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Analysis of the Ecological Footprint from the Extraction and Processing of Materials in the LCA Phase of Lithium-Ion Batteries

Dominika Siwiec [1,*], Wiesław Frącz [2], Andrzej Pacana [1], Grzegorz Janowski [2] and Łukasz Bąk [2]

[1] Department of Manufacturing Processes and Production Engineering, Rzeszow University of Technology, Powstancow Warszawy 8, 35-959 Rzeszow, Poland; app@prz.edu.pl

[2] Department of Materials Forming and Processing, Rzeszow University of Technology, Powstancow Warszawy 8, 35-959 Rzeszow, Poland; wf@prz.edu.pl (W.F.); gjan@prz.edu.pl (G.J.); lbak@prz.edu.pl (Ł.B.)

* Correspondence: d.siwiec@prz.edu.pl

Abstract: The development of batteries used in electric vehicles towards sustainable development poses challenges to designers and manufacturers. Although there has been research on the analysis of the environmental impact of batteries during their life cycle (LCA), there is still a lack of comparative analyses focusing on the first phase, i.e., the extraction and processing of materials. Therefore, the purpose of this research was to perform a detailed comparative analysis of popular electric vehicle batteries. The research method was based on the analysis of environmental burdens regarding the ecological footprint of the extraction and processing of materials in the life cycle of batteries for electric vehicles. Popular batteries were analyzed: lithium-ion (Li-Ion), lithium iron phosphate ($LiFePO_4$), and three-component lithium nickel cobalt manganese (NCM). The ecological footprint criteria were carbon dioxide emissions, land use (including modernization and land development) and nuclear energy emissions. This research was based on data from the GREET model and data from the Ecoinvent database in the OpenLCA programme. The results of the analysis showed that considering the environmental loads for the ecological footprint, the most advantageous from the environmental point of view in the extraction and processing of materials turned out to be a lithium iron phosphate battery. At the same time, key environmental loads occurring in the first phase of the LCA of these batteries were identified, e.g., the production of electricity using hard coal, the production of quicklime, the enrichment of phosphate rocks (wet), the production of phosphoric acid, and the uranium mine operation process. To reduce these environmental burdens, improvement actions are proposed, resulting from a synthesized review of the literature. The results of the analysis may be useful in the design stages of new batteries for electric vehicles and may constitute the basis for undertaking pro-environmental improvement actions toward the sustainable development of batteries already present on the market.

Keywords: battery; lithium-ion; ecological footprint; LCA; sustainability; mechanical engineering

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1. Introduction

The transport sector, mainly including passenger vehicles, is considered the main source of total greenhouse gas emissions internationally [1]. Switching to electric vehicles is considered a key aspect of reducing greenhouse gases [2]. Hence, the lithium-ion batteries (LIBs) used in electric vehicles have been key subjects of research in recent years. Although batteries for electric vehicles have many advantages, they still have a significant negative impact on the natural environment [3]. A detailed understanding of the environmental impact of lithium-ion batteries at each phase of their life cycle is essential to achieving sustainability of not only the batteries, but also vehicles powered by them [4]. Analysis of the main environmental loads of batteries and other accompanying products refers to the dynamics of enterprise development, for example, Industry 4.0 [5–8]. Additionally, it is necessary to improve these products to achieve the expected quality [9,10], while ensuring their environmentally friendly impact [11].

The literature review shows that many studies have been conducted on the life-cycle assessment of various types of lithium-ion batteries used in the automotive industry. For example, lithium–iron phosphate batteries with different solvents used for cell production have been analyzed [12]. Marques et al. [3] compared the performance of lithium manganese oxide batteries with lithium iron phosphate batteries, including assessing their life cycle, considering global warming, acidification, and eutrophication. The research conducted by the authors of studies [13–16] addressed the environmental impact of lithium-ion batteries, e.g., lithium iron phosphate and lithium nickel cobalt, during their production, use, or recycling phases, showing a significant carbon footprint in these phases. Furthermore, Chen et al. [16] investigated the potential to reduce carbon dioxide emissions in a life cycle assessment of lithium-ion batteries. Yang et al. [17] conducted predictive analyses of the production of lithium-ion batteries until 2030, taking into account possible changes in their power, energy life, and charging efficiency. Nordelöf et al. [18] modeled the end-of-life stage in the life cycle of lithium-ion batteries. In turn, Cerdas et al. [19] studied various processes within the life cycle phases of lithium-ion batteries, considering the impact of aspects such as the quality of the recovered material and the consumption of energy and materials. Similarly, Yang et al. [20] studied the environmental impact as part of battery recycling in view of economic viability and also provided an inventory of the battery life cycle. Chorida et al. [21] analyzed the environmental burden resulting from increased use of steel in battery production in terms of the life cycle. In addition, Yoo et al. [22] analyzed battery metal recycling with lithium recovery for used lithium-ion batteries, and greenhouse gas emissions during the battery life cycle were evaluated. Another type of analysis was carried out, for example, by Miranda et al. [23] as part of the application of particle swarm optimization of a neural network to assess the state of charge of a battery. Then, Bhinge et al. [24] evaluated the life cycle of a lithium-ion battery with a large amount of data in the event of product quality deterioration. In turn, Picatoste et al. [25] assessed the environmental impact of batteries, focusing on a closed-loop system and the battery life cycle, analyzing industrial challenges and also beneficial design practices for lithium-ion batteries used in the automotive industry. It is important to mention that, according to recent results, China's electric vehicle policy has been a notable success. As the number of electric vehicles in this country continues to grow, China is building more charging stations, improving the brand of the vehicles offered, and increasing their commercial sales [26]. However, the increase in the use of battery vehicles also comes with potential pitfalls, and the main one is excessive battery waste. Statistics showed that more than 200,000 tons of waste from lithium-ion batteries were created in 2020, and their number is constantly growing. This waste has a particularly significant impact on the environment, which is why China and other countries have begun to pay attention to how this waste is managed. However, it remains a pressing issue [27]. In addition, the depletion of lithium is a problem that significantly hampers efforts to reduce carbon dioxide emissions [28].

Within the literature review, a small number of studies were observed that included comparative analyses of various lithium-ion batteries, considering the environmental burden on the ecological footprint [26] arising during the extraction and processing of these battery materials during their lifetime. Therefore, the aim of this investigation was to perform an in-depth comparative analysis of electric vehicle batteries, which were analyzed in terms of environmental loads, including ecological footprint criteria from the extraction and processing of battery materials throughout their life cycle (LCA).

The originality of this research is based on the identification of the main environmental burdens regarding the ecological footprint (considering carbon dioxide emissions, land use, and nuclear emissions) in the first phase of LCA for popular lithium-ion, lithium iron phosphate, and lithium nickel cobalt-manganese batteries. The results of this analysis were supplemented with proposals for improvement actions to reduce the main environmental burdens, which may be useful to enterprises producing these types of batteries as part of their sustainable development.

2. Materials and Methods

This research included a comparative analysis of the environmental burdens arising from the extraction and processing of materials during the life cycle of batteries for electric passenger vehicles. Life cycle assessment (LCA) is one of the most common methodologies for assessing environmental impacts [27], providing an assessment of inputs and outputs and interpretation of the results of the assessment of the environmental impact of a product or process throughout its life cycle [28]. The basic life cycle approach is cradle to grave, which includes material extraction and processing, production, use, and end of life [29]. The LCA methodology is based on the ISO 14040 standard [30] according to which it proceeds according to four interactive stages: (i) defining the purpose and scope of the research, (ii) inventory, (iii) environmental impact assessment, and (iv) interpretation [31]. The use of LCA can support making more pro-ecological decisions throughout the life cycle, and it can also be a source of knowledge for selected phases of the cycle, including adapting the type of analysis to the desired criteria of environmental burdens [32,33]. Therefore, the present research method included defining the research object, the functional unit, the system boundary, and the research scope, as detailed later in this paper.

Subject of study

The subjects of this research were batteries for electric passenger vehicles, which were selected in terms of their popularity due to the cathode material [34]: lithium ion (Li-Ion) [35,36], lithium iron phosphate ($LiFePO_4$) [37], and ternary lithium nickel cobalt manganese (NCM) [38]. It is important to analyze the burdens associated with them, especially since their use is expected to increase in the coming years, even to a level of 65,000 tons on the global market by 2025 for, e.g., $LiFePO_4$ batteries [39].

A feature that characterizes vehicle batteries is their chemical composition, which generates battery performance but also contributes to the demand and method of selecting materials [40,41]. Lithium-ion batteries occupy a significant share of battery technologies, mainly due to their high efficiency provided through the right combination of high energy and power density [42]. The lithium used in them has the highest cell potential, which is due to having the lowest reduction potential among other elements [43]. Additionally, lithium is one of the lighter elements and has one of the smallest ionic radii considering all individually charged ions. It has a high gravimetric capacity but also a high volumetric capacity and a high power density [44]. The main limitation of these batteries is their relatively long charging time, caused by the diffusion in solid electrodes [45]. A lithium-ion battery contains compounds of lithium manganese oxide and lithium cobalt oxide. These batteries come in different varieties, such as the next lithium iron phosphate battery selected for analysis ($LiFePO_4$, LFP), which contained much lighter iron compounds and was produced from lithium iron phosphate cathode materials [37]. Compared with traditional lithium-ion batteries, they have higher charging and discharging efficiency, including a longer cyclic life and a more stable thermal and chemical structure [46]. They have a high level of safety, good thermal and cyclic stability, and relatively low material cost [39]. In turn, lithium nickel cobalt manganese (NCM) batteries are gaining popularity due to their large capacity, energy density, and good stability. They are lighter than previous batteries and efficient, considering the range of travel [34]. The nickel content in NCM batteries contributes to a significant reduction in problems related to their sustainability and costs due to the lower cobalt content [47].

The main elements of the selected batteries for passenger electric vehicles are the battery modules, which consist of battery cells. In turn, these cells contain, among other elements, an anode, cathode, separator, and electrode [48]. Taking these elements as the main ones, material data concerning the analyzed batteries were developed. Data were prepared based on a literature review, e.g., [35,49,50], the GREET v1.3.0.13991 model [51], and data from the Ecoinvent 3.10 database of OpenLCA 2.0.0. [52]. The materials selected for verification and the amount of their use per kilogram are presented in Tables 1–3.

Table 1. Main materials of lithium-ion (li-ion) battery.

Material	Quantity (kg)
Steel	14.74
Aluminum	386.17
Copper wire	182.08
Synthetic graphite	421.38
PVDF—poly(vinylidene fluoride)	24.78
$LiPF_6$	39.33
Ethylene carbonate	109.79
Dimethyl carbonate	109.79
Polyethylene terephthalate (PET)	4.45
Glass fiber	6.96
Polypropylene	17.57
High-density polyethylene	4.62
Lithium iron phosphate	792.87
N-Methyl-2-pyrrolidone	5.55

Table 2. Main materials of lithium iron phosphate battery ($LiFePO_4$).

Material	Quantility (kg)
$LiFePO_4$	914.35
Acetylene black	183.26
Aluminum	3.86
Acetylene black	183.26
Mesocarbon microbeads (MCMB)	914.35
Copper	13.50
Ethylene carbonate (EC)	54.01
Ethyl methyl carbonate (EMC)	135.03
$LiPF_6$ (lithium hexafluorophosphate)	293.21
Polyethylene membrane (PE)	1.35
Steel	297.82

Table 3. Main materials of lithium nickel cobalt manganese battery (NCM).

Material	Quantility (kg)
Nickel	430.60
Cobalt	53.80
Manganese	53.80
Lithium	126.30
Graphite	440.40
Carbon	36.90
Polyvinylidene fluoride	76.30
Copper	345.90
Aluminum	736.10
Lithium hexafluorophosphate	55.00
Ethylene carbonate	153.50
Dimethyl carbonate	153.50
Polypropylene	35.40
Polyethylene	7.40
Polyethylene terephthalate	6.50
Heat-insulating material (fiber)	15.20
Steel	19.20
Coolant (glycol)	138.90

Subsequently, as part of the preparation of data for analysis, the functional unit and system boundaries were defined.

Due to limited lithium resources, many countries have started using other types of batteries. For example, a lithium–sulfur battery (Li-S) with a high theoretical specific capacity and specific energy density can increase efficiency five-fold compared with traditional lithium-ion batteries [53]. Although lithium–sulfur batteries are of great interest and are considered one of the most promising new-generation batteries with high energy density, they are still far from satisfactory due to shortcomings in their practical application [54]. Among other things, these batteries are characterized by a high rate of charging and discharging, including low cycle stability [53].

There have also been studies with sodium ion batteries, which are considered cheaper alternatives and less susceptible to resource and supply risks [55]. Sodium ion batteries are a promising, relatively inexpensive, and environmentally friendly solution in terms of energy storage for sustainable development [56]. However, these batteries have low efficiency compared with the available electrode materials, so materials based on carbon, metals, and oxide alloys are still being sought [57].

Another type of battery is the sodium–sulfur battery, which is considered one of the most effective energy storage systems [58]. This type of battery is considered an effective replacement for lithium-ion batteries, mainly because it has a larger capacity, is more environmentally friendly, and is characterized by lower production costs [59]. Currently, the sodium–sulfur battery is perceived as one of the strongest solutions to stabilize the grid, supporting the efficiency and usability of renewable energy technologies. Furthermore, from a practical point of view, it is characterized by a long discharge time and a service life that reaches up to 15 years [60].

Although lithium-ion batteries are still considered the most desirable, and their satisfactory performance and low price in many cases means that the demand for these technologies will constantly increase and will reach even 2–3.5 TWh by 2030 [61], so a sodium–sulfur battery seems to be advantageous and promising. Therefore, it is possible to say that lithium–ion batteries will continue to be popular, but the development of technology and research in this area may result in their replacement in many cases with more environmentally friendly and efficient types of batteries.

There are also hydrogen fuel cells that outperform lithium-ion batteries in terms of energy storage density and therefore have a longer range. Additionally, they are lighter, more compact, and have favourable potential for reducing emissions. Hence, these attributes may suggest that they are more favourable in environmental terms [62]. However, unfortunately, they are characterized by high production costs, low hydrogen energy density, limited safety, and limited access to refuelling infrastructure, including the complexity of hydrogen storage and transport. However, technological development and political activities indicate that in the future they may become important from the point of view of sustainable transport development [63].

Functional unit

A functional unit is a quantitative description of the functions of a product, and is the basis for carrying out calculations involving environmental loads. The use of a functional unit ensures quantitative measurement of environmental burdens and comparability of results [64]. The functional unit can be freely adapted to the product. Based on other studies, for example [35,50], it was assumed that the functional unit for the analyzed batteries was 1 kg of material per 1000 kWh of energy stored in these batteries [49]. Furthermore, following the authors of a previous study [50], it was assumed that the average weight of batteries used in electric vehicles was approximately 300 kg. All data covering the materials of the tested batteries were converted according to this functional unit.

System boundary

A system boundary is a set of criteria that define the unit processes, inputs, outputs, and environmental loads to be analyzed [65]. The unit process consists of separate phases (stages) of the life cycle [64]. In certain cases, the system boundaries in LCA may also refer to a specific geographical area, time range, or data related to the product or process [66,67]. The conducted research determined the boundaries of the system, including the analysis of environmental loads in the first phase of LCA, i.e., the extraction and acquisition of materials for batteries for passenger vehicles, that is, lithium-ion, lithium iron phosphate and three-component nickel–cobalt–manganese oxide, as presented in Figure 1.

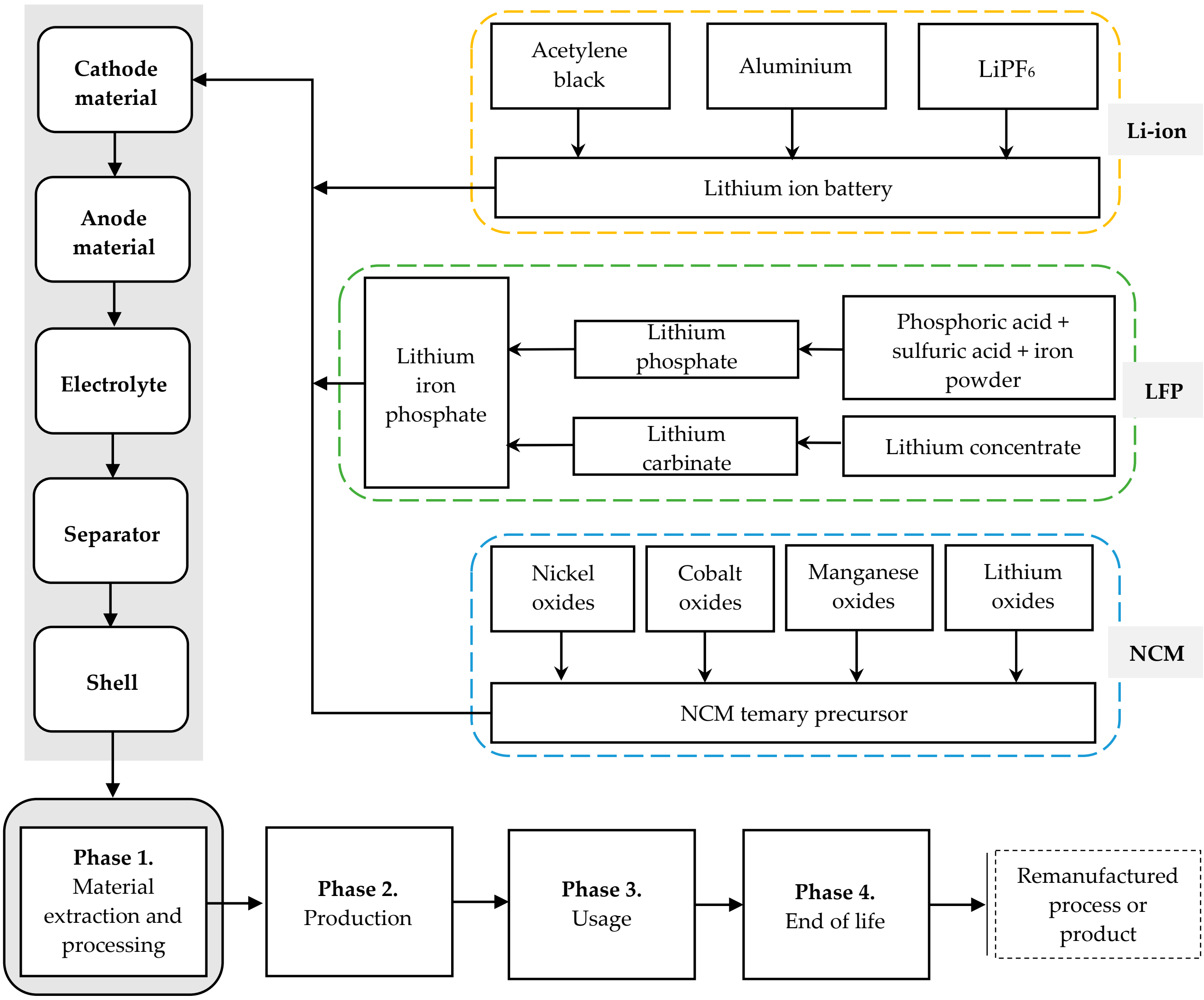

Figure 1. Boundary of the LCA system for passenger vehicle batteries. Own study based on [68].

The scope of this research was reduced to the analysis of environmental burdens in relation to the ecological footprint, which is one of the key environmental burdens [69]. Ecological footprint is used to measure the level of natural resources consumed and waste generated, among other things, as a result of human activity [26]. It is the main indicator for assessing human impact on ecosystems and the biosphere [69]; therefore, reducing it is a leading challenge, including improving the quality of the climate [70]. The literature review presented in [71] confirms that this is an important problem, and climate change has been the most common scope in studies conducted so far that cover the environmental impact of batteries for electric vehicles. The ecological footprint analysis included carbon dioxide (CO_2) emissions, land occupation (considered as land development and modernisation), and nuclear energy consumption [26]. Due to the fact that the categories covered a large number of environmental burdens, the scope of this research was limited to the main burdens in each ecological footprint category. The main loads were considered to be those that had the highest emissions (environmental impact) among all those verified. As part of the analysis, a conversion unit was selected for the ecological footprint criteria, which was a square meter of impact per year of a given impact (m^2a).

3. Results and Discussion

The ecological footprint analysis in the LCA phase with respect to the extraction and processing of lithium-ion, lithium iron phosphate, and lithium nickel cobalt manganese battery materials was carried out using the OpenLCA 2.0.0 programme with the Ecoinvent 3.10 database. The analysis was carried out in four main stages: (i) analysis of environmental burdens regarding carbon dioxide emissions, (ii) analysis of environmental burdens regarding land occupation (development and modernization), (iii) analysis of environmental burdens regarding nuclear energy, and (iv) analysis of the ecological footprint and proposals for improvement actions.

3.1. Analysis of Environmental Loads Regarding Carbon Dioxide Emissions

The main environmental burdens in relation to CO_2 emissions generated in the extraction and processing phases of materials selected for the lithium-ion battery testing were analysed. The results of the environmental loads are presented in Table 4.

Table 4. Environmental loads related to CO_2 emissions generated during the extraction and processing phase of lithium-ion, lithium iron phosphate, and NCM battery materials.

Battery Type	Environmental Load	Amount
Li-ion	Electricity production, hard coal	17,701.09
	Quicklime production (in pieces, loose)	11,641.10
	Heat production in a hard coal industrial furnace 1–10 MW	1779.65
	Hard coal mine operation	1475.59
	Electricity production, lignite	1028.54
	Heat and power co-generation, natural gas, conventional power plant	829.31
	Electricity production, natural gas, conventional power plant	792.35
$LiFePO_4$	Quicklime production (in pieces, loose)	7759.28
	Heat production in a hard coal industrial furnace 1–10 MW	2741.02
	Heat and power co-generation, natural gas, conventional power plant	2341.59
	Pig iron production	762.96
	Sweet gas, burned in a gas turbine	581.55
	Heat production, natural gas, industrial furnace > 100 kW	547.76
	Hard coal mine operation	546.15
	Electricity production, hard coal	540.61
	Coking	475.25
NCM	Electricity production, hard coal, electricity high voltage	4111.20
	Heat and power co-generation, natural gas, conventional	3491.48
	Electricity production, hard coal	2403.22
	Heat production in a hard coal industrial furnace 1–10 MW	2087.12
	Quicklime production, in pieces, loose	1975.21
	Lithium chloride production	1161.66
	Electricity production, lignite	925.55
	Treatment of used cable	846.96
	Sweet gas, burned in a gas turbine	583.47
	Heat production, natural gas, industrial furnace > 100 kW	578.86

The highest CO_2 emissions during the extraction and processing of lithium-ion battery materials arise during the production of electricity and hard coal [72] (17,701.09 m^2a). Subsequently, the largest amount of CO_2 emissions was observed in the case of quicklime production (pieces, bulk) [73] (11,641.10 m^2a). Much smaller amounts of CO_2 emissions are generated during the heat production process in an industrial hard coal furnace [74] or the operation of a hard coal mine [75] (average 1627.62 m^2a). The cogeneration of heat and energy using natural gas in a conventional power plant is relatively similar in these terms to the production of electricity with natural gas in a conventional power plant (average 810.83 m^2a).

In the case of a lithium iron phosphate battery, the highest CO_2 emissions from the extraction and processing phase arise during the production of quicklime [73] (7759.28 m^2a). A much smaller amount of CO_2 is emitted during heat production in an industrial furnace fuelled with hard coal [76] or during the cogeneration of heat and energy through natural gas in a conventional power plant (average 2541.31 m^2a). The smaller emissions refer to the production of pig iron (762.96 m^2a), sweet gas burnt in a gas turbine, heat production (natural gas in an industrial furnace), the operation of a hard coal mine [75], and the production of electricity through sintering (average 538.26 m^2a).

Analysing NCM battery materials, the highest CO_2 emissions occur during the production of electricity with hard coal [76] (high-voltage electricity) (4111.20 m^2a). Relatively slightly smaller emissions are generated during cogeneration of heat and electricity using natural gas (conventional) (3491.48 m^2a). Subsequent results refers to the production of electricity with hard coal [75], the production of heat in an industrial hard coal furnace [74] with a capacity of 1–10 MW, and the production of quicklime, in pieces, in bulk [73] (average 2155.18 m^2a). Lower CO_2 emissions were observed in the case of quicklime production in bulk, lithium chloride production, electricity production via brown coal, sweet gas burnt in a gas turbine for heat production, or natural gas in an industrial furnace >100 kW (average 819.30 m^2a).

The total amount of CO_2 emissions generated in the extraction and processing phases of the selected battery materials, as well as the amount of CO_2 emissions resulting from the two largest environmental loads, were then compared. The results are shown in Figure 2.

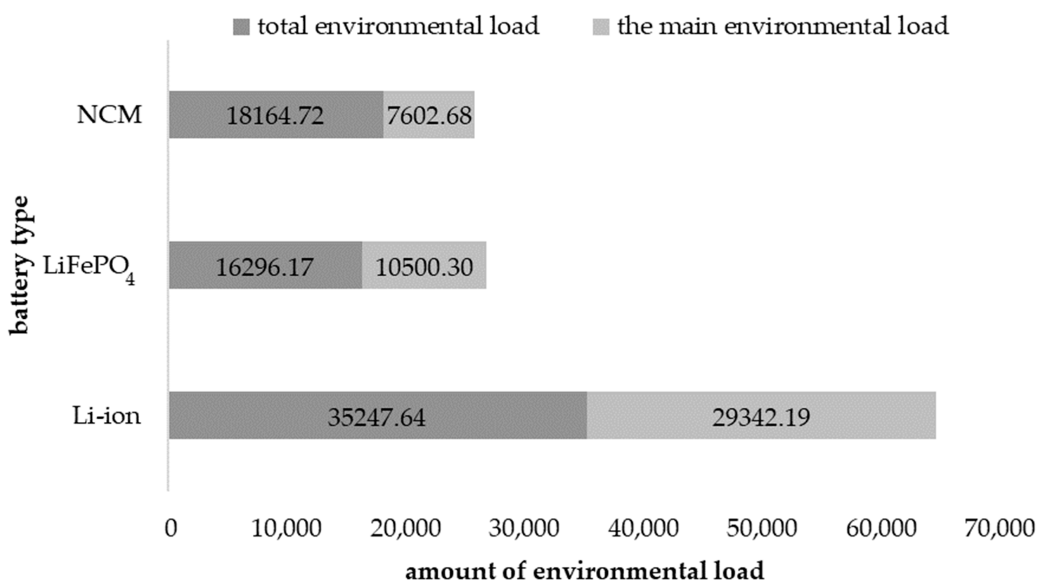

Figure 2. Comparison of CO_2 emissions of Li-ion, $LiFePO_4$, and NCM batteries generated during the extraction and processing phases of materials included in their life cycle.

When comparing the total environmental burden of CO_2 emissions in the extraction and processing phases of the materials for the analyzed batteries, it was observed that the largest negative environmental impact was has associated with the lithium-ion battery. This was characterized by approximately 49% higher CO_2 emissions compared with the NCM battery and approximately 54% higher CO_2 emissions compared with the $LiFePO_4$ battery. It has been adequately demonstrated that lower CO_2 emissions occur during the extraction and processing phases of materials in the life cycle of $LiFePO_4$ batteries, which are approximately 20% lower compared with NCM batteries.

Analysing the two main environmental loads that occur during the extraction and processing phase of materials for the different battery types, it was shown that the highest amount of CO_2 emissions was associated with the production of hard coal, as also confirmed in [77,78]. Next were the emissions generated during the production of quicklime (in pieces, in bulk)—in the case of li-ion and NCM batteries, also confirmed by previous research [33,79]—as well as cogeneration of heat and electricity via conventional natural gas in the case of $LiFePO_4$ batteries [80]. Taking into account the main loads for the tested batteries in relation to all environmental loads identified for them, it was observed that for lithium-ion batteries, they generated approximately 83% of the total emissions, for $LiFePO_4$ batteries, approximately 65% of the total emissions, and for NCM batteries, about 42% of the total emissions.

3.2. Analysis of Environmental Loads Regarding Land Occupation (Development and Modernization)

As part of the ecological footprint, another criterion was analysed: land occupation (considered as the development and modernisation of the area). The analysis included battery materials selected for testing in the extraction and processing phases of their life cycles. The results are presented in Table 5.

Table 5. Environmental loads related to land use in the extraction and processing of lithium-ion, lithium iron phosphate, and NCM battery materials.

Battery Type	Environmental Load	Amount
li-ion	Road construction	233.86
	Hard coal mine operation	206.24
	Phosphate rock beneficiation, wet	113.98
	Lithium brine inspissation	37.70
	Railway track construction	33.11
	Phosphate rock beneficiation, dry	32.11
	Treatment of sulfidic tailing, off-site	31.06
	Process-specific burdens production	13.31
	Palm fruit bunch production	12.85
	Residual material landfill construction	12.21
$LiFePO_4$	Phosphoric acid production	394.75
	Softwood forestry, spruce	287.44
	Softwood forestry, pine	265.49
	Treatment of non-sulfidic tailing	153.59
	Hardwood forestry, birch	146.76
	Road construction	112.30
	Hardwood forestry, beech	109.94
	Softwood forestry, mixed species, boreal forest	93.23
	Phosphate rock beneficiation	86.65
	Hard coal mine operation and hard coal preparation	83.77
	Treatment of non-sulfidic overburden	82.03
	Lithium brine inspissation	33.85
	Railway track construction	25.94
NCM	Softwood forestry, spruce	230.39
	Softwood forestry, pine	211.63
	Hardwood forestry, birch	148.70
	Road construction	116.64
	Hardwood forestry, beech	108.99
	Hard coal mine operation and hard coal production	90.81
	Softwood forestry, mixed species, boreal forest	44.32
	Lithium brine inspissation	41.88
	Residual material landfill construction	31.40
	Softwood forestry, mixed species	29.40
	Process-specific burdens, residual material landfill	26.58
	Railway track construction	21.93

Significant environmental loads have been observed in the phases of extraction and processing of lithium-ion battery materials that arise during the construction of roads (233.86 m^2a), as confirmed previously [81], the operation of a hard coal mine (206.24 m^2a), and the enrichment of phosphate rocks [82] (113.98 m^2a). Subsequently, a relatively similar amount of environmental loads was found to pertain to the processing of lithium brine, the construction of railway tracks, the enrichment of phosphate rocks (dry) [83], and the treatment of sulfide residues off-site (average 33.50 m^2a). The smallest emissions relate to the production of process-specific loads, the production of palm fruit bunches, and the construction of waste landfill (average 12.79 m^2a).

In the case of lithium iron phosphate batteries, the environmental burden of land occupation/modernization in the extraction and processing of materials is mainly from the production of phosphoric acid [84], the treatment of non-sulfide waste, and coniferous forestry (pine) (average 315.89 m^2a), followed by the treatment of non-sulfide waste, broadleaf forestry (birch), and road construction [85], as well as broadleaf forestry (beech) (average 130.65 m^2a). Lower environmental burdens include processes related to land development for coniferous forests (mixed species, boreal forests), phosphate rock enrichment [83], coal mining and hard coal processing, processing of non-sulfide overburden, lithium brine processes, and railway track construction (average 67.58 m^2a).

However, for the NCM battery, in the phase of extraction and processing of materials, environmental loads from the occupation/modernization of the area relate to coniferous forestry, spruce, pine, and birch (196.91 m^2a), deciduous forest (beech), and the exploitation of hard coal mining and hard coal production (average 99.90 m^2a). Minor environmental loads include coniferous forest (mixed species, boreal forest), lithium brine processing, construction of landfill, coniferous forestry (mixed species), process-specific loads, residual material, and construction of railway tracks (average 32.59 m^2a) [86].

The total amount of environmental burden related to land occupation (including its modernization) generated in the phases of extraction and processing of selected battery materials was compared. The total amount of environmental load and the amount of load resulting from the three largest environmental loads were determined (Figure 3).

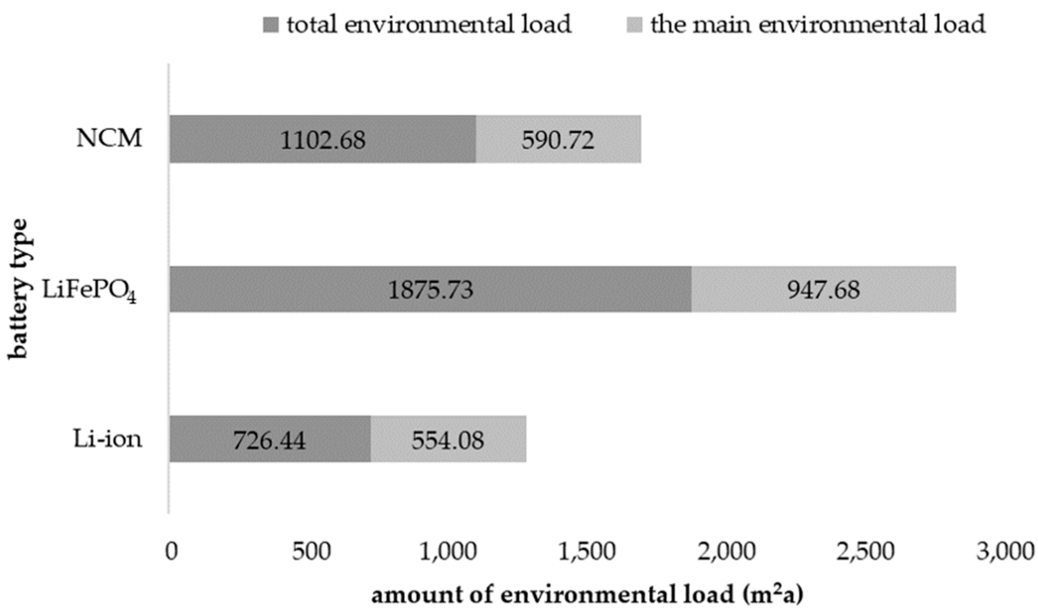

Figure 3. Comparison of the environmental loads of land occupation in the extraction and processing of Li-ion, $LiFePO_4$, and NCM battery materials.

The largest total environmental burden, including the occupation (development and modernization) of the area, was created in the extraction and processing of $LiFePO_4$ battery materials (1875.73 m^{2}a). Compared with other batteries, this figure was 68% more than for NCM batteries and 41% more than for li-ion batteries.

The main environmental loads for the occupation/development (including modernization) of the land for each battery were road construction [86], hard coal mining operations, phosphate rock beneficiation (wet) [87], phosphoric acid production [88], softwood forestry (spruce, pine), and hardwood forestry (birch). Similar main loads occurred for $LiFePO_4$ and NCM batteries and concerned softwood forestry—pine and spruce. Their relative amounts were also similar; that is, for $LiFePO_4$, these constituted approximately 50% of the total load, while for NCM, they constituted approximately 53% of the total load. However, for lithium, the main loads accounted for as much as 76% of the total load. Therefore, the main loads for lithium-ion batteries generate a more significant amount of load than the other types.

3.3. Environmental Loads Analysis for Nuclear Energy

Emissions related to nuclear energy consumption were analyzed in the extraction and processing phases of lithium ion, $LiFePO_4$, and NCM battery materials. The results are presented in Table 6.

Table 6. Environmental loads of nuclear energy emissions from the extraction and processing of lithium-ion, lithium iron phosphate, and NCM battery materials.

Battery Type	Environmental Load	Amount
li-ion	Uranium mine operation, underground	6804.50
	Uranium mine operation, open cast	2215.42
	Uranium mine operation, underground	2444.33
	Uranium production, in yellowcake, in situ leaching	1809.28
	Uranium mine operation, open cast	795.83
NCM	Uranium mine operation, underground	4501.71
	Uranium production, in yellowcake, in situ leaching	1559.58

The environmental loads related to nuclear energy for the analyzed batteries are of a similar type. For each battery, they include the exploitation of an underground uranium mine [89], and for lithium-ion and lithium iron phosphate batteries they also involve the exploitation of an open-pit uranium mine, as also confirmed in [90]. In turn, lithium iron phosphate batteries are also characterized by loads from uranium production in cake and leaching on site. Considering nuclear energy, this load is the largest in the case of lithium-ion batteries [91] (6804.50 m^{2}a), 34% for NCM batteries (4501.71 m^{2}a), and 64% for $LiFePO_4$ batteries (2444.33 m^{2}a). Considering the nuclear energy resulting from the exploitation of uranium mines in an open-pit manner [92], much larger amounts of emissions arise in the phases of extraction and processing of lithium-ion battery materials than those for lithium iron phosphate batteries (64% less). When comparing the production of uranium in cakes (site leaching), 40% differences in nuclear energy emissions were observed between the $LiFePO_4$ battery and the NCM battery.

Subsequently, total nuclear emissions during the extraction and processing phases of battery materials were compared. The comparison is shown in Figure 4.

The highest total amount of emissions from nuclear energy emissions was observed to arise during the extraction and processing of lithium-ion battery materials (9019.91 m^{2}a). A smaller and relatively comparable amount of this type of emissions occurs in the cases of lithium iron phosphate batteries (5049.44 m^{2}a) and lithium nickel cobalt manganese batteries (6061.29 m^{2}a). To reduce the emissions associated with nuclear energy, it is necessary to introduce improvement activities during the process of operating underground uranium mines, because they generate the largest emissions [93].

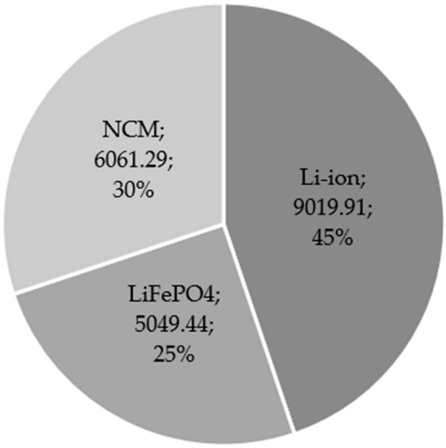

Figure 4. Comparison of the total environmental burden resulting from nuclear energy emissions during the extraction and processing of Li-ion, $LiFePO_4$, and NCM battery materials.

3.4. Ecological Footprint Analysis and Proposals for Improvement Actions

The results obtained from the detailed analysis of environmental loads were summarized in terms of the total ecological footprint created during the extraction and processing of battery materials. Summary results of environmental loads are presented in Table 7.

Table 7. Comparison of the amount of ecological footprint created during the extraction and processing of lithium-ion, lithium iron phosphate, and NCM battery materials.

Ecological Footprint Criteria	Li-Ion	$LiFePO_4$	NCM
CO_2	35,247.64	16,296.17	18,164.72
Land occupation	726.44	1875.73	1102.68
Nuclear	9019.91	5049.44	6061.29
Total environmental load	44,993.99	23,221.35	25,328.70

In terms of the total environmental burden including the ecological footprint criteria, the highest amount of emissions arises during the extraction and processing of traditional lithium-ion battery materials. Virtually half of the emissions from the ecological footprint are generated during the extraction and processing of lithium nickel cobalt manganese battery materials [4]. The situation is relatively similar in the case of lithium iron phosphate batteries [17].

Carbon dioxide (CO_2) emissions generate the greatest environmental burden during the extraction and processing of the lithium-ion battery materials under investigation. Next, it is nuclear energy, then land occupation (including development and modernization). Summarizing the analyses, it was found that the highest amount of CO_2 emissions relate to the following processes:

- production of electricity from hard coal [77,78];
- production of quicklime (in pieces, in bulk) [33,79];
- cogeneration of heat and electricity, natural gas, conventional gas [80].

In the case of occupation/development/modernization of land, the greatest environmental burdens include, for example:

- road construction [86];
- hard coal mine operation;
- phosphate rock beneficiation (wet) [87];
- phosphoric acid production [88];
- softwood forestry (spruce, pine) and hardwood forestry (birch).

In turn, in the case of nuclear energy emissions, the greatest environmental burdens relate primarily to the process of underground uranium mine exploitation [93].

In order to reduce the ecological footprint in the extraction and processing phases of materials for lithium-ion, lithium iron phosphate, and lithium nickel cobalt manganese batteries, it is necessary to take action for improvement. These activities should first cover the main environmental burdens. Examples of research with proposals for actions for improvement to reduce the ecological footprint of batteries are presented in Table 8.

Table 8. Examples of research proposing actions for improvements actions to reduce the ecological footprint of the extraction and processing of battery materials.

Issue	Description	Reference
Electricity production, hard coal	Evaluation of the eco-efficiency of the use of battery technology in the production of electricity from coal	[72]
	Carbon footprint reduction opportunities for electric vehicles and water vehicles	[90]
	Possibilities of technology for storing electricity generated in coal-fired power plants	[75]
	Proposals for optimizing electricity consumption during production, including achieving high production capacity and an electricity mix with low CO_2 emission intensity	[76]
Quicklime production (in pieces, loose)	Possible ways of improving the quality of quicklime, including reducing its negative environmental impact	[73]
	Resource depletion assessment for NCM batteries	[33]
Heat production, hard coal	Proposition of a procedure for preoxidation in the gas/liquid phase as part of the inoculation of oxygen cross-links in bituminous coal	[74]
	Research involving uncontrolled exothermic reactions as part of the safe design of a battery system with testing on various heating systems	[89]
Road construction	The possibility of reducing environmental burdens related to the need to build roads was analyzed, e.g., using nickel slag as a raw material in cement production	[81]
	Possibility of using graphite waste to produce concrete and cement	[85]
	Possibility of using graphite waste for cement production	[86]
Phosphate rock (wet)	Possibilities of the wet process method used to enrich phosphate rocks (wet), in which the phosphate concentrate was dissolved in sulfuric acid	[82]
	Possibility of using silicon powder to increase fluorine recovery during the concentration of phosphoric acid using the wet method	[87]
Phosphoric acid production	Advantages of aqueous processing of lithium-ion batteries via adjusting the pH of phosphoric acid dispersion	[88]
	Advantages of the reduction process of dissolving mixed oxide and cobalt, which is used in used batteries, via phosphoric acid	[84]
	Benefits of adding phosphoric acid to the electrolyte to improve battery performance, demonstrating that it reduced the decline in positive electrode capacity observed during long cyclic operation when charging at a low initial rate	[83]
Uranium mine operation	Analysis of land use change caused by primary resource extraction activities as part of the material demand for lithium-ion batteries	[91]
	Presentation of the latest developments in the uranium extraction process in terms of adsorption materials and technologies applicable to seawater	[93]
	Research on the operation and efficiency of batteries in terms of energy storage and effects due to gamma rays	[92]

The results of the comparative analysis of lithium-ion batteries and the activities subsequently proposed for improvement may be the basis for actions taken by manufacturing companies to optimize the extraction and processing of materials in the life cycles of the tested batteries.

The results of the analysis focus on the extraction and processing of materials, but it should also be taken into account that the production and use of lithium batteries may cause some environmental pollution. To improve environmental protection, it would be good, first of all, to increase the efficiency of battery recycling from the point of commercial use [94], in which the recycling of battery materials, e.g., through regeneration, is one of the cheapest and cleanest approaches [95]. Lithium-ion batteries contain many metals whose recovery and disposal will not only help reduce environmental pollution but will also effectively help slow down the loss of resources and increase the social and economic benefits of metals, their recovery, and disposal [96]. It is also important, for example, to increase protection against overcharging in the case of high-capacity and high-power batteries [97], to popularize pre-heating techniques, mainly in relation to low-temperature charging that causes the deposition of lithium, which after entering the separator may even cause an explosion [98], and to develop improved thermal stability and low humidity [99–102].

To avoid subsequent harm to society caused by lithium batteries, it is necessary to introduce a well-thought-out process for obtaining and extracting the materials used in them, mainly lithium, which is being depleted in significant quantities. It is also important to develop an effective production process that favors the use of these batteries, e.g., reducing the risk of explosion and the formation of dangerous gases and fumes. Another important aspect is the use of an effective recycling process for batteries that, when produced in excessive quantities, pose a risk.

4. Conclusions

Reducing the negative impact of electric vehicle batteries remains a challenge. As part of their sustainable development, it is important to find the sources of the main environmental burdens in the individual phases of the life cycles of these batteries. Therefore, the aim of this investigation was to perform an in-depth comparative analysis of electric vehicle batteries. The subjects of the research were popular batteries, i.e., lithium-ion, lithium iron phosphate, and lithium nickel cobalt manganese. They were analyzed in terms of environmental burdens, including ecological footprint criteria, i.e., carbon dioxide (CO_2) emissions, land use, and nuclear energy emissions. The analyses were based on data from the GREET model and data from the Ecoinvent database in the OpenLCA program. During the analysis, the main environmental burdens were identified, i.e., hard coal, production of quicklime, cogeneration of heat and electricity (natural gas, conventional), road construction, hard coal mine operations, phosphate rock beneficiation (wet), phosphoric acid production, softwood forestry (spruce, pine), hardwood forestry (birch), and underground uranium mine exploitation. As a result, it was shown that in the adopted scope of this research, the most advantageous battery was the lithium iron phosphate. This battery was characterized by the smallest amount of environmental burden resulting from the ecological footprint in the phases of extracting and processing the materials used in it. However, the least advantageous was the lithium-ion battery. Additionally, to minimize the main environmental burdens, activities for improvement are proposed, resulting from a synthesized review of the literature.

A certain limitation of the conducted research is its focus on the first phases of the life cycle, i.e., the extraction and processing of materials. Additionally, the research results may have been different if the study had taken into account specific aspects, e.g., the location of material extraction. Within the adopted scope of this research, the results constitute a basic view of the basic activities and processes in the extraction and processing of lithium-ion materials and their variants.

Therefore, future research will aim to extend this research to subsequent phases of the life cycles of selected batteries, including other types. It is also planned to expand the analysis to include economic aspects, including qualitative ones, which will include customers' and other interested parties' satisfaction with the use of the batteries as well as vehicles powered by them.

The results obtained from the analysis can constitute the basis for taking actions aimed at reducing negative environmental impacts arising in the phases of extraction and processing of battery materials for electric vehicles. At the same time, they can be used by manufacturing companies and also by companies dealing with the extraction and processing of materials as part of their efforts to achieve sustainable development.

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References

1. Li, X.; Lv, T.; Zhan, J.; Wang, S.; Pan, F. Carbon Emission Measurement of Urban Green Passenger Transport: A Case Study of Qingdao. *Sustainability* **2022**, *14*, 9588. [CrossRef]
2. Raugei, M.; Winfield, P. Prospective LCA of the Production and EoL Recycling of a Novel Type of Li-Ion Battery for Electric Vehicles. *J. Clean. Prod.* **2019**, *213*, 926–932. [CrossRef]
3. Marques, P.; Garcia, R.; Kulay, L.; Freire, F. Comparative Life Cycle Assessment of Lithium-Ion Batteries for Electric Vehicles Addressing Capacity Fade. *J. Clean. Prod.* **2019**, *229*, 787–794. [CrossRef]
4. Dai, Q.; Kelly, J.C.; Gaines, L.; Wang, M. Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications. *Batteries* **2019**, *5*, 48. [CrossRef]
5. Gajdzik, B. Frameworks of the Maturity Model for Industry 4.0 with Assessment of Maturity Levels on the Example of the Segment of Steel Enterprises in Poland. *J. Open Innov. Technol. Mark. Complex.* **2022**, *8*, 77. [CrossRef]
6. Siwiec, D.; Bednárová, L.; Pacana, A.; Zawada, M.; Rusko, M. Decision Support in the Selection of Fluorescent Penetrants for Industrial Non-Destructive Testing. *Przemysł Chem.* **2019**, *1*, 92–94. [CrossRef]
7. Pacana, A.; Siwiec, D. Universal Model to Support the Quality Improvement of Industrial Products. *Materials* **2021**, *14*, 7872. [CrossRef] [PubMed]
8. Siwiec, D.; Pacana, A. Model of Choice Photovoltaic Panels Considering Customers' Expectations. *Energies* **2021**, *14*, 5977. [CrossRef]
9. Siwiec, D.; Pacana, A. A New Model Supporting Stability Quality of Materials and Industrial Products. *Materials* **2022**, *15*, 4440. [CrossRef] [PubMed]
10. Ostasz, G.; Siwiec, D.; Pacana, A. Model to Determine the Best Modifications of Products with Consideration Customers' Expectations. *Energies* **2022**, *15*, 8102. [CrossRef]
11. Ostasz, G.; Siwiec, D.; Pacana, A. Universal Model to Predict Expected Direction of Products Quality Improvement. *Energies* **2022**, *15*, 1751. [CrossRef]
12. Zackrisson, M.; Avellán, L.; Orlenius, J. Life Cycle Assessment of Lithium-Ion Batteries for Plug-in Hybrid Electric Vehicles–Critical Issues. *J. Clean. Prod.* **2010**, *18*, 1519–1529. [CrossRef]
13. Lai, X.; Chen, Q.; Tang, X.; Zhou, Y.; Gao, F.; Guo, Y.; Bhagat, R.; Zheng, Y. Critical Review of Life Cycle Assessment of Lithium-Ion Batteries for Electric Vehicles: A Lifespan Perspective. *eTransportation* **2022**, *12*, 100169. [CrossRef]
14. Fan, T.; Liang, W.; Guo, W.; Feng, T.; Li, W. Life Cycle Assessment of Electric Vehicles' Lithium-Ion Batteries Reused for Energy Storage. *J. Energy Storage* **2023**, *71*, 108126. [CrossRef]

15. Wei, Q.; Wu, Y.; Li, S.; Chen, R.; Ding, J.; Zhang, C. Spent Lithium Ion Battery (LIB) Recycle from Electric Vehicles: A Mini-Review. *Sci. Total Environ.* **2023**, *866*, 161380. [CrossRef] [PubMed]
16. Chen, Q.; Lai, X.; Gu, H.; Tang, X.; Gao, F.; Han, X.; Zheng, Y. Investigating Carbon Footprint and Carbon Reduction Potential Using a Cradle-to-Cradle LCA Approach on Lithium-Ion Batteries for Electric Vehicles in China. *J. Clean. Prod.* **2022**, *369*, 133342. [CrossRef]
17. Yang, Y.; Lan, L.; Hao, Z.; Zhao, J.; Luo, G.; Fu, P.; Chen, Y. Life Cycle Prediction Assessment of Battery Electrical Vehicles with Special Focus on Different Lithium-Ion Power Batteries in China. *Energies* **2022**, *15*, 5321. [CrossRef]
18. Nordelöf, A.; Poulikidou, S.; Chordia, M.; Bitencourt de Oliveira, F.; Tivander, J.; Arvidsson, R. Methodological Approaches to End-Of-Life Modelling in Life Cycle Assessments of Lithium-Ion Batteries. *Batteries* **2019**, *5*, 51. [CrossRef]
19. Cerdas, F.; Andrew, S.; Thiede, S.; Herrmann, C. Environmental Aspects of the Recycling of Lithium-Ion Traction Batteries. In *Recycling of Lithium-Ion Batteries: The LithoRec Way*; Springer: Cham, Switzerland, 2018; pp. 267–288.
20. Yang, Y.; Okonkwo, E.G.; Huang, G.; Xu, S.; Sun, W.; He, Y. On the Sustainability of Lithium Ion Battery Industry—A Review and Perspective. *Energy Storage Mater.* **2021**, *36*, 186–212. [CrossRef]
21. Chordia, M.; Nordelöf, A.; Ellingsen, L.A.-W. Environmental Life Cycle Implications of Upscaling Lithium-Ion Battery Production. *Int. J. Life Cycle Assess.* **2021**, *26*, 2024–2039. [CrossRef]
22. Yoo, E.; Lee, U.; Kelly, J.C.; Wang, M. Life-Cycle Analysis of Battery Metal Recycling with Lithium Recovery from a Spent Lithium-Ion Battery. *Resour. Conserv. Recycl.* **2023**, *196*, 107040. [CrossRef]
23. Miranda, M.H.R.; Silva, F.L.; Lourenço, M.A.M.; Eckert, J.J.; Silva, L.C.A. Particle Swarm Optimization of Elman Neural Network Applied to Battery State of Charge and State of Health Estimation. *Energy* **2023**, *285*, 129503. [CrossRef]
24. Bhinge, R.; Srinivasan, A.; Robinson, S.; Dornfeld, D. Data-Intensive Life Cycle Assessment (DILCA) for Deteriorating Products. *Procedia CIRP* **2015**, *29*, 396–401. [CrossRef]
25. Picatoste, A.; Justel, D.; Mendoza, J.M.F. Circularity and Life Cycle Environmental Impact Assessment of Batteries for Electric Vehicles: Industrial Challenges, Best Practices and Research Guidelines. *Renew. Sustain. Energy Rev.* **2022**, *169*, 112941. [CrossRef]
26. Li, L.; Guo, S.; Cai, H.; Wang, J.; Zhang, J.; Ni, Y. Can China's BEV Market Sustain without Government Subsidies?: An Explanation Using Cues Utilization Theory. *J. Clean. Prod.* **2020**, *272*, 122589. [CrossRef]
27. Xu, C.; Zhang, W.; He, W.; Li, G.; Huang, J.; Zhu, H. Generation and Management of Waste Electric Vehicle Batteries in China. *Environ. Sci. Pollut. Res.* **2017**, *24*, 20825–20830. [CrossRef] [PubMed]
28. Li, H.; Zhu, T.; Chen, X.; Liu, H.; He, G. Improving China's Global Lithium Resource Development Capacity. *Front. Environ. Sci.* **2022**, *10*, 938534. [CrossRef]
29. Szennay, Á.; Szigeti, C.; Beke, J.; Radácsi, L. Ecological Footprint as an Indicator of Corporate Environmental Performance—Empirical Evidence from Hungarian SMEs. *Sustainability* **2021**, *13*, 1000. [CrossRef]
30. Grenz, J.; Ostermann, M.; Käsewieter, K.; Cerdas, F.; Marten, T.; Herrmann, C.; Tröster, T. Integrating Prospective LCA in the Development of Automotive Components. *Sustainability* **2023**, *15*, 10041. [CrossRef]
31. Karaman Öztaş, S. The Limitations of LCA Methodology towards Sustainable Construction Materials. In Proceedings of the 3rd International Sustainable Buildings Symposium (ISBS 2017), Dubai, United Arab Emirates, 15–17 March 2017; Springer: Cham, Switzerland, 2018; pp. 102–113.
32. Moutik, B.; Summerscales, J.; Graham-Jones, J.; Pemberton, R. Life Cycle Assessment Research Trends and Implications: A Bibliometric Analysis. *Sustainability* **2023**, *15*, 13408. [CrossRef]
33. Finkbeiner, M.; Inaba, A.; Tan, R.; Christiansen, K.; Klüppel, H.-J. The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. *Int. J. Life Cycle Assess.* **2006**, *11*, 80–85. [CrossRef]
34. Proske, M.; Finkbeiner, M. Obsolescence in LCA–Methodological Challenges and Solution Approaches. *Int. J. Life Cycle Assess.* **2020**, *25*, 495–507. [CrossRef]
35. Lagerstedt, J.; Luttropp, C.; Lindfors, L.-G. Functional Priorities in LCA and Design for Environment. *Int. J. Life Cycle Assess.* **2003**, *8*, 160–166. [CrossRef]
36. Du, S.; Gao, F.; Nie, Z.; Liu, Y.; Sun, B.; Gong, X. Assessing Resource Depletion of NCM Lithium-Ion Battery Production for Electric Vehicles: An Exergy-Based Perspective. *J. Clean. Prod.* **2023**, *420*, 138415. [CrossRef]
37. Pacana, A.; Siwiec, D.; Bednarova, L. Analysis of the incompatibility of the product with fluorescent method. *Metalurgija* **2019**, *58*, 337–340.
38. Liang, Y.; Su, J.; Xi, B.; Yu, Y.; Ji, D.; Sun, Y.; Cui, C.; Zhu, J. Life Cycle Assessment of Lithium-Ion Batteries for Greenhouse Gas Emissions. *Resour. Conserv. Recycl.* **2017**, *117*, 285–293. [CrossRef]
39. Pacana, A.; Siwiec, D. Method of Determining Sequence Actions of Products Improvement. *Materials* **2022**, *15*, 6321. [CrossRef] [PubMed]
40. Zhao, T.; Li, W.; Traversy, M.; Choi, Y.; Ghahreman, A.; Zhao, Z.; Zhang, C.; Zhao, W.; Song, Y. A Review on the Recycling of Spent Lithium Iron Phosphate Batteries. *J. Environ. Manag.* **2024**, *351*, 119670. [CrossRef]
41. Rajkamal, A.; Sharma, A.; Pullagura, B.K.; Thapa, R.; Kim, H. Engineering Lithium Nickel Cobalt Manganese Oxides Cathodes: A Computational and Experimental Approach to Bridging Gaps. *Chem. Eng. J.* **2024**, *481*, 148223. [CrossRef]
42. Zhao, T.; Mahandra, H.; Marthi, R.; Ji, X.; Zhao, W.; Chae, S.; Traversy, M.; Li, W.; Yu, F.; Li, L.; et al. An Overview on the Life Cycle of Lithium Iron Phosphate: Synthesis, Modification, Application, and Recycling. *Chem. Eng. J.* **2024**, *485*, 149923. [CrossRef]

43. Nordelöf, A.; Messagie, M.; Tillman, A.-M.; Ljunggren Söderman, M.; Van Mierlo, J. Environmental Impacts of Hybrid, Plug-in Hybrid, and Battery Electric Vehicles—What Can We Learn from Life Cycle Assessment? *Int. J. Life Cycle Assess.* **2014**, *19*, 1866–1890. [CrossRef]
44. Baskar, S.; Vijayan, V.; Isaac Premkumar, I.J.; Arunkumar, D.; Thamaran, D. Design and Material Characteristics of Hybrid Electric Vehicle. *Mater. Today Proc.* **2021**, *37*, 351–353. [CrossRef]
45. Harper, G.; Sommerville, R.; Kendrick, E.; Driscoll, L.; Slater, P.; Stolkin, R.; Walton, A.; Christensen, P.; Heidrich, O.; Lambert, S.; et al. Recycling Lithium-Ion Batteries from Electric Vehicles. *Nature* **2019**, *575*, 75–86. [CrossRef]
46. Siwiec, D.; Pacana, A.; Gazda, A. A New QFD-CE Method for Considering the Concept of Sustainable Development and Circular Economy. *Energies* **2023**, *16*, 2474. [CrossRef]
47. Ji, G.; Wang, J.; Liang, Z.; Jia, K.; Ma, J.; Zhuang, Z.; Zhou, G.; Cheng, H.-M. Direct Regeneration of Degraded Lithium-Ion Battery Cathodes with a Multifunctional Organic Lithium Salt. *Nat. Commun.* **2023**, *14*, 584. [CrossRef]
48. Nitta, N.; Wu, F.; Lee, J.T.; Yushin, G. Li-Ion Battery Materials: Present and Future. *Mater. Today* **2015**, *18*, 252–264. [CrossRef]
49. Lin, X.; Meng, W.; Yu, M.; Yang, Z.; Luo, Q.; Rao, Z.; Zhang, T.; Cao, Y. Environmental Impact Analysis of Lithium Iron Phosphate Batteries for Energy Storage in China. *Front. Energy Res.* **2024**, *12*, 1361720. [CrossRef]
50. Britala, L.; Marinaro, M.; Kucinskis, G. A Review of the Degradation Mechanisms of NCM Cathodes and Corresponding Mitigation Strategies. *J. Energy Storage* **2023**, *73*, 108875. [CrossRef]
51. Yang, L.; Hao, C.; Chai, Y. Life Cycle Assessment of Commercial Delivery Trucks: Diesel, Plug-In Electric, and Battery-Swap Electric. *Sustainability* **2018**, *10*, 4547. [CrossRef]
52. Sadhukhan, J.; Christensen, M. An In-Depth Life Cycle Assessment (LCA) of Lithium-Ion Battery for Climate Impact Mitigation Strategies. *Energies* **2021**, *14*, 5555. [CrossRef]
53. Wang, S.; Yu, J. A Comparative Life Cycle Assessment on Lithium-Ion Battery: Case Study on Electric Vehicle Battery in China Considering Battery Evolution. *Waste Manag. Res.* **2021**, *39*, 156–164. [CrossRef]
54. Wong, E.Y.C.; Ho, D.C.K.; So, S.; Tsang, C.-W.; Chan, E.M.H. Life Cycle Assessment of Electric Vehicles and Hydrogen Fuel Cell Vehicles Using the GREET Model—A Comparative Study. *Sustainability* **2021**, *13*, 4872. [CrossRef]
55. Ciroth, A. ICT for Environment in Life Cycle Applications OpenLCA—A New Open Source Software for Life Cycle Assessment. *Int. J. Life Cycle Assess.* **2007**, *12*, 209–210. [CrossRef]
56. Yang, R.; Li, L.; Ren, B.; Chen, D.; Chen, L.; Yan, Y. Doped-Graphene in Lithium-Sulfur Batteries. *Prog. Chem.* **2018**, *30*, 1681–1691.
57. Liu, B.; Fang, R.; Xie, D.; Zhang, W.; Huang, H.; Xia, Y.; Wang, X.; Xia, X.; Tu, J. Revisiting Scientific Issues for Industrial Applications of Lithium–Sulfur Batteries. *Energy Environ. Mater.* **2018**, *1*, 196–208. [CrossRef]
58. Nayak, P.K.; Yang, L.; Brehm, W.; Adelhelm, P. From Lithium-Ion to Sodium-Ion Batteries: Advantages, Challenges, and Surprises. *Angew. Chem. Int. Ed.* **2018**, *57*, 102–120. [CrossRef]
59. Libich, J.; Máca, J.; Chekannikov, A.; Vondrák, J.; Čudek, P.; Fíbek, M.; Artner, W.; Fafilek, G.; Sedlaříková, M. Sodium Titanate for Sodium-Ion Batteries. *Surf. Eng. Appl. Electrochem.* **2019**, *55*, 109–113. [CrossRef]
60. Skundin, A.M.; Kulova, T.L.; Yaroslavtsev, A.B. Sodium-Ion Batteries (a Review). *Russ. J. Electrochem.* **2018**, *54*, 113–152. [CrossRef]
61. Lin, L.; Zhang, C.; Huang, Y.; Zhuang, Y.; Fan, M.; Lin, J.; Wang, L.; Xie, Q.; Peng, D. Challenge and Strategies in Room Temperature Sodium–Sulfur Batteries: A Comparison with Lithium–Sulfur Batteries. *Small* **2022**, *18*, 2107368. [CrossRef]
62. Adelhelm, P.; Hartmann, P.; Bender, C.L.; Busche, M.; Eufinger, C.; Janek, J. From Lithium to Sodium: Cell Chemistry of Room Temperature Sodium–Air and Sodium–Sulfur Batteries. *Beilstein J. Nanotechnol.* **2015**, *6*, 1016–1055. [CrossRef]
63. Hirai, N. Development of Sodium Sulfur Battery. In Proceedings of the 2019 IEEE Third International Conference on DC Microgrids (ICDCM), Matsue, Japan, 20–23 May 2019; IEEE: Matsui, Japan, 2019.
64. Frith, J.T.; Lacey, M.J.; Ulissi, U. A Non-Academic Perspective on the Future of Lithium-Based Batteries. *Nat. Commun.* **2023**, *14*, 420. [CrossRef]
65. Fan, L.; Tu, Z.; Chan, S.H. Recent Development of Hydrogen and Fuel Cell Technologies: A Review. *Energy Rep.* **2021**, *7*, 8421–8446. [CrossRef]
66. Hassan, Q.; Azzawi, I.D.J.; Sameen, A.Z.; Salman, H.M. Hydrogen Fuel Cell Vehicles: Opportunities and Challenges. *Sustainability* **2023**, *15*, 11501. [CrossRef]
67. Arzoumanidis, I.; D'Eusanio, M.; Raggi, A.; Petti, L. Functional Unit Definition Criteria in Life Cycle Assessment and Social Life Cycle Assessment: A Discussion. In *Perspectives on Social LCA: Contributions from the 6th International Conference, Chongqing, China, 20–22 November 2020*; Springer: Cham, Switzerland, 2020; pp. 1–10.
68. Li, T.; Zhang, H.; Liu, Z.; Ke, Q.; Alting, L. A System Boundary Identification Method for Life Cycle Assessment. *Int. J. Life Cycle Assess.* **2014**, *19*, 646–660. [CrossRef]
69. Gao, L.; Wang, Z.; Wang, Y.; Peng, T.; Liu, W.; Tang, R. LCA-Based Multi-Scenario Study on Steel or Aluminum Wheel Hub for Passenger Vehicles. *Procedia CIRP* **2023**, *116*, 191–196. [CrossRef]
70. Tillman, A.-M.; Ekvall, T.; Baumann, H.; Rydberg, T. Choice of System Boundaries in Life Cycle Assessment. *J. Clean. Prod.* **1994**, *2*, 21–29. [CrossRef]
71. Pacana, A.; Siwiec, D. Analysis of the Possibility of Used of the Quality Management Techniques with Non-Destructive Testing. *Tech. Gaz.* **2021**, *28*, 45–51. [CrossRef]
72. Mancini, M.S.; Galli, A.; Niccolucci, V.; Lin, D.; Bastianoni, S.; Wackernagel, M.; Marchettini, N. Ecological Footprint: Refining the Carbon Footprint Calculation. *Ecol. Indic.* **2016**, *61*, 390–403. [CrossRef]

73. Kazemzadeh, E.; Fuinhas, J.A.; Salehnia, N.; Koengkan, M.; Silva, N. Assessing Influential Factors for Ecological Footprints: A Complex Solution Approach. *J. Clean. Prod.* **2023**, *414*, 137574. [CrossRef]
74. Tolomeo, R.; De Feo, G.; Adami, R.; Sesti Osséo, L. Application of Life Cycle Assessment to Lithium Ion Batteries in the Automotive Sector. *Sustainability* **2020**, *12*, 4628. [CrossRef]
75. Krawczyk, P.; Śliwińska, A. Eco-Efficiency Assessment of the Application of Large-Scale Rechargeable Batteries in a Coal-Fired Power Plant. *Energies* **2020**, *13*, 1384. [CrossRef]
76. Eriksson, M.; Sandström, K.; Carlborg, M.; Broström, M. Impact of Limestone Surface Impurities on Quicklime Product Quality. *Minerals* **2024**, *14*, 244. [CrossRef]
77. Lou, Z.; Wang, H.; Wu, D.; Sun, F.; Gao, J.; Lai, X.; Zhao, G. Microcrystalline Regulation of Bituminous Coal Derived Hard Carbon by Pre-Oxidation Strategy for Improved Sodium-Ion Storage. *Fuel* **2022**, *310*, 122072. [CrossRef]
78. Krawczyk, P.; Śliwińska, A.; Ćwięczek, M. Evaluation of the Economic Efficiency of Storage Technology for Electricity from Coal Power Plants in Large-Scale Chemical Batteries. *Polityka Energetyczna Energy Policy J.* **2020**, *23*, 67–90. [CrossRef]
79. Philippot, M.; Alvarez, G.; Ayerbe, E.; Van Mierlo, J.; Messagie, M. Eco-Efficiency of a Lithium-Ion Battery for Electric Vehicles: Influence of Manufacturing Country and Commodity Prices on GHG Emissions and Costs. *Batteries* **2019**, *5*, 23. [CrossRef]
80. Sobol, Ł.; Dyjakon, A. The Influence of Power Sources for Charging the Batteries of Electric Cars on CO2 Emissions during Daily Driving: A Case Study from Poland. *Energies* **2020**, *13*, 4267. [CrossRef]
81. Cox, B.L.; Mutel, C.L. The Environmental and Cost Performance of Current and Future Motorcycles. *Appl. Energy* **2018**, *212*, 1013–1024. [CrossRef]
82. Lappalainen, H.; Rinne, M.; Elomaa, H.; Aromaa, J.; Lundström, M. Environmental Impacts of Lithium Hydroxide Monohydrate Production from Spodumene Concentrate—A Simulation-Based Life Cycle Assessment. *Miner. Eng.* **2024**, *209*, 108632. [CrossRef]
83. Bastos, J.; Prina, M.G.; Garcia, R. Life-Cycle Assessment of Current and Future Electricity Supply Addressing Average and Marginal Hourly Demand: An Application to Italy. *J. Clean. Prod.* **2023**, *399*, 136563. [CrossRef]
84. Wu, Q.; Wu, Y.; Tong, W.; Ma, H. Utilization of Nickel Slag as Raw Material in the Production of Portland Cement for Road Construction. *Constr. Build. Mater.* **2018**, *193*, 426–434. [CrossRef]
85. Wingate, E.; Prasad, R.; Liu, Y. Phosphorus—A Circular Journey from the Ground to the Recycling Line. *Min. Metall. Explor.* **2023**, *40*, 1469–1485. [CrossRef]
86. Meissner, E. Phosphoric Acid as an Electrolyte Additive for Lead/Acid Batteries in Electric-Vehicle Applications. *J. Power Sources* **1997**, *67*, 135–150. [CrossRef]
87. Pinna, E.G.; Ruiz, M.C.; Ojeda, M.W.; Rodriguez, M.H. Cathodes of Spent Li-Ion Batteries: Dissolution with Phosphoric Acid and Recovery of Lithium and Cobalt from Leach Liquors. *Hydrometallurgy* **2017**, *167*, 66–71. [CrossRef]
88. Kathirvel, P.; Kwon, S.-J.; Lee, H.-S.; Karthick, S.; Saraswathy, V. Graphite Ore Tailings as Partial Replacement of Sand in Concrete. *ACI Mater. J.* **2018**, *115*, 481–492. [CrossRef]
89. Liu, H.; Zhang, Y.; Li, B.; Wang, Z. Combined Effects of Graphite Tailings and Curing Conditions on the Early-Age Performances of Cement Mortar. *Adv. Civ. Eng.* **2020**, *2020*, 5965328. [CrossRef]
90. Chen, Y.; Viridiana García-Meza, J.; Zhou, B.; Peng, Z.; Chen, Q.; Kasomo, R.M.; Weng, X.; Li, H.; Song, S. Efficient Recovery of Fluorine from Wet-Process Phosphoric Acid Using Silicon Powder as a New and Eco-Friendly Reagent. *Sep. Purif. Technol.* **2024**, *337*, 126435. [CrossRef]
91. Kukay, A.; Sahore, R.; Parejiya, A.; Blake Hawley, W.; Li, J.; Wood, D.L. Aqueous Ni-Rich-Cathode Dispersions Processed with Phosphoric Acid for Lithium-Ion Batteries with Ultra-Thick Electrodes. *J. Colloid Interface Sci.* **2021**, *581*, 635–643. [CrossRef]
92. Yang, X.; Wang, H.; Li, M.; Li, Y.; Li, C.; Zhang, Y.; Chen, S.; Shen, H.; Qian, F.; Feng, X.; et al. Experimental Study on Thermal Runaway Behavior of Lithium-Ion Battery and Analysis of Combustible Limit of Gas Production. *Batteries* **2022**, *8*, 250. [CrossRef]
93. Jursova, S.; Burchart-Korol, D.; Pustejovska, P. Carbon Footprint and Water Footprint of Electric Vehicles and Batteries Charging in View of Various Sources of Power Supply in the Czech Republic. *Environments* **2019**, *6*, 38. [CrossRef]
94. Kosai, S.; Takata, U.; Yamasue, E. Natural Resource Use of a Traction Lithium-Ion Battery Production Based on Land Disturbances through Mining Activities. *J. Clean. Prod.* **2021**, *280*, 124871. [CrossRef]
95. Gao, Y.; Qiao, F.; Hou, W.; Ma, L.; Li, N.; Shen, C.; Jin, T.; Xie, K. Radiation Effects on Lithium Metal Batteries. *Innovation* **2023**, *4*, 100468. [CrossRef]
96. Lim, Y.J.; Goh, K.; Goto, A.; Zhao, Y.; Wang, R. Uranium and Lithium Extraction from Seawater: Challenges and Opportunities for a Sustainable Energy Future. *J. Mater. Chem. A Mater.* **2023**, *11*, 22551–22589. [CrossRef]
97. Pacana, A.; Siwiec, D.; Bednarova, L.; Petrovsky, J. Improving the Process of Product Design in a Phase of Life Cycle Assessment (LCA). *Processes* **2023**, *11*, 2579. [CrossRef]
98. Wan, J.; Lyu, J.; Bi, W.; Zhou, Q.; Li, P.; Li, H.; Li, Y. Regeneration of Spent Lithium-Ion Battery Materials. *J. Energy Storage* **2022**, *51*, 104470. [CrossRef]
99. Wen, R.M.; Qi, F.P.; Hu, Y.J.; Liu, C.H.; You, P.Q. Progress of Recycling and Seperation of the Electrode Materials from Spent Lithium-Ion Batteries. *Adv. Mat. Res.* **2012**, *550–553*, 2319–2324. [CrossRef]
100. Hsieh, T.-Y.; Duh, Y.-S.; Kao, C.-S. Evaluation of Thermal Hazard for Commercial 14500 Lithium-Ion Batteries. *J. Therm. Anal. Calorim.* **2014**, *116*, 1491–1495. [CrossRef]

101. Wang, Y.; Zhang, X.; Chen, Z. Low Temperature Preheating Techniques for Lithium-Ion Batteries: Recent Advances and Future Challenges. *Appl. Energy* **2022**, *313*, 118832. [CrossRef]
102. Zhu, L.; Ding, G.; Han, Q.; Yang, X.; Xie, L.; Cao, X. Review—Recent Developments in Safety-Enhancing Separators for Lithium-Ion Batteries. *J. Electrochem. Soc.* **2021**, *168*, 100524. [CrossRef]