sustainability

Review

Reviewing the Cost–Benefit Analysis and Multi-Criteria Decision-Making Methods for Evaluating the Effectiveness of Lithium-Ion Batteries in Electric Vehicles

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Abstract: Lithium-ion batteries (LIBs) have a wide range of applications in different fields, starting with electronics and energy storage systems. The potential of LIBs in the transportation sector is high, especially for electric vehicles (EVs). This study aims to investigate the efficiency and effectiveness of, and justification for, the application of LIBs in the field of transport, primarily in EVs. The research focuses on single and multi-criteria evaluations of the efficiency of LIBs. Previous studies in which LIBs were evaluated using cost–benefit analysis (CBA) and multi-criteria decision-making methods (MCDM) were analysed. An electronic literature search of the Web of Science, Scopus, and other relevant databases was performed. The literature was searched using the keywords: "lithium-ion batteries"; "multi-criteria decision-making"; "cost-benefit analysis"; "energy storage"; "vehicles"; "PROMETHEE" (or other MCDM method)". A total of 40 scientific articles concerning the application of CBA (of which are 20%) and MCDM methods between 1997 and 2023, worldwide, were analysed. The results show multiple applications of both CBA and MCDM methods. The main findings of the areas of application were summarised and future research was discussed.

Keywords: lithium-ion batteries; electric vehicles; evaluation; transportation; CBA; MCDM

Citation: Barić, D.; Grabušić, S.; Jakara, M.; Emanović, M. Reviewing the Cost–Benefit Analysis and Multi-Criteria Decision-Making Methods for Evaluating the Effectiveness of Lithium-Ion Batteries in Electric Vehicles. *Sustainability* **2024**, *16*, 233. https://doi.org/10.3390/su16010233

Academic Editors: Jiajun Chen and Jiachang Zhao

Received: 15 November 2023
Revised: 22 December 2023
Accepted: 24 December 2023
Published: 26 December 2023

1. Introduction

As the market for electric vehicles (EVs) continues to grow, lithium-ion batteries (LIBs) present a crucial role in the transition to cleaner and more sustainable transport. These batteries are in high demand due to their superior energy density, giving EVs greater ranges and better performance. They are also known for their longevity, with a longer cycle life than conventional lead-acid batteries, making them a cost-effective choice in the long run. In addition, their relatively lightweight and compact design enables more efficient use of the space in a vehicle, optimising both the driving dynamics and the interior space for passengers. Despite the barriers to the widespread adoption of EVs, such as their limited range, charging infrastructure, and cost, governments, car manufacturers and the battery industry are investing in and incentivising the development of EVs. Today, LIBs continue to dominate the electric vehicle market, with ongoing efforts to overcome existing challenges and facilitate a broader transition to EVs [1]. From a technological perspective, the use of LIBs has become popular and dominant in the automotive industry [2]. Ongoing developments are focused on improving LIB characteristics, including cost, energy, safety, and power capability [3]. Research into novel concepts, such as vehicle-to-grid (V2G) integration and second-life batteries, is essential to maximise capacity utilisation and extend the battery lifecycle [4]. The recycling of EV batteries is crucial for environmental sustainability, economic viability, and strategic resource management [5]. While LIBs have transformed energy storage, understanding, and mitigating, their limitations are essential for the continued progress and sustainable integration of this technology in various applications.

1.1. The Evolution of Lithium-Ion Batteries

In the evolution of energy storage technologies for EVs, various battery types and systems were used before LIBs emerged as the predominant choice. These included lead-acid, nickel-metal hydride (NiMH), sodium-sulphur, and nickel-cadmium (NiCd) batteries, as well as fuel cells. Each technology had its advantages and disadvantages, contributing to the early development of electric mobility. The history of battery electric vehicles (BEVs) dates back to the 1830s [1]. In 1991, rechargeable LIBs changed the EV market and dominated consumer electronics. The introduction of rechargeable LIBs to the world market in 1991 changed the EV market and has dominated consumer electronics. LIBs were an important milestone in the automotive industry's transition to cleaner energy sources. Due to their high-energy density, low weight and longer lifespan, they have been used in EVs and hybrid electric vehicles (HEVs), making them the best option [1,3,4].

Of the six existing types of LIBs, three have proven to be unsuitable: LCO (lithium-cobalt oxide), LMO (lithium-manganese oxide), and LTO (lithium-titanium oxide). The best known among these is the LMO battery found in cars from 2016 or earlier, and it is precisely because of these that LIBs are remembered as expensive, heavy, and short-lived. Today, however, the chemistry of LIBs has developed in three directions. LFP batteries (lithium-iron phosphate batteries) are metal-free, have low toxicity, and are non-flammable, and long-lasting batteries with low costs. LFP batteries have better operating performance compared to LMO batteries and need to be replaced less frequently during the lifetime of EVs, primarily due to their superior lifecycle [6]. The second direction consists of NCA (lithium-nickel cobalt) batteries, which contain some rare metals, are relatively flammable, have high density and low weight, but are 30 to 50% more expensive than LFP batteries. The third battery type is the NMC battery, a version of the LIB consisting of nickel, manganese, and cobalt. They are very similar to NCA batteries in terms of their properties but are less flammable. The decision in favour of a particular battery type depends on factors such as energy capacity, power, safety, and cost. As the industry strives to develop safer, more cost-effective, and more powerful EV batteries, the choice of materials for the anode, cathode, and electrolyte in LIBs plays a crucial role in ensuring high performance and safety. Although LFP-based LIBs have a relatively lower nominal voltage, they are more environmentally friendly, cheaper, and more reliable and durable in EVs [7,8]. LFP batteries have a higher environmental impact in terms of lifecycle, mainly due to the greater impacts incurred during manufacturing. The choice of battery type has a significant impact on the overall environmental performance of EVs [6]. In the near term, reserves of lithium are unlikely to present a constraint [5].

1.2. Advantages and Challenges for Lithium-Ion Batteries

LIBs have several favourable properties that make them key components in various applications. They are known for their low weight and rechargeability. They are characterised by low self-discharge and eliminate the memory effect, ensuring long and constant performance. The fast charging capability combined with a remarkable lifecycle of 15–20 years, makes LIBs a sustainable choice that lasts three times longer than lead-acid alternatives [9]. Their high voltage performance and adaptability to different designs also contribute to their widespread use. Due to their high efficiency and long lifecycle, LIBs have become indispensable in portable electronics, as they enable fast discharge. In the field of EVs, LIBs have proven to be the most suitable energy storage device, characterised by high energy efficiency, the absence of a memory effect, a long lifecycle, and impressive energy and power density. Thanks to this unique combination, they are smaller and lighter than conventional rechargeable batteries, making them a cornerstone of advanced EV technology [1,10].

LIBs offer numerous advantages, but they also come with significant challenges. Limited battery life and longevity, battery range, sensitivity to extreme temperatures, and their environmental impacts are major drawbacks [6]. LIBs have a limited energy density, long charging times compared to refuelling with fossil fuels, and a limited shelf life. EVs equipped with LIBs need to be carefully maintained for safety and cost reasons [11]. High-power applications, such as EVs and energy storage systems, face challenges in terms of cost, stability, consistency, and safety [12]. Further research is needed for fast charging at low temperatures, advanced battery management systems (BMS) with cell-balancing functions and the optimisation of thermal management systems [13]. LIBs must be protected against overcharging and over-discharging, and the depth of the discharge cycle can affect the life of the LIBs [10,14]. Addressing the temperature challenges of LIBs is crucial for the continuous and reliable operation of EVs across diverse climates. Current studies explore various methods, such as air, liquid, electric heating, and phase change materials (PCMs), to enhance low-temperature performance and manage high temperatures, but future research should focus on developing adapted methods for maintaining stable battery-pack temperatures, integrating heating and cooling systems with vehicle air conditioning, modifying LIB electrolytes for improved low-temperature performance, and studying the ageing effects of thermal management on battery longevity [15].

1.3. Evaluation of the Lithium-Ion Batteries Effectiveness in Electric Vehicles

LIBs have many advantages (see Section 1.2). Their application in EVs is already present. However, the research question is, how effective and efficient is the application of LIBs in EVs? Therefore, the present study aimed to examine previous evaluations of LIBs that were conducted using cost–benefit analysis (CBA) and multi-criteria decision-making (MCDM) methods to justify their application in the field of transportation, particularly in electric vehicles. The reason that these methods were chosen is due to the fact that CBA is primarily used to evaluate efficiency from a financial perspective, while MCDM methods consider multiple criteria for evaluation, and not cost alone.

The motivation for this research is directly linked with the former. LIBs provide a good alternative to fossil fuel usage and are a general step towards green energy transition. However, like any source of energy, LIBs have their advantages and disadvantages. The CBA and MCDM methods can therefore provide a good evaluation methods to analyse LIBs effectiveness. The review consists of examples of good practices in the application of CBA and MCDM methods (case studies and other research). To our knowledge, no previous review of LIB efficiency evaluations using CBA and MCDM methods has been conducted.

2. Materials and Methods

In this paper, an approach including the application of CBA and MCDM methods to evaluate the efficiency and effectiveness of, and justification for, the use of LIBs in vehicles was used.

2.1. Study Inclusion Criteria

The process of literature collection was based on several restrictions: (1) publications must have been written in the English language or at least have had an abstract written in the English language; (2) publications must have included references to EVs and CBA or MCDM methods; (3) the collection period was determined based on the earliest found publication during the literature databases search; and (4) only journal papers were included in review.

2.2. Literature Search Methods

Two databases that cover an extensive range of scopes of journals were searched: Web of Science (WoS) and Scopus. Additional search check was made through other literature databases e.g., ScienceDirect, ResearchGate, Taylor and Francis and Elsevier.

The literature search process was finalised in October 2023. The input search in the WoS database had no restrictions based on the field of search (all possible fields in the search were used e.g., Title, Abstract, Authors, Keywords, etc.). However, a search in the Scopus database revealed many publications. Based on the above, restrictions were made, and the search was based only on the article title, abstract and abstract keywords fields. Input keywords for the literature search were as follows: (1) "Lithium-Ion batteries" AND "Multi-Criteria Decision making" AND "Energy storage" AND "Vehicles"; (2) "Lithium-Ion batteries" AND "Cost-benefit analysis" AND "Energy storage" AND "Vehicles"; (3) "PROMETHEE" (or other MCDM method) AND "Lithium-Ion batteries" AND "Vehicles". To clarify (3), a separate search was conducted based on the most used MCDM methods (AHP, TOPSIS, ANP, DEMATEL, DEA, etc.).

The next step was to filter the collected literature to remove duplicates. The final number of studies included in the review is shown in Section 3.

2.3. Data Analysis and Literature Synthesis

The papers were categorised based on the used method for evaluation, application areas, year of publication, and based on the author's country. Separate sub-sections were formed according to the previous. Areas of application were formed and grouped by authors based on the content of each publication.

3. Results

The literature collected for the review ranges from 1997 to 2023. The search by keywords in the WoS database yielded a total of $n = 94$ results. The screening process was based on the inclusion criteria in Section 3.1. There were 14 duplicate searches in the collected literature and 47 publications were rejected because they did not fulfil the inclusion criteria. WoS search yielded a total of $n = 33$ accepted publications. Scopus search resulted in a total of $n = 106$ results. There were 23 duplicate studies and 76 were rejected because they did not fulfil the inclusion criteria. Scopus search yielded a total of $n = 7$ publications. A separate literature search was conducted through databases mentioned in Section 3.2. but no additional publications were found. Finally, the total number of $n = 40$ studies was included in the literature review.

3.1. Classification of Applied Methods

In the process of collecting the literature, research was singled out and classified in which the CBA and MCDM methods were applied. The MCDM methods were applied in 80% of studies and the CBA in 20%. The CBA was used in 8 studies. When compared to the total number of MCDM methods from Table 1. the percentage of studies that contained the application of the CBA method is 15.7%.

Table 1. Classification of MCDM methods in the collected literature.

MCDM Method	Method Name	Number	Percentage
AHP [16–24]	Analytic Hierarchy Process	9	17.6%
TOPSIS [17,21,23,25–30]	Technique for Order of Preference by Similarity to Ideal Solution	9	17.6%
ANP [16,30–32]	Analytic Network Processes	4	7.8%
C-MCDM [33–35]	Combination of Multi-Criteria Decision-Making methods	3	5.9%
PROMETHEE [16,31,36]	Preference Ranking Organisation Method for Enrichment Evaluation	3	5.9%
FAHP [37,38]	Fuzzy Analytic Hierarchy Process	2	3.9%
Fuzzy TOPSIS [20,38]	Fuzzy Technique for Order of Preference by Similarity to Ideal Solution	2	3.9%
DEA [39,40]	Data Envelopment Analysis	2	3.9%
DEMATEL [35]	Decision-Making Trial and Evaluation Laboratory	1	2.0%

Table 1. *Cont.*

MCDM Method	Method Name	Number	Percentage
Fuzzy MCDM [41]	Fuzzy Multi-Criteria Decision-Making	1	2.0%
MCGDM [42]	Multi-Criteria Group Decision-Making	1	2.0%
Fuzzy DEMATEL [43]	Fuzzy Decision-Making Trial and Evaluation Laboratory	1	2.0%
Fuzzy MULTIMOORA [43]	Fuzzy Multi-objective Optimisation by Ratio Analysis plus Full Multiplicative Form	1	2.0%
HDM [16]	Hierarchical Decision Modelling	1	2.0%
ELECTRE [16]	Elimination and Choice Translating Reality	1	2.0%
DSS [16]	Decision support systems	1	2.0%
CM [16]	Cognitive or Causal Maps	1	2.0%
FCM [16]	Fuzzy Cognitive Maps	1	2.0%
BN [16]	Bayesian Networks	1	2.0%
MAUT [16]	Multi-Attribute Utility Theory	1	2.0%
Choquet multi-criteria preference aggregation model [44]	Choquet Multi-Criteria Preference Aggregation Model	1	2.0%
SMAA [45]	Stochastic Multicriteria Acceptability Analysis	1	2.0%
VIKOR [46]	Multi-Criteria Optimisation and Compromise Solution	1	2.0%
Delphi study and methods of multi-criteria decision-making [47]	Delphi Study and Methods of Multi-Criteria Decision-Making	1	2.0%
Borda's counting method [20]	Borda's Counting Method	1	2.0%
	Total	51	100.0%

The distribution of MCDM methods by number and percentage is shown in Table 1. In several studies, multiple MCDM methods were used in combination. The most applied methods are the AHP (analytic hierarchy process) method (17.6%) and the TOPSIS (technique for order of preference by similarity to ideal solution) method (17.6%) followed by ANP (analytic network processes) method (7.8%).

3.2. Areas of Application CBA

The areas of CBA application were determined by authors based on the content of each study. Studies are sorted according to the following areas: (1) optimal battery technology and energy storage systems; (2) recycling of LIBs; (3) LIBs efficiency; and (4) EV charging stations.

3.2.1. Optimal Battery Technology and Energy Storage Systems

With the growing need for cleaner energy for transportation, there is an increasing need for research regarding optimal technology and the selection of optimal energy storage for LIBs. Several researchers have applied CBA to evaluate the former (Table 2). An example of this is a study from Italy where researchers analysed four variants of storage systems for collecting energy generated by the braking of a tram. The CBA application resulted in choosing the stationary systems as the best choice [48]. Sharing results and advances is crucial for LIB technology optimisation. In joint cooperation between the USA and China, CBA was one of the methods applied to evaluate plug-in hybrid electric vehicles with the objective of reducing dependency on fossil fuels [49]. Implementation of energy storage systems in energy networks could potentially reduce the price at which the energy is sold on a commercial level by 4–7%, reducing system power needs by 26%, as determined by the authors [50]. Similarly, in 2020, a study on the best strategy for an energy storage configuration of a general power network was assessed by the CBA method. The results included better efficiency and an improved profit return for the system [51].

Table 2. Studies regarding optimal battery technology and energy storage systems (CBA method).

Authors	Title
Ceraolo and Lutzemberger, 2014 [48]	Stationary and On-Board Storage Systems to Enhance Energy and Cost Efficiency of Tramways
Ouyang et al., 2018 [49]	Progress Review of US-China Joint Research on Advanced Technologies for Plug-In Electric Vehicles
Nian et al., 2019 [50]	A Feasibility Study on Integrating Large-Scale Battery Energy Storage Systems with Combined Cycle Power Generation—Setting the Bottom Line
Sun et al., 2020 [51]	Control Strategies and Economic Analysis of an LTO Battery Energy Storage System for AGC Ancillary Service

3.2.2. Recycling of Lithium-Ion Batteries

The recycling process of LIBs is one of the key problems in their use. Determining the most efficient recycling process can be especially challenging. Studies regarding the recycling process of LIBs are shown in Table 3. The application of the CBA method for the long-term process of recycling LIBs by the authors of one study revealed that 40% savings can be achieved when compared to new battery manufacturing [52]. In China, the application of the CBA method revealed good potential for the battery recycling process for secondary use, especially where grid companies are concerned [53].

Table 3. Studies regarding recycling of lithium-ion batteries (CBA method).

Authors	Title
Foster et al., 2014 [52]	Feasibility Assessment of Remanufacturing, Repurposing, and Recycling of End-of-Vehicle Application Lithium-Ion Batteries
Sun et al., 2020 [53]	Economic Analysis of Lithium-Ion Batteries Recycled from Electric Vehicles for Secondary Use in Power Load Peak Shaving in China

3.2.3. Lithium-Ion Battery Efficiency

For LIBs to be commercially implemented, they must be efficient or reach a breaking point in terms of cost and benefit. One study in this subsection, shown in Table 4, discussed the degradation of batteries, which was explored as a cost, while the investment return was considered as a benefit. The results can be used by investors to calculate investment returns [54].

Table 4. Studies regarding lithium-ion battery efficiency (CBA method).

Authors	Title
Bera et al., 2020 [54]	Maximising the Investment Returns of a Grid-Connected Battery Considering Degradation Cost

3.2.4. Electric Vehicle Charging Stations

The process of the literature search yielded only one result where the CBA method was applied for optimal EV charging stations. The results are shown in Table 5. In the study [55], researchers discussed how the integration of new power stations could put a strain on the electric power network. A new model of a fast-charging power station was proposed with the application of the CBA method, with mixed results regarding the installation cost, grid integration, and lifecycle of batteries.

Table 5. Studies regarding electric vehicle charging stations (CBA method).

Authors	Title
Gjelaj et al., 2018. [55]	Grid Integration of DC Fast-Charging Stations for EVs by Using Modular Li-Ion Batteries

3.3. *Areas of Application MCDM*

The areas of MCDM application were determined by authors based on the content of each study. Studies are sorted according to the following areas: (1) EV charging stations; (2) energy storage systems; (3) hazardous risks; (4) optimal battery technology; (5) recycling of LIBs; and (6) supply of materials for LIBs.

3.3.1. Electric Vehicle Charging Stations

The selection of suitable locations for EVs charging stations with the application of MCDM methods was explored by multiple studies (Table 6). In a Chinese study, the PROMETHEE (preference-ranking organisation method for enrichment evaluation) method and ANP method together with the cloud model were chosen by the authors for the selection of optimal EV charging station sites [31]. Another study from China used the DEMATEL (decision-making trial and evaluation laboratory) method for weight calculation and fuzzy MULTIMOORA (multi-objective optimisation by ratio analysis plus full multiplicative form) for ranking the location [43]. In India, the TOPSIS method was used to evaluate sites for EV charging stations based on the previously calculated weights, which were analysed using a geographical information system. The aim of the study was to help decision-makers in future planning and strategy development [25].

Table 6. Studies regarding electric vehicle charging stations (MCDM methods).

Authors	Title	MCDM Method
Wu et al., 2016 [31]	Optimal Site Selection of Electric Vehicle Charging Stations Based on a Cloud Model and the PROMETHEE Method	PROMETHEE, ANP
Gao and Cheng, 2023 [43]	Electric Vehicle Solar Charging Station Siting Study Based on GIS and Multi-Criteria Decision-Making: A Case Study of China	Fuzzy DEMATEL, Fuzzy MULTIMOORA
Rane et al., 2023 [25]	An Integrated GIS, MIF, and TOPSIS Approach for Appraising Electric Vehicle Charging Station Suitability Zones in Mumbai, India	TOPSIS

3.3.2. Energy Storage Systems

Studies regarding the selection of energy storage systems for LIBs by applying MCDM methods are shown in Table 7. The first recorded study is an investigation of the two-phase model of operation of lithium-ion phosphate batteries AM (automotive mode) and SM (energy storage mode). The DEA (data envelopment analysis) method was used to estimate the best point for a shift from AM to SM [39]. In the USA, a review of electric energy storage resulted in multiple MCDM methods and approaches to problem-solving [16]. In contrast, researchers [33] developed a new MCDM that resulted in the selection of 2MW LIBs as the optimal electric storage energy system. In a case study (Tibet, China) researchers developed a new fuzzy MCDM method based on IULCWA (the intuitionistic uncertain language

Choquet ordered weighted aggregation operator) for selection with the same objective as the former. Results showed the need for a comparison with other MCDM methods to determine the new method's advantages and disadvantages [41]. Furthermore, to test the effectiveness of energy storage systems (amongst which LIBs were included) researchers used the AHP-TOPSIS methodology. The study results highlighted the importance of the lifecycle and discharge in optimal battery selection [17]. The AHP method (with five criteria) was also applied in a similar study. Results showed that cost is the biggest problem in the implementation of LIBs [18]. A new framework for the evaluation of energy storage was also developed based on MCMD methods. Through its usage, LIBs were presented as multi-purpose energy storage systems [44].

Table 7. Studies regarding Energy Storage Systems (MCDM methods).

Authors	Title	MCDM Method
Lee and Chang, 2016 [39]	Allocative Efficiency of High-Power Li-Ion Batteries from Automotive Mode (AM) to Storage Mode (SM)	DEA
Kim et al., 2017 [16]	Evaluation of Electrical Energy Storage (EES) Technologies for Renewable Energy: A Case from the US Pacific Northwest	MAUT, AHP, HDM, PROMETHEE, ELECTRE, DSS, ANP, CM, FCM, BN
Li et al., 2020 [33]	How to Select the Optimal Electrochemical Energy Storage Planning Program? A Hybrid MCDM Method	C-MCDM
Pang et al., 2021 [41]	Multi-Criteria Evaluation and Selection of Renewable Energy Battery Energy Storage System-A Case Study of Tibet, China	Fuzzy MCDM
Bulat and Ozcan, 2021 [17]	A Novel Approach Towards Evaluation of Joint Technology Performances of Battery Energy Storage System in a Fuzzy Environment	AHP, TOPSIS
Liaqat et al., 2022 [18]	Multicriteria Evaluation of Portable Energy Storage Technologies for Electric Vehicles	AHP
Pereira and Pereira, 2023 [44]	Energy Storage Strategy Analysis Based on the Choquet Multi-Criteria Preference Aggregation Model: The Portuguese Case	Choquet multi-criteria preference aggregation model

3.3.3. Hazardous Risks

The major concerns regarding LIBs are the hazardous risks associated with energy storage usage and, the risk of burning or battery explosions in specific cases. Studies concerning the former are shown in Table 8. In one study, researchers applied the AHP method to improve the safety of batteries. The method was used to evaluate tests regarding the hazardous risks, with the key risks being thermal instability and the warning systems of EVs [19]. Another example was the application of the SMAA (stochastic multi-criteria acceptability analysis) method to evaluate multiple energy sources (including LIBs). The objective of the study, confirmed by the results, was to decrease the usage of dangerous materials in production [45]. A key component of LIBs is the cooling system. The ANP method was applied to evaluate five liquid-cooled temperature control models. Model 1 was determined to be optimal, and met the required criteria [32]. A high risk of fire in electric vehicles is associated with LIB applications. Using the TOPSIS method for the optimisation and design of LIBs, one study [26], one study aimed to reduce the risk of the battery catching fire during a collision (traffic accident). The risk of terminal runaway was investigated in one study [37], where the FAHP method was used to apply weights to collect and exert knowledge on the subject.

Table 8. Studies regarding hazardous risks (MCDM methods).

Authors	Title	MCDM Method
Hu et al., 2021 [19]	Comprehensively Analysis the Failure Evolution and Safety Evaluation of Automotive Lithium Ion Battery	AHP
He et al., 2022 [45]	Advancing Chemical Hazard Assessment with Decision Analysis: A Case Study on Lithium-Ion and Redox Flow Batteries Used for Energy Storage	SMAA
Zhao et al. 2023 [32]	Design and Performance Evaluation of Liquid-Cooled Heat Dissipation Structure for Lithium Battery Module	ANP
Stephenson Biharta et al., 2023 [26]	Design and Optimization of Lithium-Ion Battery Protector with Auxetic Honeycomb for In-Plane Impact using Machine Learning Method	TOPSIS
Meng et al., 2023 [37]	An Integrated Methodology for Dynamic Risk Prediction of Thermal Runaway in Lithium-Ion Batteries	FAHP

3.3.4. Optimal Battery Technology

The previously mentioned increasing need for the transition from fossil fuels to sustainable sources of energy requires further research and optimisation of the current technology. In Table 9, a collection of studies on optimal battery technology is presented. In 1997, researchers from Taiwan tested seven batteries for electric motorcycle driving. The batteries were evaluated by a combination of multiple MCDM methods with the optimal solution being LIBs [20]. When the VIKOR (multi-criteria optimisation and compromise solution) method was applied, the best solution for hybrid EVs was the LIB and the second-best was the Ni-MH battery [46]. In the previous subsection, the problem of temperature regulation within LIBs was discussed. Researchers from China used the TOPSIS method to optimise the rising temperature in the process of battery charging. The results are faster charging and a small temperature rise (charging within 1534 s with a rise of 4.1 °C) [27]. In the study focused on maritime transport, researchers used the TOPSIS method to evaluate energy storage systems for ship propulsion engines. The optimal solution was a lithium-iron phosphate battery [28]. The integration of renewable energy and fossil fuel-generated energy is essential for the eventual transition to “green energies”. A case study conducted in Germany applied the AHP-TOPSIS methodology for optimal battery energy technology. Again, LIBs were selected as an optimal solution [21]. The results of the application of PROMETHEE also resulted in LIBs being chosen as the best solution. A sensitivity analysis of the results also confirmed that this was the case [36]. Lastly, for the process of usage of LIBs to be effective, manufacturers must optimise their production. In one study, researchers used the DEA method to evaluate the effectiveness of different manufacturers. The resulting methodology can be used for the future assessment of LIB manufacturing [40].

Table 9. Studies regarding optimal battery technology (MCDM methods).

Authors	Title	MCDM Method
Gwo-Hshiung et al., 1997 [20]	Evaluation and Selection of Suitable Battery for Electrics Motorcycle in Taiwan —Application of Fuzzy Multiple Attribute Decision-Making	AHP, fuzzy TOPSIS and Borda's counting method
Panday and Bansal, 2016 [46]	Multi-Objective Optimization in Battery Selection for Hybrid Electric Vehicle Applications	VIKOR
Sun et al., 2019 [27]	A Novel Multi-Objective Charging Optimization Method of Power Lithium-Ion Batteries Based on Charging Time and Temperature Rise	TOPSIS
Bayraktara and Nuranb, 2022 [28]	Multi-Criteria Decision-Making Using TOPSIS Method for Battery Type Selection in Hybrid Propulsion System	TOPSIS
Marcelino et al., 2022 [21]	A Combined Optimisation and Decision-Making Approach for Battery-Supported HMGS	AHP, TOPSIS
Azzouz et al., 2023 [36]	Integration of Multi-Criteria Decision-making for Performance Evaluation of Different Solar Batteries Technologies	PROMETHEE
Wang et al., 2023 [40]	Enhancing Lithium-Ion Battery Manufacturing Efficiency: A Comparative Analysis using DEA Malmquist and Epsilon-Based Measures	DEA

3.3.5. Recycling of Lithium-Ion Batteries

A key problem for LIB production is the high cost of manufacturing. If the cost can be reduced, large-scale production and affordable production can be developed. The studies in Table 10 contain research regarding the recycling of LIBs. The scarcity of materials and the recycling process are evaluated in a study [38] using fuzzy AHP and fuzzy TOPSIS methods. Fuzzy AHP was used to calculate weight and fuzzy TOPSIS was used for variants assessment. The possibility of repurposing end-of-life LIBs was investigated in one study [34]. LIBs can be repurposed for stationary use. The MCDM methodology was used to evaluate suitable locations for secondary use. However, materials for lithium-ion production are scarce and, as previously mentioned, contain some hazardous risks. The MCDGM (multi-criteria group decision-making) method can be used in the evaluation and selection of the optimal recycling process [42]. Several barriers to the process of LIBs were investigated in the study by using the DEMATEL method. The key factors influencing smooth recycling were government regulations and the process of take-back products at the end-of-life cycle by manufacturers [35]. This is an essential process because of the supply problem of cobalt and lithium for battery production, as mentioned by the authors [29]. Safety concerns for the re-usage of end-of-life batteries were evaluated by the TOPSIS method. Similarly, a study by the authors [47] investigated the circular economy of LIB recycling. The key driving factor was government policies (recycling support). The basics of any recycling policy include the selection of an optimal recycling method. A Turkish study evaluated three different recycling methods by applying the ANP and TOPSIS methods. The results showed that direct recycling is the best solution [30].

Table 10. Studies regarding recycling of lithium-ion batteries (MCDM methods).

Authors	Title	MCDM Method
Sangwan and Jinda, 2012 [38]	An Integrated Fuzzy Multi-Criteria Evaluation of Lithium-Ion battery Recycling Processes	FAHP, Fuzzy TOPSIS
Moore et al., 2020 [34]	Spatial Modelling of a Second-Use Strategy for Electric Vehicle Batteries to Improve Disaster Resilience and Circular Economy	C-MCDM
Chakraborty and Kumar Saha, 2022 [42]	Selection of Optimal Lithium-Ion Battery Recycling Process: A Multi-Criteria Group Decision-Making Approach	MCGDM
Bhuyan et al., 2022 [35]	Evaluating the Lithium-Ion Battery Recycling Industry in an Emerging Economy: A Multi-Stakeholder and Multi-Criteria Decision-Making Approach	DEMATEL, C-MCDM
Chen et al., 2023 [29]	Safety in Lithium-Ion Battery Circularity Activities: A Framework and Evaluation Methodology	TOPSIS
Tripathy et al., 2023 [47]	Drivers of Lithium-Ion Batteries Recycling Industry toward Circular Economy in Industry 4.0	Delphi study and methods of multi-criteria decision-making
ÖztÜrk et al., 2023 [30]	Comparison of Waste Lithium-Ion Batteries Recycling Methods by Different Decision-Making Techniques	ANP, TOPSIS

3.3.6. Supply of Materials for Lithium-Ion Batteries

Multiple problems involving LIBs somewhat overlap. For example, the problem of the supply of materials can be directly associated with the recycling process. Studies regarding the supply of materials for LIBs are shown in Table 11. In one study, the AHP method was used to assess the supply risk of materials for four different batteries with lithium and cobalt identified as the highest risk for supply [22]. On another occasion, researchers [23] investigated the best supplier of LIBs from manufacturing and customer points-of-view using AHP and TOPSIS methods (the supplier one being optimal). A study from Indonesia also used the AHP method to determine the best raw material locations and markets for the sale of electric batteries (formulation of the supply chain for EVs). At the end, the researcher determined the optimal location for the EV factory [24].

Table 11. Studies regarding supply of materials for lithium-ion batteries (MCDM).

Authors	Title	MCDM Method
Helbig et al., 2018 [22]	Supply Risks Associated with Lithium-Ion Battery Materials	AHP
Tusnial et al., 2021 [23]	Supplier Selection using Hybrid Multicriteria Decision-Making Method	AHP, TOPSIS
Siahaan et al., 2021 [24]	Formulating the Electric Vehicle Battery Supply Chain in Indonesia	AHP

3.4. Distribution Paper Based on Publication Year

Studies included in the literature review range from the year 1997 to 2023. Data on the distribution of papers based on the publication year are shown in Figure 1. Up until 2009, research regarding applications of the MCDM or CBA method for the evaluation of LIBs was scarce. A sudden spike in the number of studies can be seen from 2013 to 2023. In 2023, the largest number of papers on the topic was published for a total of n = 10 studies.

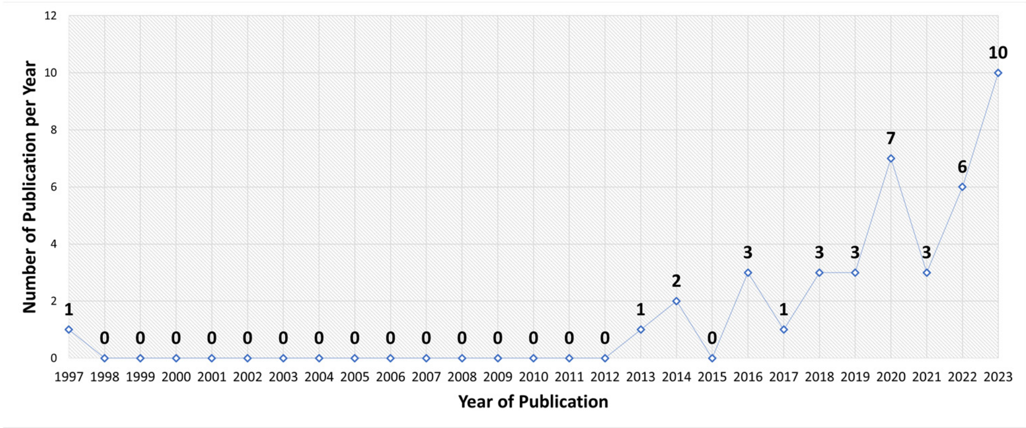

Figure 1. Distribution of published papers by year (1997–2023).

3.5. Distribution Paper Based on Author's Country

Studies included in the review were written by multiple authors from different continents and countries. Based on the data analysis in Table 12, it was concluded that the largest number of studies were from the People's Republic of China (21.6%), followed by the United States of America (17.6%) and India (13.7%). When studies are analysed by continent, 64.7% are from Asia, 17.6% are from North America, 15.7% are from Europe, and 2.0% are from Africa.

Table 12. Distribution of studies based on the author's country.

Authors Country	Count by Country	Percentage by Country
People's Republic of China	11	21.6%
United States of America	9	17.6%
India	7	13.7%
Turkey	4	7.8%
Taiwan	3	5.9%
Italy	2	3.9%
Germany	2	3.9%
France	2	3.9%
Indonesia	2	3.9%
Saudi Arabia	1	2.0%
Denmark	1	2.0%
Iraq	1	2.0%
Malaysia	1	2.0%
Pakistan	1	2.0%
Portugal	1	2.0%
Tunisia	1	2.0%
United Arab Emirates	1	2.0%
Vietnam	1	2.0%

4. Discussion

The main focus of this study is a review application of CBA (cost–benefit method) and MCDM methods in the field of transportation and lithium-ion batteries. Studies on the subject were collected and broken down into several subsections (categories of application). The analysis of the paper distribution also yielded interesting results. The discussion is divided into two subsections, one showing key findings in the literature review and an analysis of the results (Section 4.1) and an analysis of the paper-based distribution (Section 4.2).

4.1. Key Findings in Areas of Application and Analysis of Results—CBA and MCDM

Different areas of application of CBA and MCDM methods show the diversity of the applied methods. Categories in which the CBA and MCDM methods were divided were proposed by the authors. Summaries of the areas of the CBA method application are shown in Table 13 and for MCDM methods in Table 14, respectively.

Table 13. Summary of areas of application—CBA method.

Areas of Application	Key Findings (Areas)
Optimal Battery Technology and Energy Storage Systems	◦ Optimal energy storage for trams [48] ◦ Plug-in vehicles [49] ◦ Large-scale battery implementation in the energy grid [50] ◦ General power network energy configuration [51]
Recycling of LIBs	◦ End-of-life battery recycling for secondary use [52]; ◦ Recycling EV batteries for secondary use in power load peak shaving [53].
LIBs Efficiency	◦ Investment return considering the degradation of LIBs [54]
EV Charging Stations	◦ EV charging station [55]

Table 14. Summary of areas of application—MCDM methods.

Areas of Application	Methods	Key Findings (Areas)
EV Charging Stations	PROMETHEE; ANP; Fuzzy DEMATEL; Fuzzy MULTIMOORA; TOPSIS	◦ Cloud model-based selection of charging station [31] ◦ Two method-based selection of optimal charging locations (case study) [43] ◦ Multiply method-based selection of optimal charging zones [25]
Energy Storage Systems	DEA; MAUT; HDM; PROMETHEE, ELECTRE; DSS; ANP; CM; FCM; BN, C-MCDM; Fuzzy MCDM; AHP; TOPSIS; Choquet multi-criteria preference aggregation model	◦ Automotive mode (AM) to storage mode (SM) [39] ◦ Review of electric energy storage (problem-solving approach [16] ◦ Optimal electrochemical energy storage [33] ◦ New MCDM method (IULCWA)—energy storage system (case study) [41] ◦ Multiple energy storage efficiency analysis [17] ◦ Investigation into LIBs implementation problems [18] ◦ Development of a new framework for LIB evaluation [44]
Hazardous Risks	AHP; SMAA; FAHP; ANP; TOPSIS	◦ Safety analysis of batteries in EVs [19] ◦ Reduction of dangerous materials in battery production [45] ◦ Evaluation of five liquid-cooled temperature control models [32] ◦ Fire risk in accidents involving EVs [26] ◦ Risk of thermal runaway [37]
Optimal Battery Technology	AHP; fuzzy TOPSIS and Borda's counting method; PROMETHEE VIKOR; TOPSIS; DEA	◦ Suitable battery for motorcycles [20] ◦ Hybrid vehicle, selection of optimal battery [46] ◦ The problem of temperature rise in the charging process [27] ◦ Hybrid propulsion system battery selection [28] ◦ Integration and selection of optimal battery (case study) [21] ◦ Solar battery technologies MCDM evaluation [36] ◦ Lithium-ion production optimisation [40]

Table 14. *Cont.*

Areas of Application	Methods	Key Findings (Areas)
Recycling of LIBs	FAHP; Fuzzy TOPSIS; MCGDM; DEMATEL; C-MCDM; TOPSIS; Delphi study and methods of multi-criteria decision-making; ANP	◦ Scarcity of battery materials and the recycling process [38] ◦ Repurposing end-of-life LIBs [34] ◦ Repurposing batteries for stationary use [42] ◦ Investigation into barriers to the process of LIBs [35] ◦ LIB materials supply problems and safety concerns [29] ◦ Circular economy of LIBs recycling [47] ◦ Evaluation of three different recycling methods [30]
Supply of Materials for LIBs	AHP; TOPSIS	◦ Assessing the supply risk for four different batteries [22] ◦ Investigation into the best supplier of LIBs [23] ◦ Vehicle battery supply chain [24]

4.2. Analysis of Paper-Based Distribution

In this paper, multiple analyses of the collected literature were conducted. All studies were indexed in the WoS or Scopus databases, which emphasises the quality of the research conducted by numerous researchers around the world. Compared to the studies using the CBA method, more studies used MCDM methods. This is particularly true for the EV charging station application area, where only one study using the CBA method was evaluated, compared to four studies using the MCDM method. Most of the studies on the application area of the CBA method were for optimal battery technology and energy storage systems (four studies), while MCDM methods included optimal battery technology, the recycling of LIBs, and energy storage systems (seven studies). The distribution of studies according to MCDM methods is not even. This means that the authors mostly used the most common MCDM methods for different assessments in several application areas. This may be due to the advantages and disadvantages of the method or the possibility of applying it to specific problems. A tendency to use methods that had already proven themselves for certain problem-solving applications was observed. This is clearly shown in the percentage of distributed methods by paper, where, for example, the AHP method was slightly favoured compared to other methods. Again, it is important to carefully consider the problem faced by the decision-maker.

The main results and explanations of the criteria used by the authors to categorise the literature collected are explained in Section 4.1. The distribution of the other journal publications included is evenly distributed amongst the others. This can be considered a good sample and should reduce the risk of bias. This means that the studies are spread across different journals with different topics and criteria for publication. A smaller number of conference-published papers is somewhat recommended. Looking at the distribution of papers by year of publication, there is a clear increase in the number of papers published in 2013. One possible reason for this is the transition to cleaner forms of energy or a general push for a clean energy transition. It is worth noting that the number of publications from CBA and MCDM were analysed together. Finally, the distribution of studies based on the author's country yielded the following results. The studies are mostly from the largest countries in the world (the People's Republic of China, the United States of America, and India). This means that 52.9% of the studies originate from the aforementioned countries.

The review also offers a diverse range of publications related to EV policies and industrial practices. This means that the review is not only useful for the production companies of LIBs and electric vehicles but also for the logistics supply chain, storage and distribution of LIBs, and energy and recycling methods. For example, studies in the review offer solutions to the production phase (e.g., optimisation of process and technology [33], etc.), distribution phase (end-user delivery—electric stations [31,55]), integration of new electric vehicles in the energy grid [50], the risks associated with LIB usage [19,37] and the recycling phase of LIBs (materials recycling because of scarce resources [22,38,52]). Studies that are referenced in this paragraph serve as examples for each phase, and more are mentioned in Section 3.

Considering the cost of LIBs it is crucial to connect all stakeholders in the production, distribution, and recycling process of LIBs. The CBA and MCDM methods are very useful for the optimisation of each process formerly mentioned; however, the application of just the CBA method offers a narrow view of cost criteria, while MCDM methods consider multiple criteria (e.g., cost criteria, construction timeframe criteria, safety criteria, etc.).

5. Conclusions

This study examined the efficiency and effectiveness of LIBs in EVs, which were evaluated in previous research using the CBA and MCDM methods. We found that CBA and MCDM methods were used to evaluate LIBs in several areas:

- Optimal technology selection (CBA and MCDM methods);
- Optimal energy storage system (CBA and MCDM methods);
- Recycling process (CBA and MCDM methods);
- Efficiency testing (CBA method);
- Selection of EV charging location (CBA and MCDM methods);
- Risk assessment (MCDM methods);
- Materials supply problem (MCDM methods).

There are some limitations of this research. Only publications published in English and in scientific journals were evaluated. In the process of collecting the literature, there were inconsistent publication search results regarding both the CBA method and MCDM methods due to the use of the full name and abbreviation/acronym of the method. Inputting the full name cost–benefit analysis and abbreviation (CBA) produced different search results. This was also the case for MCDM methods. Finally, the authors did not limit the research to specific EVs (e.g., road EVs). Future work should focus on diversifying the methods used in the assessment of the different application areas. The potential benefits of using different methods could lead to solutions with multiple perspectives for decision-makers and the optimisation of the use of LIBs in different areas. It would also be advantageous if several methods were used for only one problem (e.g., for calculating the weighting, selecting the optimal alternative, etc.). Focus can be placed on the effectiveness of classic (fossil) vehicles in relation to electric vehicles (with LIBs) if the need for a green energy transition is taken into account. In addition to the former, the study did not include MADM methods (multi-attribute decision-making methods); therefore, the authors plan to explore how the methods mentioned in this review would handle multiple attributes in the decision process.

Author Contributions: All authors contributed to the writing of structure, method, and analysis of the collected literature. Conceptualisation, D.B. and S.G.; methodology, D.B.; validation, D.B. and S.G.; formal analysis, D.B. and S.G.; investigation, S.G., M.J. and M.E.; data curation, D.B. and S.G.; writing—original draft preparation, D.B., S.G., M.J. and M.E.; writing—review and editing, D.B.; visualisation, S.G.; supervision, D.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

BEV	battery electric vehicle
BMS	battery management systems
CBA	cost–benefit analysis
EV	electric vehicle
HEV	hybrid electric vehicles
LCO	lithium-cobalt oxide
LFP	lithium-iron-phosphate
LIB	lithium-ion batteries
LMO	lithium-manganese oxide
LTO	lithium-titanium oxide
MCDM	multi-criteria decision-making
NCA	lithium-nickel-cobalt
NiCd	sodium-sulphur and nickel-cadmium
NiMH	nickel-metal hydride
NMC	nickel, manganese, and cobalt
PCM	phase change material

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