced in the United States (US) and European Union (EU). Understanding the GHGs of battery production is critical to fairly evaluating the environmental impact of battery electric vehicles.

Keywords: LCA; solid-state batteries; Li-ion batteries; electric vehicles; transportation

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1. Introduction

The transportation sector accounted for approximately 15% of the global GHG emissions in 2022, representing a 3% increase over the 2021 figures (reaching 7.95 Gt CO_2) [1]. Within the realm of transportation emissions, road transport is the dominant contributor, constituting 74% [2,3]. While electric vehicles (EVs) offer a promising solution in many regions of the world, the life cycle greenhouse gas emissions of these vehicles extend beyond the elimination of tailpipe emissions.

Numerous studies unequivocally attest to the superior environmental advantage of battery electric vehicles (BEVs) in comparison to their counterpart—the internal combustion engine vehicles (ICEVs) [4–8]. In 2023, a report from the European Union's Policy Department for Structural and Cohesion Policies indicated that, under average European Union (EU) conditions, a contemporary BEV already achieves a noteworthy reduction of over 60% in kg CO_2-eq compared to a comparable conventional gasoline car [9]. Furthermore, the study forecasts substantial reductions in GHG emissions across various scenarios and countries over the vehicle's entire life cycle. Projections indicate that by 2030, the average GHG emissions impact of BEVs in the EU27 could be 78% less than that of equivalent conventional gasoline cars, with the potential to reach an 86% reduction by 2050 [10]. This remarkable transition is underscored by a rapid growth in the adoption of lithium-ion batteries (LIBs), either exclusively in BEVs or in combination with conventional engines, as observed in plug-in hybrid electric vehicles (PHEVs).

Currently, the EV sector global spend is valued at over \$425 billion in 2022, with projections pointing to substantial expansion in the forthcoming years, as it is predicted to grow up to 350 million by 2030 compared to 6.5 million in 2021 [11]. According to the international energy agency (IEA), the global population of BEVs was projected to surpass 14 million by the end of 2023, representing that one out of every five new car sales in 2023 were electric vehicles [11]. The entire sales of electric cars tripled within a four-year span, transitioning from 3% in Q1 of 2021 to more than 10% in Q3 of 2023 [12]. While several studies affirm their substantial emission reduction potential compared to conventional vehicles, the focus is shifting towards a holistic understanding of their environmental footprint.

Despite the BEV slowdown, China continues to lead the BEV market, accounting for 8.1 million stocks in 2023 [13]. The sales are expected to increase by 18% in 2024 compared to the previous year. Similarly, the United States' sales increased by 47% in 2023 compared to preceding year, reaching a total of 1.4 million. According to BNEF, the US sales are expected to reach 1.9 million in 2024 [14,15]. Nevertheless, the adoption of electric vehicles remains sluggish in developing countries, primarily due to the elevated costs associated with them [16]. Some of the key players in the battery value chain are listed below in Figure 1. As previously mentioned, the trajectory of BEV sales growth observed in recent years could potentially align the carbon dioxide (CO_2) emissions stemming from cars with the trajectory required for the Net Zero Emissions by 2050 scenario. Despite the common reference to BEVs as "zero-emission" vehicles, there exists a debate, alongside a consensus, that while fully electric vehicles do not emit greenhouse gases directly during operation, their ecological impact does shift to the electricity generation process [17,18]. Therefore, the setup for charging these vehicles plays a crucial role in determining their overall environmental impact [19].

Figure 1. Key players in the current battery value supply chain based on the life cycle stages.

Furthermore, the total GHG emissions produced during the manufacturing of batteries vary in many ways, due to location. The emissions during the manufacturing of batteries in China could be three times higher than those manufactured in the United States (US) [20,21]. As a result, comprehending how the environmental efficiency of these batteries is influenced by both their chemical composition and the location of their production holds significant importance. BEVs exhibit higher GHG impacts during their production phase, mainly due to the battery packs. However, this initial drawback is counterbalanced by significantly lower GHG emissions during the usage phase. The manufacturing and assembly of batteries involve energy consumption, the release of harmful emissions, and safety concerns during the material extraction process. Additionally, understanding the risks associated with battery disposal, including high voltage dangers, disassembly costs, and toxicity, is essential.

The emissions during EV battery production can vary significantly depending on the source, methods used, assumptions made, and geographic location. According to Beiker et al., it is noted that the environmental impact of producing batteries can range from approximately 60 kg CO_2-eq/kWh to 146 kg CO_2-eq/kWh [22]. This variability is due to factors like the source of electricity, variations in production methods, efficiency, and raw material sourcing. On the other hand, Yu et., al. revealed wider consequences such as special advantages for plug-in electric vehicles (PEVs), leading to higher greenhouse gas emissions due to lenient regulations and indirect influences. This argument covers various areas and underscores the importance of including greenhouse gases in regulations to encourage the adoption of electric vehicles [18]. Regulations play an important role in deciding the future of transportation. Recently, Europe underwent significant changes with the implementation of battery passports. These passports help in the transparency on environmental footprint of different battery material and their manufacturing throughout the life cycle of the batteries. This mandate allows the manufacturers to provide detailed information on the sourcing of battery materials and recycling methodologies, helping the manufacturers to achieve the sustainable design and disposal of battery materials [23,24].

Conventional lithium-ion batteries (LIBs), despite dominating the market, come with a carbon-intensive manufacturing process involving energy-intensive steps like mining, refining, and electrode fabrication. This review investigates emerging alternatives like solid-state batteries (SSBs) and sodium-ion batteries (SIBs) as potential solutions for enhancing vehicle efficiency and minimizing the carbon footprint. Beyond mere battery chemistry, regional variations in manufacturing emissions highlight the importance of responsible sourcing and clean energy integration. Leading battery manufacturers like CATL, BYD, LG Chem, Panasonic, and Samsung SDI play a crucial role in shaping this landscape. Furthermore, the challenges of battery disposal, recycling, and second-life applications demand innovative solutions to ensure true sustainability. This review comprehensively analyzes the life cycle analysis (LCA) methodologies employed to assess the environmental impact of various battery technologies for passenger vehicle electrification. We compare key performance metrics, environmental trade-offs, and challenges associated with Lithium Nickel Cobalt Manganese (NCM) Oxide, Lithium Nickel Cobalt Aluminum (NCA), Lithium Iron Phosphate (LFP), SSB, and SIB technologies. By offering insights into these emerging options, we aim to inform stakeholders in navigating the complex landscape of sustainable EV battery development and deployment.

2. Materials and Methods

A variety of battery technologies are used in different automobiles, and they are driven by numerous factors, including pricing, battery lifespan, duration of charge, safety, environmental adaptability, and sustainability [25]. Nowadays, batteries come in various forms, including lithium-ion, nickel–metal hydride, lead–acid, and ultracapacitors (listed below). There are a variety of battery technologies, which are listed below [25]:

2.1. Conventional Technologies

1. Lead–Acid Batteries
2. Nickel–Metal Hydride
3. Lithium-Ion
4. NCM—Lithium Nickel Cobalt Manganese Oxide ($LiNiMnCoO_2$)
    I NCA—Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$)
    II LFP—Lithium Iron Phosphate ($LiFePO_4$)
5. Zn-Ion batteries

2.2. Emerging Technologies

1. Solid state batteries (SSB's)
2. Sodium ion batteries (SIB's)

Lead–acid batteries, nickel–metal hydride, lithium-ion, and zinc-ion batteries are a few conventional technologies, while solid-state batteries, solid ion batteries, Li–S, Li–Air, flow batteries, etc., are emerging technologies [26]. The classical representation of both the conventional and emerging batter technologies is shown in Figure 2. Several researchers have stated that Li-ion batteries are the most dominant in the automobile industry [25,27]. Studies have reported that Li- and Zn-ion batteries have been trending in the field over the past seven years [28]. These are well-suited technologies for electric vehicles [25], devices, and storage systems because of their good energy density range, cost, and performance [29,30]. Both the transparency and accuracy of data quality are required to study the environmental footprint of LIBs [29]. However, due to its high energy density, it is the most accepted battery technology [20].

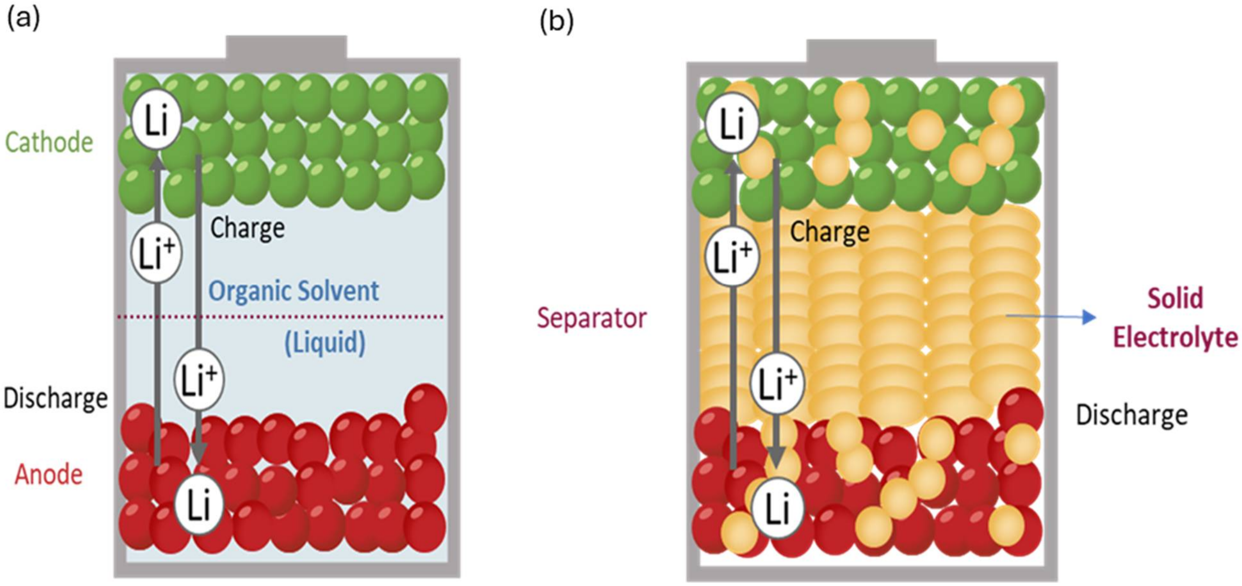

Figure 2. Classical representation of (**a**) conventional Li-ion batteries and (**b**) Solid-state batteries.

Benveniste [31] noted that the EV driving range is dependent on limiting factors like volume and weight baselined by the energy densities of the vehicles, through which even having the driving range approach 500 km (about 310.69 mi) for battery-powered vehicles is difficult. Just a few years from now, solid-state batteries will be employed in EVs, which will revolutionize how people view electric vehicles. Authors have reported that Li–S batteries are the cleanest batteries of all during their usage life [30]. Benveniste [31] has interpreted that the Global Warming Potential (GWP) released from the manufacturing sector for Li–S batteries is 31% lower than that of Li-ion battery manufacturing. Researchers have rigorously studied solid-state battery technologies for the past few years, yet they are unable to hold their position due to certain drawbacks related to ionic conductivity, electrode suitability, and lack of awareness in the market [32]. However, researcher Lia [33] mentioned that extensive studies have not been carried out focusing on the comparative aspects of these batteries. Metal–air batteries are 100× times better than ordinary Li-ion batteries [26].

During our research, we collected data represented in Table 1, including different gravimetric energy density (Wh/kg) and volumetric energy density (Wh/L) data for both conventional and emerging battery technologies. Some of these energy densities are based on their material characteristics, which can help us identify the maximum potential of their battery chemistry [34]. Studying the complex chemistries of the emerging battery technology will help us double or triple the range of EVs compared to conventional battery technologies [35].

Table 1. Gravimetric (Wh/kg) and volumetric (Wh/L) energy densities of conventional and emerging technologies.

Technology Type	Battery Technologies	Energy Density Ranges	Reference
Conventional Technology	NCA (Nickel Cobalt Aluminum Oxide)	200–260 Wh/kg 700 Wh/L	[36]
	LFP (Lithium Iron Phosphate)	90–165 Wh/kg	[37]
	NCM (Nickel-Cobalt-Manganese)	150–300 Wh/kg	[37]
		260 Wh/kg	[32]
		770 Wh/L	[32]
	Li-ion	250 Wh/kg	[38]
		200–250 Wh/kg	[39]
		450 Wh/kg (Expected by 2030)	[40]
Emerging Technology	Li-Air	11,400 Wh/kg (Theoretical)	[41]
	Li_2O_2	3505 Wh/kg (Theoretical)	[42]
		700 Wh/kg (Achieved)	[43]
	SIB’s	100–150 Wh/kg	[37]
	Li-S	2600 Wh/kg (Theoretical)	[31]
		500–550 Wh/kg	[44]
	Li-MnO_2	150–250 Wh/kg	[45]
		500–650 Wh/L	[45]
	Li-(CF)n	200–300 Wh/kg	[45]
		500–600 Wh/L	[45]
	Li-SO_2	240–315 Wh/kg	[45]
		350–450 Wh/L	[45]
	Li-$SOCl_2$	500–700 Wh/kg	[45]
		600–900 Wh/L	[45]

Other types of conventional batteries are LFP batteries; LFP and LMO batteries are considered mature battery technologies within the realm of conventional battery technologies [46]. Although the battery chemistry of LFP possesses lower energy density than NCA and NCM battery chemistries [47], characteristics like specific energy density and power make these two batteries reliable enough in EVs [40]. A brief comparison made by Ambrose and Kendall [48] expounds that when battery chemistries, i.e., NCA/NCM, LMO, and LFP, are compared, their chemistries exhibit greater thermal stability and a longer cycle life when examined in ascending order. While comparing in reverse order, these automotive lithium batteries possess a higher operating voltage and high energy densities. The efficacy of these battery technologies depends on the type of cathode material, the costs, and their life cycle, so LMO has been noted to have low costs and a low life cycle expectancy [48], even though researchers still consider LMO a developing battery technology [49].

According to Ramjan Ali et al. [49], the Jan–Teller phenomenon of Mn^{3+} has raised concerns in general, even when their cathode material has a good surface area and high thermal stability. The electrochemical performance of LMO battery chemistries was noted to represent the assertive scope of LMO batteries in the EV market [49]. Furthermore, Chatzogiannakis et al. [50] claimed that high rates of energy density enhancement are obtained by blending NCM and LMO, with the mixture containing 25% LMO showing the highest electrochemical performance. He worked around several combinations of NCM and LMO blending during his experiment and concluded that such an approach can unveil the synergic effects of the electrodes [50] and help researchers enhance their rate capabilities, life cycles, and energy densities. Thus, researchers can broaden the scope of their design strategies by blending different electrode compositions in search of more approachable and efficient battery technologies in the EV market.

Besides LMO batteries, the battery chemistry of LFP is such that it favors fire safety, operating costs, and potentially good flexibility in discharge depth, which contemplates a significant benefit for short-term applications, resulting in the popularity of LFP in the EV market [51]. Unlike Li-ion batteries, LFP and LMO batteries are not made with toxic and hazardous metals, lowering their ecological impacts [46].

2.3. Life Cycle Assessment Methodology

The automotive industry's shift towards sustainable technologies necessitates a comprehensive understanding of battery technologies' environmental impact across their entire life cycle. LCA emerges as an invaluable tool, enabling comparative analysis and informed decision-making. By quantifying the environmental burdens associated with raw material extraction, production, use, and end-of-life management, LCA allows for:

1. Comparative analysis: Highlighting the environmental strengths and weaknesses of different battery chemistries (e.g., NCM, LFP, LMO).
2. Informed decision-making: Guiding manufacturers and policymakers in developing sustainable practices for battery production and use.
3. Continuous improvement: Identifying hotspots (processes with significant environmental impacts) across the life cycle, promoting innovation and optimization.

Irrespective of the current trend, most of the past research has been limited to analyzing GHG emissions, considering the kg CO_2 equivalent as emitted [52,53]. The current impact categories include factors like material depletion potential, toxicity, fossil depletion, etc. [54]. These environmental factors provide us with a broader view of identifying the impacts encountered using different battery technologies.

A comprehensive picture of the significant impacts originating from the different uses of battery technologies in EVs can be studied by LCA. The LCA analyzes the potential environmental impacts of a product or service throughout its life cycle, including the extraction of raw materials and the production, use, and final disposal of the product, as shown in Figure 3.

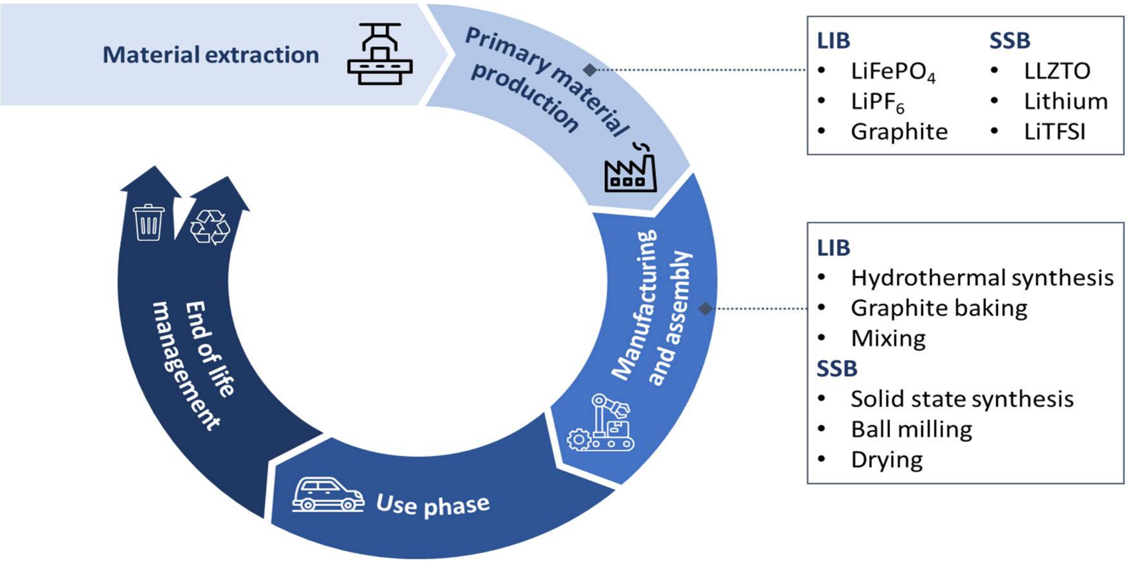

Figure 3. System boundary of both conventional and emerging battery technologies.

The implementation of the LCA is regulated by the International Organization for Standardization (ISO): ISO 14040 Environmental Management [55], covering life cycle assessment principles and framework, and ISO 14044 Environmental Management [56], covering life cycle assessment requirements and guidelines (ISO 14040:2006, 2006 (ISO, 2006)) (ISO 14044:2006, 2006 ISO, 2006). The goal and scope definition are as follows: Specifying the study's objectives, functional unit (e.g., per kWh of battery capacity), technologies to compare, and life cycle stages to analyze. The inventory analysis includes the following: Compiling data on all inputs and outputs associated with each life cycle stage, including materials, energy consumption, emissions, and waste generated. The impact assessment is as follows: Quantifying environmental impacts based on inventory data using various categories like climate change, resource depletion, and human health. Furthermore, the interpretation encompasses the following: Drawing conclusions and recommendations based on the study's objectives, identifying hotspots, potential improvements, and study limitations. Standardized frameworks like ISO 14040 and 14044 ensure the quality, transparency, and consistency of the LCA results [55,56].

The scope of LCA is defined as "from the cradle to the grave", i.e., the environmental impact will be assessed from the extraction of raw materials through the manufacturing phase, the phase of use in an EV, until its final management, including the recycling operations and potential material recovery.

3. Discussion

3.1. Regional Differences in Life Cycle Greenhouse Gas Emissions of NCM Batteries

This section gives an overview of life cycle GHG emissions of NCM batteries across the different countries around world. Kelly et al. [57] presented the differences in GHG emissions in their study, considering the electricity grids of five different locations (55–73 g CO_2-eq/kWh) as shown in Figure 4. They concluded that the production of NCM 111 batteries produced the least amount of GHG emissions in the US and European regions. Also, Winjobi et al. [58] produced similar results while considering that nickel resulted in higher energy densities at lower costs compared to cobalt. In nickel-based battery technologies, it was notably observed that with an increase in nickel content, the amount of GHG emissions decreased due to the specific energy variations. In accordance with the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) baseline study, researchers noted that the GHG emissions are driven by the feedstocks of $NiSO_4$ production, which has a substantial impact. The $NiSO_4$ production from Class I Nickel alone released higher emissions of SOx, which in turn increased the GHG emissions of NCM 111 by 66%. If the same production was completed with mixed hydrogen precipitate (MHP), then the GHG emissions would have been reduced by 46%. Considering the region-specific emissions, researchers observed lower GHG emissions when the production of NCM 111 batteries sourced energy from wind or hydroelectric plants. The overall GHG emissions from China were high, but it did divert a certain amount of GHG emissions, considering their hydro-powered energy use for aluminum electricity production instead of using coal. In terms of aluminum production, Winjobi referred to the variations noted during the aluminum production, with the impact categories being less than 20% while considering SOx emissions, which were recorded to increase by 30% when considering battery technologies with higher nickel content. In the case of hydropower-sourced categories, the authors contemplate the variation ranging from 37% to 46% as being influenced by the water consumption during the production. The insights into the remaining cathode contributions from research were triggered by NCM-powered production in the region, where researchers observed a 9% hike in NCM111 GHG emissions from coal-dependent electricity grids compared to hydro-powered electricity grids. The results for cell assembly in hydro-powered electricity sources had a 100% influence from water consumption during production compared to the NCM111 GREET 2020 baseline, while the battery management systems reflected slight variations only. Thus, each sub-component has their own involvement in influencing the productions based on their properties with different electricity mixes. The environmental impacts may vary depending on individual properties, requiring thorough study to exert the least GHG emissions from the production streamline.

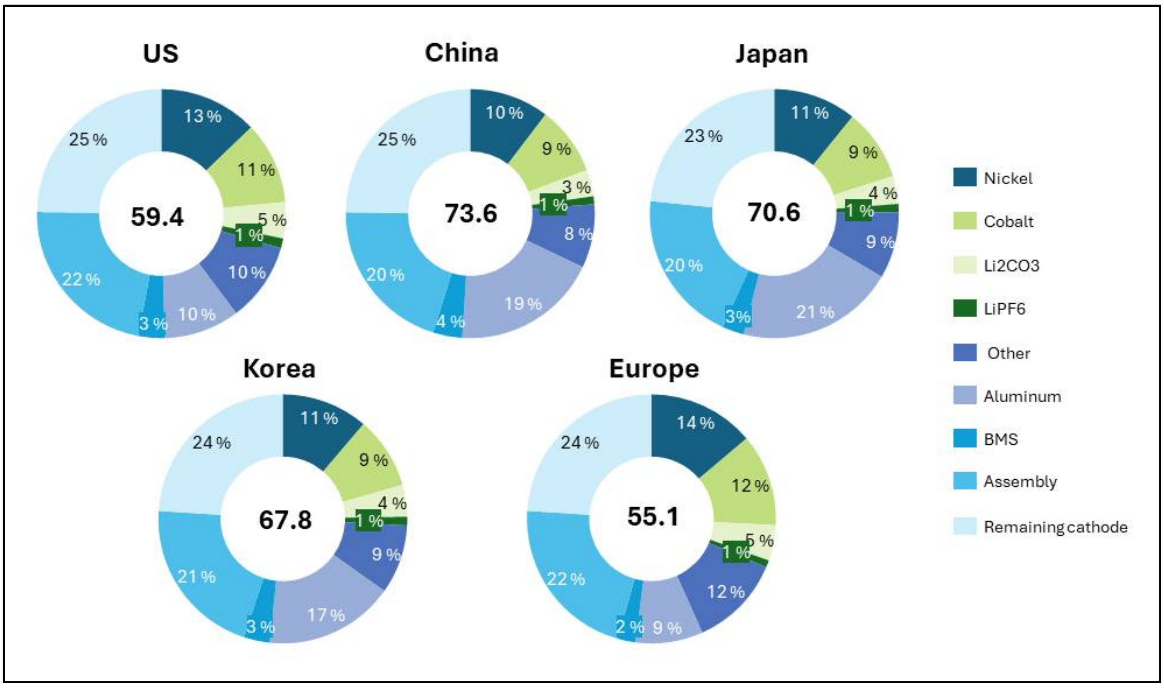

Figure 4. LC GHG emissions of NCM batteries across countries of world.

3.2. Research Gaps and Recommendations

3.2.1. Life Cycle Analysis of Conventional Batteries for Automobiles

A review of the environmental performance indicators also explored GHG emissions from different battery technologies during this proposed study. Research on certain battery technologies is less extensive than the widely adopted ones. We observed that the field is emerging, and fewer research articles have been materialized by researchers related to the LCA of different battery technologies. Batteries like Li-ion, LFP, and LMO batteries are the most researched technologies. Emerging technologies are merely touched on and materialized as per the LCA approach. A lack of technical data for these emerging battery technologies is responsible for their low reliability. Further research is required to recognize the compatible battery technologies that fulfill the environmental and economic requirements.

This section presents a review of the LCA of conventional batteries (NCM/NCA, LFP, and LMO). Among the reviewed articles, the conventional battery LCA reported emissions using three different functional units as follows: Life of the vehicle per km basis [38,48,59], per kWh, or battery pack mass. The system boundaries reported in the literature are either cradle-to-gate [30], cradle-to-cradle [60,61], cradle-to-grave [62], or well-to-wheels [63]. The typical battery-making process involves five major steps, which include the following: cathode production, anode production, electrolyte production, assembly, and conditioning [64,65]. Cathode production and electrolyte production play a significant role in evaluating the impacts of batteries.

Lithium Nickel Cobalt Manganese Oxide (NMC) Batteries

The life cycle impacts of batteries evaluated in the recent studies are either based on the previous literature, simulated models such as a bat pack, or lab-scale studies. It is crucial to know the composition of batteries to evaluate their impact, and only a few studies have provided a detailed analysis of the composition of several types of LIBs [66]. The basic conventional batteries are NCM batteries, where NCM refers to key materials used in the cathode (nickel, cobalt, and manganese), and a suffix number attached to the battery represents the composition ratio of each material. Though some studies provide detailed compositions of batteries (NCM 111, NCM 622, and NCM 811), they do not include detailed material specifics such as the composition of the battery case [67] or a particular component [68]. Some studies relied on weight proportions from other NCM batteries to estimate the composition of new battery technologies such as NCM523 [69]. However, none of the studies evaluated the impact of the complete life cycle of batteries [70–72]. Another important aspect of LIB is the increased energy density that can be obtained with high nickel use in the composition, which results in decreased use of lithium and cobalt [73]. Silicon is one of the promising solutions, but it has issues with stability in the long term.

A complete list of studies and impacts is highlighted in Appendix A, Table A1, showing GHG emissions ranging from 30 to 400 kg CO_2-eq/kWh. The emissions vary largely, mainly due to the different electricity grids used in the manufacturing of batteries, which are specific to the location of the study. Other key parameters affecting the variation in emissions are the use of tetrafluoroethylene, which has high CO_2 emissions in its production [74]. Most of the studies are based on Ellingsen et al. [75], which uses industrial data. It was observed that the data from the manufacturing energy calculations of Dunn et al. [76] were not clear. Kim et al. [70] studied real-time industrial battery specs, and the NCM/LMO-type batteries showed low emissions with 65 kg CO_2-eq/kWh of battery energy. All the studies show some differences due to data quality and assumptions in the studies. The studies use different anode materials for different battery types; the main anode materials include acrylonitrile butadiene styrene, Polytetrafluoroethylene (PTFE), carboxymethyl cellulose, Polyvinylidene fluoride (PVDF), and acrylic acid. Further research in the field is conducted with newer battery technologies, even though NCM is a widely used battery technology. Researchers have observed that other newer technologies have lower environmental impacts compared to NCM [74].

Lithium Iron Phosphate (LFP) and Lithium-Ion Manganese Oxide (LMO) Batteries

Similarly, researchers have noted that energy consumption varies based on the cathode material during the battery manufacturing phase [31]. Dunn's interpretation (as cited in Benveniste [31]) implies that LFP has the least energy consumption during the manufacturing phase compared to lithium cobalt oxide (LCO) and NCM batteries, and the environmental impact of LFP was less than that of other LIB batteries. Other LIBs like LFP and LMO release GHG emissions at various stages of the battery's life cycle. However, they still have lower environmental impacts than other LIB batteries (Tolo Mea et al., 2020, as cited in [46]). The overall LCA studies by Arshad et al. [46] reflected that the battery chemistry of LMO has the lowest environmental impacts compared to LFP and NCM battery chemistries, as we refer to the data in Figure 5. They studied the environmental impacts like global warming potential, ozone depletion, acidification potential, ozone depletion potential, particulate matter formation potential, cumulative energy potential, human toxicity potential, metal depletion potential, photochemical ozone formation potential, eutrophication potential, and abiotic depletion potential for these battery technologies. The environmental performance of these batteries could result in lower emissions if renewable energy is utilized to charge them [40], which indeed reflects the importance of identifying the electric grid. LFP is way easier to recycle than LMO as the material complexities [40] added by nickel and cobalt are not found in LFP [47], which reduces the CO_2 during the recycling process [46,49]. The life cycle environment cost of the LFP is recorded to be the lowest by Hao et al. [50]. Hao also noted the contribution of GHG emissions, considering the production of a rated capacity of 28 kWh of LFP vehicle use, which is 109.3 kg CO_2-eq/kWh, and LMO vehicle use, which is 96.6 kg CO_2-eq/kWh.

Revolutionizing these battery-operated vehicles can only be enhanced by deepening our understanding of battery chemistry. Different cell formats, such as pouches, cylinders, and prismatic, also play an important role when it comes to the battery's energy efficiency [46]. It has been reported that few researchers have assumed that the energy efficiency of the batteries is recorded to be 80–95% when they studied cell formats during their research [46]. Thus, it is suggested to consider all the important factors while doing an LCA for automotive battery technologies to be able to sustain themselves in the fast-growing EV market.

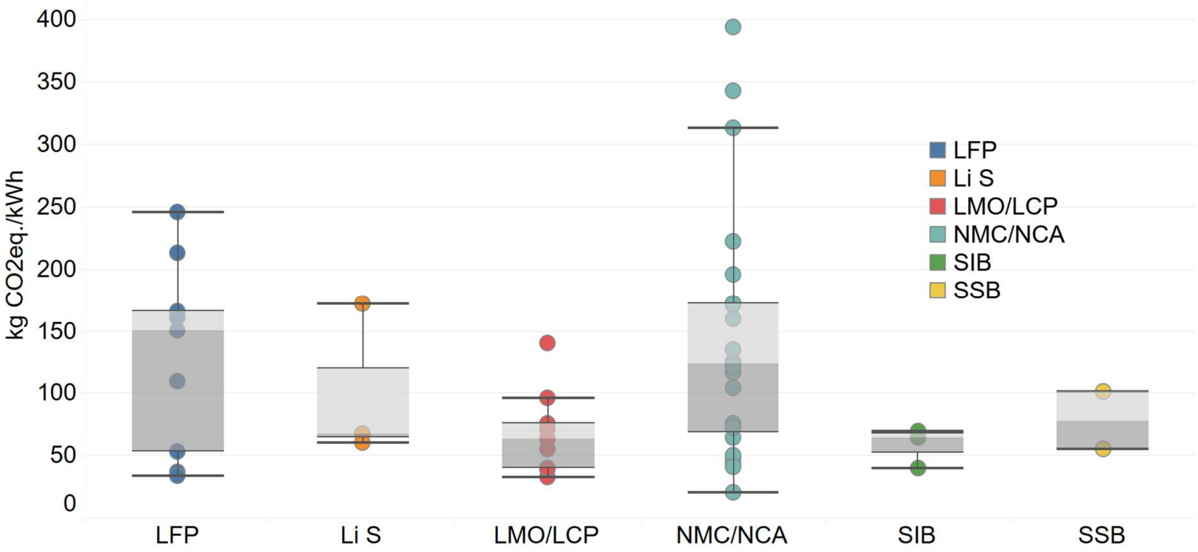

Figure 5. Greenhouse gas emissions of conventional and emerging technologies in the literature (underlying data for the figure is provided Appendix A Table A1).

3.2.2. Life Cycle Assessment of Emerging Batteries for Automobiles

Solid State Batteries (SSBs)

The following section will provide a review of the LCA of most emerging battery technologies, such as SSBs and SIBs. Since conventional batteries have reached a plateau, enhancements of their energy densities are limited if used individually [75,76]. Therefore, there is a substantial focus on emerging technologies such as solid-state batteries. However, there are very few studies looking at the LCA of SSBs, and most of them are based on lab scale data. Most of the studies focus on either the economics of SSBs or omit the comparison of SSBs in the study. The studies use a bottom-up approach to evaluate the impacts, and each study uses different functional units (kWh, mAh, kg, and cell). The studies in the literature evaluate the impacts of SSBs on a wide variety of applications, such as energy storage systems, aircraft, and research. The main advantage of SSBs is the use of a solid electrolyte, which increases the conductivity and energy density [75,77] and requires fewer materials as they do not require a separator. The SSBs improve safety because of the use of solid material in the battery [77].

The emissions of solid-state batteries range from 20 to 305 kg CO_2-eq/kWh and the differences in emissions are mainly due to a wide range of parameters, including the location of the study, differences in energy demand, and country-specific grid mix. Popien et al. [78] conducted a comparative LCA in Germany between different LIBs and SSBs, and results from the study are listed in Table 2. They use Li_2S–Li_3PS_4 (LPS) as a solid electrolyte due to its high ionic conductivity [79], and Li metal is used as an active material. The BatPaC model [80] was used to estimate the composition and material proportions of the battery, and the total mass of the SSBs reported ranges from 220 to 360 kg, and the specific energies range from 200 (SSB–LFP) to 362 (SSB–LSB). Four key impact categories were analyzed, namely climate change, material resource depletion, human toxicity, and photochemical oxidation. It was also indicated that the environmental performance of SSBs could be increased by coating the active cathode material with Lithium Niobate using the Atomic Layer Deposition (ALD) and Physical Vapor Deposition (PVD) techniques. Wickerts' [81] study focused on the application of SSBs for energy storage purposes and analyzed six different scenarios with LiTFSI as the electrolyte and found that the electricity source, life cycle of the batteries, and the specific energy density are the key parameters to reduce the environmental impacts. They considered different electricity mixtures (low intensity, medium intensity, and high intensity) with a scope of both cradle-to-gate and cradle-to-grave, considering the end of the life of LIS. Battery production was based on the previous literature [81] and the emissions ranged from ~40 to 305 kg CO_2/kWh based on the configuration. Barke et al. [82] conducted a similar study on Li–S batteries with different high-performance solid electrolytes such as $Li_{10}Ge\ (PS_6)_2$, $Li_{10}Sn\ (PS_6)_2$, $Li_{10}Si\ (PS_6)_2$, and Li_6PS_5Cl, and evaluated emissions and other impact categories for aircraft applications. The emissions reported from the study ranged from 56.6 to 64.3 kg CO_2 eq/kWh. Benveniste [31] noted that Li–S has significant potential to land as a promising electrochemical storage technology with a theoretical value of 2600 Wh/kg energy densities, and they used the Gabi Database to study the energy consumption of Li-ion and Li–S batteries during their manufacturing and use phases. He considered the database for the Li–S batteries from a partner project, the high energy lithium sulfur batter (HELIS) project [44]. The functional unit defined during the study was 1 kWh for both batteries to be able to deliver the energy for a 150,000 km (about 93,205.68 mi) vehicle drive. The study used CML 2011 and ReCiPe 2008 to interpret several environmental impact categories. Overall, solid-state batteries face several technical issues, such as maintaining a dry atmosphere inside the battery, that act as a barrier for the technology to scale up industrially [32,83,84]. The key findings from different studies are tabulated below in Table 2. In Mandade et al. [32], the authors did an extensive review of six LCA studies on SSBs.

Table 2. Comprehensive review of a few Life Cycle Analyses of SSBs.

Year	Source of Study	GHG Emissions	Battery Format Type	Cathode Type	Research Insights
2016	Troy et al. [85]	0.2–5.4 kg CO_2-eq per pouch	Pouch with 43.75 mAH	Inorganic	LLZO electrolyte production accounts for the majority of energy consumption.
2017	Vandepaer et al. [86]	70-98.12 kg CO_2-eq./kWh of storage	LMP-75 kWh LMP-6MWh for stationary storage	Polymer (LMP)	Pilot scale project with low ionic conductivity and low Temperatures
2022	Zhang et al. [87]	0.103 gm CO_2 eq./km	Coin cell using primary data literature	ASSB with inorganic electrolyte LATP	Lowering thickness improves energy efficiency and reduces impacts
2020	Smith et al. [88]	79.11 kg of CO_2-eq./kg cell material	$Li_7La_3Zr_2O_{12}$ (LLZO) garnet-structured electrolyte	Inorganic	Electrolyte production has major impacts due to the high temperature sintering process during manufacturing.
2014	Lastoskie et al. [71]	25–85 kg CO_2-eq/kWh	Pack	Inorganic	Silver, Nickel, or Cobalt have high emissions. LVO and LNMO have the least
2023	Popien et al. [78]	79–123 kg CO_2-eq/kWh	SSB-NCA, SSB-LFP, SSB-NMC, and SSB-Li-S	ASSB with inorganic electrolyte	More environmental benefits to LSB, even more with the use of renewables in production process
2023	Wickerts et al. [81]	40–305 kg CO_2-eq/kWh	LIS	SSB with LiTFSI as electrolyte	LiTFSI as electrolyte production was key contributor
2023	Barke et al. [82]	56.6–64.3 kg CO_2-eq/kWh	LIS	With different electrolyte configurations	LiS-ASSB[Ge] performs worst, and LiS-ASSB[Cl] performs best in all categories

Sodium Ion Batteries (SIBs)

Due to the technology readiness level of these emerging batteries, conducting LCAs is slightly difficult. However, there are three diverse ways one can conduct the analysis, which include the following: (1) Simple screening based on uncertain data; (2) cell-level analysis; and (3) based on the engineering approach. In the literature, very few studies have focused on the LCA of sodium-ion batteries. Some of the key studies and their results are highlighted below in Table 3.

Table 3. Review of LCA of SIB battery technologies.

Source of Study	Recorded GHG Emissions in the Proposed Study	Type of Electrode	Research Interpretation
Peters et al. [89]	50–90 kg CO_2-eq./kWh	NaNMC, NaMMO, NaNMMT, NaPBA, and NaMVP	The manganese and nickel–manganese-based SIB chemistries show promising environmental benefits compared to other chemistries
Rey et al. [90]	423.9–1380.0 kg CO_2-eq./ kg cathode, 18–38% reductions can be achieved by shifting to renewable electricity sources	$Na_3V_2(PO_4)_3$ Cathode active material (CAM)	The $Na_3V_2(PO_4)_3$ cathode code is as follows: 1: "hierarchical carbon-NVP" 2: "rGO-LbL NVP" 3: "µPorous NVP" 4: "N-doped carbon NVP" 5: "N,B-doped carbon/NVP" 6: "La^{3+}-doped NVP" 7: "3D NVP nanofiber" 8: "Nanoplatelet NVP" 9:"Agarose carbon NVP" and 10: "Glucomannan NVP"
Mozaffarpor et al. [91]	15.3, 14.2, and 20.0 kg CO_2-eq. per kg NMCP	NMCP CAM	NMCP materials produced via ball milling, hydrothermal, and stirring-assisted hydrothermal methods
Liu et al. [92]	4.07 and 4.61 kg CO_2 eq/kg anode	Different hard carbon anodes	Hydrothermal carbonization (HTC), followed by pyrolysis and direct pyrolysis (5.82 industry scale graphite)
Peters et al. [93]	10–70 CO_2-eq/kWh	42 different cathode materials	Emissions related to cell material and cell manufacturing are ignored
Trotta et al. [94]	615, 500 and 5.5 kg CO_2/kg anode	Glucose, Kuranode, and graphite Anode material	Due to well-established industry process, graphite anode has lower emissions compared to other anode material

Liu [92] and Peters [89] looked at the LCA of different hard carbon anodes for SIBs, while Trotta [94] focused on biomass-derived hard carbon anodes (Glucose, Kuranode, Graphite). Other studies focused on different cathode materials, such as $Na_3MnCO_3PO_4$ [91] and $Na_3V_2(PO_4)_3$ [90], while Peters [93] screened around 42 different sodium-based cathode materials and compared them with conventional LFP and NCM batteries' cathode materials. The cell energy densities ranged from 120 to 150 Wh/kg [37]. These studies did not conduct a complete life cycle of SIBs, nor did they use the primary source of data to conduct the analysis. However, Peters [89] conducted a full life cycle analysis of SIBs with 2000 life cycles and reported high emissions of 140.3 kg CO_2-eq/kWh battery because of the low energy density (102 Wh/kg). The study uses an organic solvent with a $NaPF_6$ electrolyte and a polyethylene/polypropylene separator. The key parameters impacting the overall global warming potential include the following: (1) hard carbon production (24%), the production of sugar, which is a precursor in hard carbon production; (2) the cathode (55%); and (3) electricity used for manufacturing the pack (21%). Another major study by Peters [95] compared the full life cycle analysis of sodium-ion batteries with that of conventional batteries. This study evaluated five distinct types of sodium-ion batteries, among which the NaNMMT ($Na_{1.1}(Ni_{0.3}Mn_{0.5}Mg_{0.05}Ti_{0.05})O_2$) and the NaMMO ($Na_{2/3}(Mn_{0.95}Mg_{0.05})O_2$) SIBs are notable for significantly lower GHG emissions (50.6 and 52.3 kg CO_2-eq/kWh, respectively). Not only do the NaNMC and NaPBA cells but also the

NaMVP (Na_4-$MnV(PO_4)_3$) show much higher emissions compared to conventional LFP batteries, due to the low energy capacity of the SIB batteries, since more cells are required to achieve a similar capacity range. In addition, they considered the full cradle-to-grave life cycle analysis using BatPaC simulations for life cycle inventory (LCI) with 1000–4000 life cycles and 136 Wh of usable capacity.

3.3. Recommendations

1. Transport stakeholders should invest in research and development to reduce the reliance on critical materials like cobalt and nickel in battery production and promote hybridization since our study reported lower greenhouse gas emissions on new emerging technologies compared to conventional batteries with cobalt and nickel. Minimal usage of batteries helps to reduce the footprint such as with its implementation in hybrid vehicles.
2. Our review suggests that the manufacturers should prioritize the development of sustainable sourcing practices and ethical mining for critical materials to reduce the carbon intensity of battery production and overall impacts of electrical vehicles.
3. Our study found that the SSB's and SIB's have the lowest emissions due to the materials, which will suggest that (a) the manufacturers and researchers should work towards broadening their spectrum towards designing battery technologies more sustainably with enhanced results. (b) There should be continued research into solid-state battery technology which should focus on improving the environmental footprint and scalability of solid electrolytes. (c) The transport industry key stakeholders should support the development and adoption of sodium-ion batteries as a more sustainable alternative to lithium-ion batteries.
4. Battery recycling and second-life applications should be encouraged to minimize waste and resource depletion in the electric vehicle industry.

Figure 6 is a breakdown of some potential factors that play a crucial role in driving these battery technologies toward a sustainable energy transition. Several studies note that material composition plays a decisive role in these battery technologies. The material composition, source availability, and cost dependencies, all falling under scope 3 emissions, have various environmental impacts. The toxicity of the materials was also recorded as a potential threat to the battery chemistries, making these sources more complex and unreliable. Thermal stability, life span, operating voltage, and energy densities are some factors that are critically dependent on the material composition of these battery technologies.

Figure 6. Potential factors driving battery technologies towards a sustainable energy transition.

In summary, beyond individual chemistries, efficient and sustainable recycling infrastructure is crucial for minimizing the environmental impact of all battery technologies. Ongoing research and development efforts aim to improve the sustainability of battery production, use, and end-of-life management across all chemistries. The choice of battery technology should consider not only performance and cost but also the aspects of environmental and resource sustainability to build a cleaner and greener future.

4. Conclusions

A comprehensive literature review was conducted to better understand the life cycle greenhouse gas emissions of conventional and emerging battery technologies. This LCA study plays an imperative role as it enables us to analyze significant factors, guiding us toward building better and more sustainable batteries. Since the battery production itself has significant emissions contribution and requires critical materials, the transport industry's key stakeholders should shift their focus towards alternatives such as hybrid vehicles that utilize significantly smaller batteries. Detailed studies on various battery compositions were assessed, such as NCM111, NCM222, and NCM811, along with the newer technology such as NCM523. Critical impacts on the environment are majorly expected to be governed based on the type of electrolyte (cathode and anode) selected for these battery technologies. Overall, the studies on these batteries should emphasize all aspects of the materials, including their chemistry, extraction, supply chain, cost, and life cycle.

Since the selection of battery technology for electric vehicles is a complex decision that involves the consideration of multiple factors, including resource availability, economic feasibility, and environmental impact, researchers and industry experts are continually investigating innovative solutions to address the shortcomings of the existing battery technologies and meet the growing demand for efficient and sustainable energy storage. Here are some key conclusions and recommendations based on the critical resource analysis:

- NCM/NCA batteries, while offering high energy density, pose significant challenges due to the limited availability of cobalt and nickel.
- LFP batteries, with their lower environmental impact and abundance of iron and phosphate, present a more sustainable option for electric vehicles, especially in applications where high energy density is not critical.
- Research related to combinations/blending of different battery technologies has significant potential to produce synergic effects on their electrodes, enriching their energy densities, improving their rate capabilities, and increasing their life cycle.
- SSB technology holds promise in terms of safety and energy density but requires further research and development to address the environmental impact and scalability challenges associated with solid electrolytes.
- SIBs, utilizing abundant sodium, offer a viable alternative to lithium-ion batteries, especially in regions where sodium resources are more accessible.

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Appendix A

Table A1. Comprehensive review of a few Life Cycle Analyses of conventional and emerging battery technologies.

Battery Technology	Literature	kg CO_2-eq/kwh	References	Functional Unit	Impact Assessment Method	System Boundary
LFP	Amarakoon et al., 2013	151	[96]	Distance travelled by vehicles lifetime	-	Cradle to grave
LMO/LCP	Amarakoon et al., 2013	63.4	[96]	Distance travelled by vehicles lifetime	-	Cradle to grave
NMC/NCA	Amarakoon et al., 2013	121	[96]	Distance travelled by vehicles lifetime	-	Cradle to grave
LFP	Ambrose and Kendall, 2016	33.9	[48]	1 metric ton of batteries	GWP, TETP and HTP	End-of-Life (Recycling phase)
LMO/LCP	Ambrose and Kendall, 2016	39.83	[48]	1 metric ton of batteries	GWP, TETP and HTP	End-of-Life (Recycling phase)
NMC/NCA	Ambrose and Kendall, 2016	41.39	[48]	1 metric ton of batteries	GWP, TETP and HTP	End-of-Life (Recycling phase)
Li S	Barke et al., 2022	60.4	[82]	1 battery pack	ReCiPe Midpoint (H) V1.13 method	cradle-to-gate
NMC/NCA	Bauer et al., 2010	135	[97]	-	GWP, HTP, AP, EP and ETP/CML and EI99	Cradle-to-Gate
SIB	Peters et al., 2017	40	[93]	1 kg and 1kWh	GWP, AP, EP, ODP, HTP, ADP and CED/Ecoinvent 3.4 ReCiPe 2008, Eco-Indicator 99/minerals and CML-IA 2002	-
NMC/NCA	Benveniste et al., 2022	394	[31]	1 kWh	CML and ReCiPe 2008	cradle to the grave
NMC/NCA	Cusenza et al., 2019	313	[98]	One LMO-NMC battery pack 140,000 km	CED, ADP, ODP, PMFP, IR, GWP, HTP, POFP, AP and EP/IPCC 2007	End-of-Life (Recycling phase)
NMC/NCA	Dai et al., 2019	72.9	[99]	1 kWh	GWP, AP and PMFP/GREET 2018	Cradle-to-gate
NMC/NCA	Deng et al., 2018	343	[100]	km	13 impact categories measured using ReCiPe method	Cradle-to-grave
LMO/LCP	Dunn et al., 2012	39	[101]	kg battery	GWP using GREET	cradle-to-gate and recycling stages
NMC/NCA	Dunn et al., 2012	50	[101]	kg battery	GWP using GREET	cradle-to-gate and recycling stages
NMC/NCA	Ellingsen et al., 2014	172	[102]	1 battery	GWP, FDP, ODP, POFP. PMFP, TAP, FEP, MEP, FETP, METP, TETP, HTP and MDP/ReCiPe Midpoint	Cradle-to-gate
LMO/LCP	Faria et al., 2014	70.9	[103]	200,000 vehicle km (service life of the vehicle)	ADP, AP, EP and GWP/CML-IA 2001	well-to-wheel
LFP	GREET, 2018	36.5	[66]	1 kWh	GWP, AP and PMFP/GREET 2018	Cradle-to-Gate
LMO/LCP	GREET, 2018	32.9	[66]	1 kWh	GWP, AP and PMFP/GREET 2018	Cradle-to-Gate
LFP	Hao et al., 2017	109.3	[50]	1 kWh	GREET 2015	Cradle-to-Gate
LMO/LCP	Hao et al., 2017	96.6	[50]	1 kWh	GREET 2015	Cradle-to-Gate
NMC/NCA	Hao et al., 2017	104	[50]	1 kWh	GREET 2015	Cradle-to-Gate
NMC/NCA	Hendrickson et al., 2015	44	[104]	1 battery	GREET 2015	End-of-Life (Recycling phase)
NMC/NCA	Jenu et al., 2020	172	[105]	1 kWh	GWP, Ecoinvent 3.5	Cradle-to-Gate
NMC/NCA	Kallitsis et al., 2020	171	[106]	Production of one traction battery	GWP, FDP, ODP, POFP, PMFP, TAP, FEP, HTP, MEP, FETP, METP, TETP and MDP	Cradle-to-Gate-
NMC/NCA	Kelly et al., 2020	65	[57]	1 kWh	GREET	well-to-wheels
LMO/LCP	Kim et al., 2016	140	[72]	1 kWh	GWP, AP, EP, PMFP and POFP	Cradle-to-Gate

Table A1. *Cont.*

Battery Technology	Literature	kg CO_2-eq/kwh	References	Functional Unit	Impact Assessment Method	System Boundary
SSB	Lastoskie et al., 2015	55	[71]	120,000 km	CED, GWP, HTP, WDP, MDP, PMFP, POFP and FEP	Cradle-to-Gate
NMC/NCA	Philippot et al., 2019	123	[107]	1 kWh	IPCC 2013 method V1.03.	Cradle-to-Gate
LFP	Majeau-Bettez et al., 2011	246	[108]	50 MJ (100 km)	GWP, CED, FDP, FETP, FEP, HTP, METP, MEP, MDP, ODP, PMFP, TAP and TETP/ReCiPe Midpoint	well-to-wheel
NMC/NCA	Majeau-Bettez et al., 2011	196	[108]	50 MJ (100 km)	GWP, CED, FDP, FETP, FEP, HTP, METP, MEP, MDP, ODP, PMFP, TAP and TETP/ReCiPe Midpoint	well-to-wheel
LMO/LCP	Raugei et al., 2019	76.1	[109]	17 kWh battery pack	CED, GWP	'cradle-to-gate' + End-of-Life boundary
NMC/NCA	Mohr et al., 2020	75.5	[110]	1 kWh	GWP and ADP/ILCD midpoint, OpenLCA 1.7.4 and Ecoinvent 3.4	-
LFP	Notter et al., 2010	53	[111]	1 kg	CED, AP, ODP, EP, PMFP, GWP and ADP/EI 99 Endpoint and CML-IA 2002	well-to-wheels
SIB	Peters et al., 2016	70	[112]	1 kg and 1 kWh	GWP, AP, EP, ODP, HTP, ADP and CED/Ecoinvent 3.4 ReCiPe 2008, Eco- Indicator 99/minerals and CML-IA 2002	-
LFP	Peters et al., 2016	161	[112]	1 kg and 1 kWh	GWP, AP, EP, ODP, HTP, ADP and CED/Ecoinvent 3.4 ReCiPe 2008, Eco-Indicator 99/minerals and CML-IA 2002	-
LMO/LCP	Peters et al., 2016	55	[112]	1 kg and 1 kWh	GWP, AP, EP, ODP, HTP, ADP and CED/Ecoinvent 3.4 ReCiPe 2008, Eco-Indicator 99/minerals and CML-IA 2002	-
NMC/NCA	Peters et al., 2016	160	[112]	1 kg and 1 kWh	GWP, AP, EP, ODP, HTP, ADP and CED/Ecoinvent 3.4 ReCiPe 2008, Eco-Indicator 99/minerals and CML-IA 2002	-
SSB	Popien et al., 2023	101	[78]	1 traction battery	climate change, human toxicity, mineral resource depletion, photochemical oxidant formation	cradle-to-gate
NMC/NCA	Qiao et al., 2017	117	[113]	-	CED, GWP	Cradle-to-Gate
NMC/NCA	Sun et al., 2020	124.5	[114]	1 kWh	PED, GWP, AP, POCP, PMFP, MDP, FDP, EP and HTP/CML-IA baseline V3.02	cradle-to-grave
LFP	Thomas et al., 2020	213	[115]	8.1 kWh	CED, GWP and MRS/ReCiPe Endpoint (H) V1.13 and World ReCiPe H/A	cradle-to-gate
Li S	Wang et al., 2020	67.94	[116]	200,000 km	GWP, ODP, PMFP, TAP, TETP, METP, FEP, FETP, HTP, MEP, METP, POFP and MDP/ReCiPe midpoint (H) and Gabi 9.2 software	Cradle-to-grave
SIB	Wang et al., 2020	64.35	[116]	200,000 km	GWP, ODP, PMFP, TAP, TETP, METP, FEP, FETP, HTP, MEP, METP, POFP and MDP/ReCiPe midpoint (H) and Gabi 9.2 software	Cradle-to-grave
Li S	Wickerts et al., 2023	172.5	[81]	1 MWh	ReCiPe 2016	cradle-to-gate and cradle-to-grave
NMC/NCA	Sun et al., 2020	124.5	[114]	1 kWh	PED, GWP, AP, POCP, PMFP, MDP, FDP, EP and HTP/CML-IA baseline V3.02	cradle-to-grave
LFP	Zackrisson et al., 2010	166	[117]	10 kWh	GWP, AP, EP, ODP and POFP/CML	well-to-wheel

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