

Review

Optimized Energy Management Schemes for Electric Vehicle Applications: A Bibliometric Analysis towards Future Trends

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Abstract: Concerns over growing greenhouse gas (GHG) emissions and fuel prices have prompted researchers to look into alternative energy sources, notably in the transportation sector, accounting for more than 70% of carbon emissions. An increasing amount of research on electric vehicles (EVs) and their energy management schemes (EMSs) has been undertaken extensively in recent years to address these concerns. This article aims to offer a bibliometric analysis and investigation of optimized EMSs for EV applications. Hundreds (100) of the most relevant and highly influential manuscripts on EMSs for EV applications are explored and examined utilizing the Scopus database under predetermined parameters to identify the most impacting articles in this specific field of research. This bibliometric analysis provides a survey on EMSs related to EV applications focusing on the different battery storages, models, algorithms, frameworks, optimizations, converters, controllers, and power transmission systems. According to the findings, more articles were published in 2020, with a total of 22, as compared to other years. The authors with the highest number of manuscripts come from four nations, including China, the United States, France, and the United Kingdom, and five research institutions, with these nations and institutions accounting for the publication of 72 papers. According to the comprehensive review, the current technologies are more or less capable of performing effectively; nevertheless, dependability and intelligent systems are still lacking. Therefore, this study highlights the existing difficulties and challenges related to EMSs for EV applications and some brief ideas, discussions, and potential suggestions for future research. This bibliometric research could be helpful to EV engineers and to automobile industries in terms of the development of cost-effective, longer-lasting, hydrogen-compatible electrical interfaces and well-performing EMSs for sustainable EV operations.

Keywords: energy management; optimization; converter; controller; battery storage; electric vehicle

1. Introduction

The demand for urban mobility is rapidly increasing [1]. CO₂ concentrations in 2012 were roughly 40% higher than in the mid-1800s, based on the International En-

ergy Agency [2,3]. Electric vehicles (EVs) offer significant promise in terms of reducing transportation-related energy and emissions [4,5]. Due to the growing concerns over global warming, the development of EV applications has recently received much attention because of its benefits in decreasing CO₂ and GHG. EVs require a low-emission electric motor and advanced power electronics technology as well as improved energy management methods for energy sources and storage systems such as fuel cells (FCs), supercapacitors (SCs), and batteries to achieve adequate driving performances [6–9]. Energy management schemes (EMSs) benefit EVs by improving reliability, flexibility, and power quality [10]. To meet transit power supply and demand, the development of EVs with adequate energy and power density to achieve suitable driving performances, and the connection of FC sources to SC storage systems, is critical [11]. When sufficient fuel (gases and hydrogen) is available, FCs sources can provide an uninterrupted power supply. Due to the time responsiveness of the gas supply system, these energy sources can have a relatively slow transient dynamic. On the other hand, supercapacitor energy storage systems may provide high instantaneous power for short periods but have a lower energy density than other traditional storage elements such as batteries [12–14].

In the literature, many EMSs for EV applications have been described [15–17]. Optimization, filters, controllers, and rule-based techniques are the four types of methods that can be categorized. Neural Networks, Fuzzy Logic, and State Machines are the most common rule-based methods [16,18]. Each rule or state is defined either heuristically or experimentally for State Machine control [16]. Furthermore, Fuzzy Logic rule-based techniques attach membership functions to the inputs and outputs to attain the necessary performance. The performance of rule-based techniques is linked to the system's knowledge. The basic idea of controller-based EMSs is to employ control rules to correct the error between desired and actual states. Backstepping control [19], Sliding control [20], H-infinity control [21], Passivity control [22], Flatness-based control [23], Proportional–Integral (PI) control [24], and so on are examples of energy management-based controllers. Even when the operating point is unknown, these approaches can precisely estimate the reference while accounting for system losses. Filter techniques use a frequency decoupling strategy that considers the energy system's dynamic properties and physical features. Fast Fourier Transform methods [25], the Wavelet technique [26], and Low-Pass filter methods [27] are mostly used to accomplish this. When the system frequencies are accurately determined, the filter-based management method is straightforward and may greatly increase the lifetime of EV applications. Optimization-based approaches have recently been investigated for dealing with complicated management objectives (lifetime, efficiency, cost, etc.). The desired references are obtained via minimizing an instantaneous cost function in such techniques. Particle Swarm Optimization [28], Optimal Power Distribution Control [29], Adaptive Optimal Control [30], Neural Networks [24], Stochastic Dynamic Programming [31], and Model Predictive Control [32] are some of the techniques mentioned in the literature. These techniques are complicated and involve many calculations, slowing down the energy management system's response time.

Bibliometrics is a research strategy that uses library and information science to offer information and analysis in various formats, such as statistics and quantitative approaches [33,34]. Bibliometrics is a vital research topic because it provides specific and historical data that may be utilized to forecast future research trends [35,36]. Universities, instructors, researchers, and professors can use bibliometric studies to assess the quality of research using a variety of important indicators such as h-indexes, impact factors, citations, and current standing. Gingras [37] addressed the influence of bibliometric analysis on research direction and proposed some criteria for developing a suitable assessment procedure at a specific size of research plan and analysis. Andres [38] detailed the steps for conducting bibliometric analysis with many real-world samples and interpreted the results. In the bibliometric study, the authors also explained the significance of Scientometric investigations. The current condition of publishing activity in EMSs for EV application is examined in this article using a bibliographic analysis. Numerous bibliometric techniques

have been used in recent years to assess the research progress in various fields, such as healthcare simulation [39], Pediatric Surgery [40], drug repurposing [41], technological innovation [42], Strategic Management [43], Industrial Ecology [44], climate engineering research [45], applications of artificial intelligence [46], Computers and Industrial Engineering [47], quantum electronics [48], engineering nanomaterials [49], and software engineering [50].

There are a couple of bibliometric analyses performed on the EV applications related topics such as life cycle cost analysis for EVs [51], bibliometric analysis on EVs [52], EV reliability [53], next-generation vehicles [54], fuzzy optimization-based EVs energy technologies [55], carbon emissions from the transport sector [56], autonomous vehicles [57], and the development of China's EV battery industry [58]. As per our knowledge, no bibliometric analysis on EMSs for EV applications has been conducted so far. As a result, this paper outlines the first bibliometrics analysis of EMSs for EVs, which was carried out during the last eleven years (from 2010 to September 2021) to examine the assessments, research community, and current developments in this area. The following findings emphasize the paper's key contributions.

- A brief summary of EMSs for EV applications is presented regarding the number of articles published to date. The analysis is carried out on a yearly basis, subsequently includes a discussion.
- The most prolific authors, the most productive university, and the nation dominating the publishing are all used to analyze EMSs for EV.
- The keywords and themes that were utilized for content analysis and gap analysis are evaluated.
- Publication document types such as original papers, systematic and non-systematic reviews, and book chapters are investigated. In addition, the journals' impact factors and publisher distributions are investigated.
- The amount of researcher collaboration is determined. The number of authors in the articles and the connection between diverse universities and nations are also used to assess the team.
- The most influential authors, universities, institutions, and nations with the most published research are identified. This is critical for determining the productivity of authors, organizations, and nations in the research sector and improving research output and collaboration among authors.

The bibliometric review aims to find the top 100 most relevant publications in the field of EMSs for EV applications. As a result, a comprehensive report on these publications' facts, critical debates, analyses, contributions, and flaws is provided. The following are some of the advantages that the article will provide.

- A better understanding of the history and evolution of EMSs for EV applications will be available to future researchers.
- A comparative analysis of the most relevant articles for EMS in the EV applications field, which will aid in the future construction of existing knowledge and practice, will be given.
- Finally, this bibliometric analysis will include fruitful recommendations for the prospects and developments of EMSs for EV applications.

This bibliometric analysis is arranged as follows: Section 1 offers an overview of the EMSs, bibliometric study, research gaps, and contributions; Section 2 presents a detailed overview of the surveying methodologies used in bibliometric analysis; and Section 3 presents a comprehensive analysis on the selected papers on EMSs for EV applications. Section 4 discusses the various issues, challenges, and problems. The future trends and recommendations are highlighted in Section 5, followed by conclusions in Section 6.

2. Surveying Methods

A statistical, bibliometric study of the Scopus database (www.scopus.com), was utilized to conduct this research. Since it contains a higher number of articles than other databases, such as Web of Science [59], the Scopus database was chosen as a source in this study's bibliometric analysis. Due to the lack of reliable results, Google Scholar was not evaluated in this study [60]. The "energy management schemes" study was recorded in the Scopus database at the end of September 2021. Figure 1 depicts the bibliometric analysis methodologies employed in the Scopus database. As indicated in the picture below, the procedure was divided into six stages:

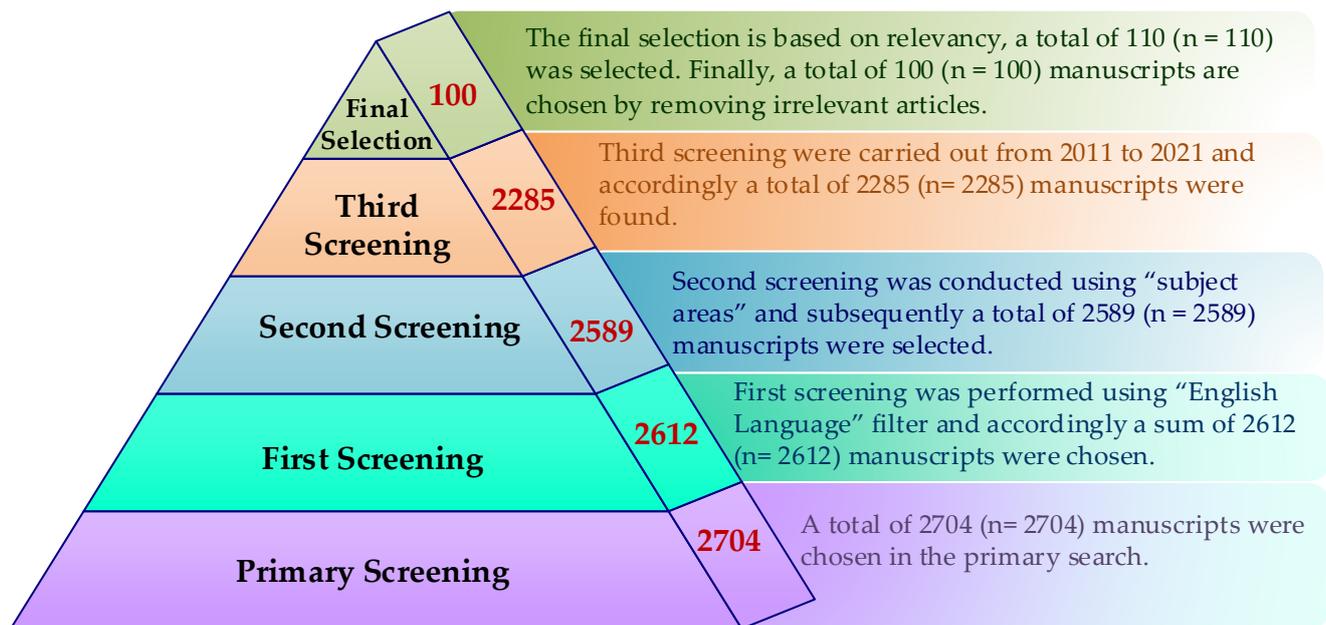


Figure 1. Manuscript selection steps from Scopus database.

2.1. Selection and Exclusion Criteria

Some predefined criteria were used to select the articles from a specific Scopus database. Table 1 represents the primary search keyword codes used for the article search of the Scopus database. The following are the criteria for article inclusion and exclusion for the 100 most relevant manuscripts in the field of EMSs for EV applications:

- The primary criteria for including manuscripts were the following keywords: energy management system, converter, controllers, optimization, and EVs. Some articles were excluded from this list based on the irrelevancy of the field.
- For the objectives of the study, articles published in the English language between 2012 and 2021 were examined.

Table 1. Keyword codes used to search for potential manuscripts in the Scopus database.

Stages	Filter	Keyword Codes	Number of Manuscripts
1st stage	Energy Management system, Electric vehicle applications	TITLE-ABS-KEY (energy AND management AND system AND for AND electric AND vehicle AND applications)	2704
2nd stage	English	TITLE-ABS-KEY (energy AND management AND system AND for AND electric AND vehicle AND applications) AND (LIMIT-TO (LANGUAGE, "English"))	2612

Table 1. Cont.

Stages	Filter	Keyword Codes	Number of Manuscripts
3rd stage	Subject area	TITLE-ABS-KEY (energy AND management AND system AND for AND electric AND vehicle AND applications) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "MATH") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "PHYS") OR LIMIT-TO (SUBJAREA, "MATE") OR LIMIT-TO (SUBJAREA, "CHEM"))	2589
4th stage	Year range (2010–2021)	TITLE-ABS-KEY (energy AND management AND system AND for AND electric AND vehicle AND applications) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "MATH") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "PHYS") OR LIMIT-TO (SUBJAREA, "MATE") OR LIMIT-TO (SUBJAREA, "CHEM")) AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2013) OR LIMIT-TO (PUBYEAR, 2012) OR LIMIT-TO (PUBYEAR, 2011) OR LIMIT-TO (PUBYEAR, 2010))	2285

2.2. Screening Procedures

As there are vast numbers of articles published in the various journals, the following criteria were applied to select the most relevant articles from the Scopus database.

- Based on the primary selection, a total of 2704 (n = 2704) articles were chosen.
- By applying "English Language", a sum of 2612 (n = 2612) publications were filtered.
- Then, a total of 2589 (n = 2589) manuscripts were selected by limiting the subject areas.
- After limiting the year ranges from 2010 to 2021, a total of 2285 articles were filtered.
- The final selection was based on relevancy; a sum of 110 (n = 110) was selected.
- After manually removing irrelevant articles, a total of 100 (n = 100) manuscripts from the Scopus database published in various journals were selected for the final evaluation.

2.3. Research Trend

Researchers are currently demonstrating interest in developing more efficient EMSs for EV applications [6,61]. They used a variety of approaches to find suitable EMSs for EV applications to ensure more efficient energy management. Figure 2 depicts the trend in research from 2010 to 2021. Overall, the number of papers produced every year due to the primary screening of the chosen database increased. Figure 2 shows that as the number of published papers rises, so does the number of researchers with related research interests. From 2019 through 2021, a total of 927 manuscripts were published. In comparison, there were 1774 papers published in the nine years leading up to 2018. In the first nine years of publication (2010–2018), 65% of all papers were published, while papers produced between 2019 and 2021 account for 35% of the total. According to the graph, the last three years show a linear growth of publications in EMSs related to EV applications.

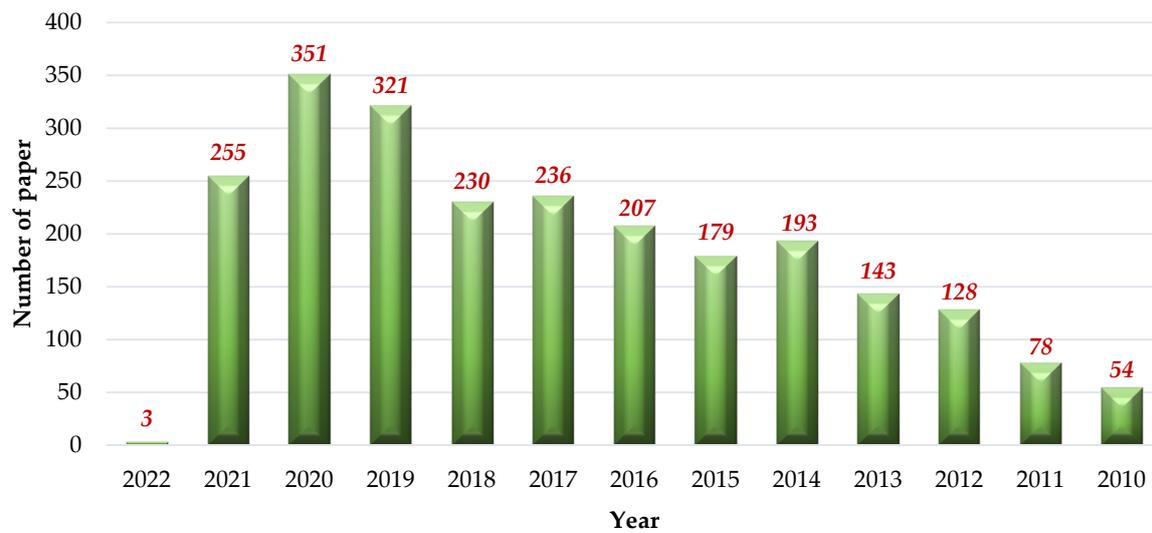


Figure 2. Manuscript distribution over the years from 2010 to 2022.

2.4. Data Extraction

By utilizing the Scopus database, information on manuscripts was extracted based on the following variables: names of the authors; doi of the manuscript; keywords list; year of publication; the name of the manuscript's publisher; type of manuscript; the name of the publication country based on the first author's affiliations; the total number of citations; the number of citations in the last five years. Following the data analysis from the chosen article, observations were made to present a clearer picture of EMSs for EV applications.

2.5. Study Characteristics and Outcomes

From the primary search, the Scopus database yielded a sum of 2704 manuscripts. By applying numerous filtering methods, the most relevant 100 articles were chosen and listed in Table 2 with the names of the authors; the doi of the manuscripts; the keywords lists; the years of publication; the names of the manuscripts' publishers; the types of the manuscripts; the names of the publication countries based on the first authors' affiliations; the total number of citations; and the total number of citations in the last five years. The total number of citations for the chosen manuscripts is 4903 (mean 49.52; median 14; and citation range 0 to 673). Furthermore, 11 of the 100 manuscripts were cited over 100 times.

Table 2. The most relevant 100 manuscripts in the field of EMSs for EV applications.

Rank	Ref. no.	Keywords	Type of Article	Abbreviated Journal Name	Publisher Name	Year	Country	Citation
1	[62]	BMS, EV, LIB, SOC	Review	RSERF	Elsevier Ltd	2017	Malaysia	673
2	[63]	BMS, BT, Charge/discharge, EV, SOC, SOH	Article	IEM	IEEE	2013	United States	487
3	[6]	EV, ESS, Hybridization, Power electronics	Review	RSERF	Elsevier Ltd	2017	Malaysia	384
4	[64]	EL, Forgetting factor, Kullback–Leibler divergence, PM, RL	Article	APEND	Elsevier Ltd	2018	China	222
5	[65]	EV, EMS, LIB, SOC	Review	IEEE Access	IEEE	2018	Malaysia	211
6	[66]	EV, EMS, HESS	Article	APEND	Elsevier Ltd	2014	China	206

Table 2. Cont.

Rank	Ref. no.	Keywords	Type of Article	Abbreviated Journal Name	Publisher Name	Year	Country	Citation
7	[67]	CC, EV, LIB, TD, TMS	Review	JPSOD	Elsevier B.V.	2017	China	186
8	[68]	EV, EM, ES, Optimization, Real-time	Article	APEND	Elsevier Ltd	2016	France	163
9	[69]	EMS, EV, Charging/Discharging, Photovoltaic System	Article	ITCED	IEEE	2013	South Korea	131
10	[70]	Eco-driving, EV, Optimal control	Article	COEPE	Elsevier Ltd	2014	France	126
11	[71]	Asynchronous machine, dc-link voltage control, converter, EM, FC, HEV, LIB, SC	Article	ITVTA	IEEE	2012	France	105
12	[72]	DP, EMS, Global optimization, Modeling, PHEV	Article	Energies	MDPI AG	2015	China	94
13	[61]	BMS, EV, Charge Equalization Controller, Drive Train Architecture	Review	RSERF	Elsevier Ltd	2017	Malaysia	85
14	[73]	EV, HESS, LIB, Integrated optimization, Operation cost	Article	ENEYD	Elsevier Ltd	2018	China	82
15	[74]	BMS, ES, EV, LIB, SOC	Review	Energies	MDPI AG	2019	South Korea	80
16	[75]	Brushless DC motor drive, EV, ES, FC, EMS	Review	RSERF	Elsevier Ltd	2017	United States	80
17	[76]	Fuel consumption, PHEV, Quadratic programming, Simulated annealing, SOH	Article	APEND	Elsevier Ltd	2015	United States	80
18	[77]	Electricity retailer and smart grid, HSS, PEV, Selling price determination	Article	ECMAD	Elsevier Ltd	2017	Iran	77
19	[78]	Driving pattern, EMS, OC, PHEV	Article	IETTE	IEEE	2014	United States	72
20	[79]	Energy saving, Environmental sustainability, Metro-transit system, PEV, Regenerative braking	Article	EPSRD	Elsevier Ltd	2011	Italy	72

Table 2. Cont.

Rank	Ref. no.	Keywords	Type of Article	Abbreviated Journal Name	Publisher Name	Year	Country	Citation
21	[80]	EM, fuel economy benefits, heavy duty diesel engines; HEV, online optimization	Article	IETTE	IEEE	2015	United Kingdom	66
22	[81]	EV, LIB, MPC, PAC, Remaining discharge energy	Article	APEND	Elsevier Ltd	2015	China	64
23	[82]	Chevrolet Volt, NN, genetic algorithm, HEM	Article	ITVTA	IEEE	2019	China	61
24	[83]	EV, EV tools, Grid tools, Smart grid; V2G tools, VT	Review	APEND	Elsevier Ltd	2016	Australia	61
25	[84]	Battery lifetime, EV, EMS, HESS, Pontryagin's minimum principle	Article	TSTE	IEEE	2018	China	57
26	[85]	Batteries, EMS, SC, fully active parallel topology, EV	Article	ITVTA	IEEE	2017	Canada	53
27	[86]	Basic operation mode, EMS, Modeling, PHEV	Article	Energies	MDPI AG	2013	China	53
28	[87]	Autonomous EV, EM, Cyber-physical systems, Event-based control, Wireless sensor networks	Article	CMPJA	Oxford University Press	2013	China	50
29	[88]	Battery, EM, Flatness, FC, Fuzzy logic, HV, SC	Article	ECMAD	Elsevier Ltd	2019	Tunisia	39
30	[89]	EMS, HEV, Q-learning, Reinforcement learning	Article	APEND	Elsevier Ltd	2020	United States	38
31	[90]	battery life, EV, EM, HESS	Article	ITPEE	IEEE	2020	China	38
32	[91]	BMS, HEV, SOC, global positioning system, Petri net, rule-based strategy	Article	TASE	IEEE	2017	Egypt	38
33	[92]	Battery, EM, PHEV, Component sizing, Optimization	Article	Energies	MDPI AG	2012	United Kingdom	37
34	[93]	EV, ES, LIB, SOC, SOH	Review	JEECS	ASME	2019	India	35
35	[94]	Deep reinforcement learning, DP, EM, MPC, Generalization	Article	ITVTA	IEEE	2019	China	34

Table 2. Cont.

Rank	Ref. no.	Keywords	Type of Article	Abbreviated Journal Name	Publisher Name	Year	Country	Citation
36	[95]	Driving cycle identification, EV, EMS, Haar wavelet transform	Article	Energies	MDPI AG	2016	China	32
37	[96]	EV, ES, fuzzy logic control, genetic algorithm, optimization	Article	IJERD	John Wiley & Sons Ltd	2018	Brazil	30
38	[97]	EV, EMS, FC, SC, Grey wolf optimizer	Article	IJHED	Elsevier Ltd	2019	Algeria	25
39	[98]	EMS, FC, Multi-objective optimization, PHEV, Velocity forecasting	Article	JPSOD	Elsevier B.V.	2020	France	24
40	[99]	DC–DC converter, DTC-SVM, EV, FC, PM	Article	JPSOD	Elsevier B.V.	2020	Algeria	23
41	[100]	EMS, HEV, Markov chain, Operation-mode prediction	Article	JCROE	Elsevier Ltd	2018	China	23
42	[101]	Aircraft engine, EM, HEV, Propulsion, Vehicle sizing	Review	AATEE	Emerald Group Holdings Ltd.	2014	United States	23
43	[102]	HESS, EV, Perturbation observer, Robust fractional-order sliding-mode control	Article	JPSOD	Elsevier B.V.	2020	China	21
44	[103]	ECMS, EM, HEV, OC, Pontryagin's minimum principle	Article	APEND	Elsevier Ltd	2017	United States	21
45	[104]	Engine on/off control, Estimation distribution algorithm, Pontryagin's minimum principle	Article	ENEYD	Elsevier Ltd	2018	China	18
46	[105]	EV, EM, OC, gain scheduling, linearization techniques, real-time simulation	Article	IETTE	IEEE	2015	France	18
47	[106]	EV, EMS, FC, SC, permanent-magnet synchronous motor	Article	ETEP	John Wiley & Sons Ltd	2017	Algeria	17
48	[107]	ANN, forecasting, Battery degradation cost model, ES, EV, Stochastic programming	Article	SETA	Elsevier Ltd	2020	Iran	16

Table 2. Cont.

Rank	Ref. no.	Keywords	Type of Article	Abbreviated Journal Name	Publisher Name	Year	Country	Citation
49	[108]	Adaptive equivalent consumption minimization strategy, MPC, PHEV	Article	ENEYD	Elsevier Ltd	2020	China	14
50	[109]	Adaptive controller, Battery, EV, EMS, Semi-active hybrid energy storage system, SC	Article	Energies	MDPI AG	2019	South Korea	14
51	[110]	Continuously variable transmission, EV, HESS, SC	Article	ENEYD	Elsevier Ltd	2019	China	14
52	[111]	Energy optimization, PHEV, RL, PM, Q-learning	Article	TNNLS	IEEE	2020	United States	13
53	[112]	Automotive applications, OC, internal combustion engines, nonlinear control systems	Article	ITVTA	IEEE	2018	Spain	13
54	[113]	Dynamic programming, MPC, PEV, NN, Pontryagin's minimum principle	Article	ENEYD	Elsevier Ltd	2020	China	12
55	[114]	HEV, Hybrid sliding mode controller, Invasive weed optimization	Article	EST	Elsevier Ltd	2018	Iran	11
56	[115]	Demand side management, Energy, EM, HEMS, PEV, V2G	Article	Energies	MDPI AG	2019	Canada	10
57	[116]	fuzzy logic control, HESS, EMS, PHEV, SC, wavelet transform	Article	IEEE Access	IEEE	2018	China	10
58	[117]	Dynamic programming, EV, EM, OC, Stochastic systems	Article	IJAP	SAE International	2013	Germany	10
59	[118]	EM, HESS, PEV, Temperature uncertainty, Wavelet transform	Article	APEND	Elsevier Ltd	2019	Australia	9
60	[119]	Diesel engine modelling, EM, FC, HEV, Multivariable control systems, Robust feedback control	Article	IJVDD	Inderscience Publishers	2012	United Kingdom	9

Table 2. Cont.

Rank	Ref. no.	Keywords	Type of Article	Abbreviated Journal Name	Publisher Name	Year	Country	Citation
61	[120]	EMS, RL, Markov chain, Stochastic model prediction control, Velocity prediction	Article	ENEYD	Elsevier Ltd	2020	China	8
62	[121]	Direct refrigerant cooling, EV, LIB, EMS	Article	ESD	Elsevier B.V.	2020	China	8
63	[122]	fuel consumption, Grey wolf optimizer, HEV, rules-based energy management	Article	TICOD	SAGE Publications Ltd	2020	Tunisia	8
64	[123]	EV, EMS, FC, HEV, Energetic macroscopic representation	Article	MCSID	Elsevier B.V.	2020	France	8
65	[124]	Intelligent energy management, Multi-agent; Proton Membrane Exchange fuel cell, Real-time, SC	Article	Energies	MDPI AG	2019	Tunisia	8
66	[125]	EV, Loop Heat Pipe, Lumped parameter, Thermal management	Article	ATENF	Elsevier Ltd	2018	United Kingdom	8
67	[126]	Connected and automated vehicles, hierarchical model predictive control, thermal management	Article	IETTE	IEEE	2021	United States	7
68	[127]	Battery degradation, EV, EM, HESS, Sizing	Article	ENEYD	Elsevier Ltd	2020	United Kingdom	7
69	[128]	EMS, FC, HEV, Hierarchical clustering, Rule learning	Article	JCROE	Elsevier Ltd	2020	China	7
70	[129]	Back propagation NN, EMS, HEV, Compound structured permanent-magnet motor	Article	Energies	MDPI AG	2018	China	7
71	[130]	Dual droop control, EV, HESS, Frequency diving coordinated control	Article	JMPSCE	Springer	2015	China	7
72	[131]	Construction vehicle, EM, FC, MPC, NN, Wavelet	Article	ENEYD	Elsevier Ltd	2020	China	6

Table 2. Cont.

Rank	Ref. no.	Keywords	Type of Article	Abbreviated Journal Name	Publisher Name	Year	Country	Citation
73	[132]	Distributed energy management, V2G, greedy-based algorithm, mixed integer non-linear programming	Article	IEEE Access	IEEE	2020	United Kingdom	5
74	[133]	Algorithm, Classification, EMS, HEV, Optimization	Review	Energies	MDPI AG	2020	China	4
75	[134]	Batteries, EMS, FC, EV, Fuzzy inference system, Hull moving average	Article	Energies	MDPI AG	2019	China	4
76	[135]	Equivalent Consumption Minimization Strategy, equivalent factor, fuzzy logic	Article	JIFS	IOS Press	2017	China	4
77	[136]	Advanced model, battery lifetime, EV, EMS, HESS, LIB, SC	Article	ITIED	IEEE	2021	France	3
78	[137]	BMS, EV, LIB, Cost estimation, Fiber optic sensor	Review	Sensors	MDPI AG	2021	United States	3
79	[138]	Charging (batteries), EV, EE, EM, EPTN	Article	RPG	John Wiley & Sons Inc	2020	Denmark	3
80	[139]	Bidirectional power flow, DC–DC converters, EV, SC	Article	EENGF	Springer	2020	Brazil	3
81	[140]	Battery, EV, EMS, SC, Jaya algorithm	Article	IJERD	John Wiley & Sons Inc	2020	Turkey	3
82	[141]	SOC, DC, EM, FC, HEV, Pattern recognition, Supervisory control	Article	IJEHV	Inderscience Publishers	2010	Iran	3
83	[142]	Fuzzy based EM, HESS, FC, Super twisting sliding mode control	Article	EST	Elsevier Ltd	2021	Pakistan	2
84	[143]	Bidirectional DC–DC converter, EV, FC, Real time digital simulator	Article	JPE	Korean Institute of Power Electronics	2011	United States	2
85	[144]	EV, EE, NN, Fuzzy logic, Intelligent controllers, Regenerative braking	Review	Energies	MDPI AG	2021	Estonia	1

Table 2. Cont.

Rank	Ref. no.	Keywords	Type of Article	Abbreviated Journal Name	Publisher Name	Year	Country	Citation
86	[145]	ES, EV, Isolated power grids, Transport decarbonization, V2G	Article	Energies	MDPI AG	2021	Portugal	1
87	[146]	battery swapping station, EV, V2G, stochastic model predictive control	Article	IJERD	John Wiley & Sons Ltd	2021	China	1
88	[147]	EV, EM, Energy consumption, Supply chain, Vehicle routing problem	Article	Energies	MDPI AG	2021	United States	1
89	[148]	Commercial building, EV, retired electric vehicle battery, Risk management strategy	Article	ECMAD	Elsevier Ltd	2021	China	1
90	[149]	Auxiliary power unit, Charging strategy, Cost analysis, EM, HESS	Review	RSERF	Elsevier Ltd	2021	Australia	0
91	[150]	Coolant, direct cooling system, EV, LIB, two-phase flow	Review	IJERD	John Wiley & Sons Ltd	2021	China	0
92	[151]	Cost optimization, EV, EM, HESS, NN, Variable perception horizon	Article	APEND	Elsevier Ltd	2021	United Kingdom	0
93	[152]	Deep Q learning, HEV, MPC, Prioritized replay	Article	ENEYD	Elsevier Ltd	2021	China	0
94	[153]	Dynamic programming, Electrified powertrain, EMS, OC, HEV	Article	Energies	MDPI AG	2021	Italy	0
95	[154]	Battery, Gain scheduled, Linear parameter varying, SC	Article	ITCNE	IEEE	2021	France	0
96	[155]	Energy harvesting, EM, HEV, SC	Article	Energies	MDPI AG	2021	Greece	0
97	[156]	hybrid sources, LIB, SC	Review	IJERD	John Wiley & Sons Ltd	2021	China	0
98	[157]	EMS, MPC, integrated power system, load power prediction	Article	IEEE Access	IEEE	2021	China	0

Table 2. Cont.

Rank	Ref. no.	Keywords	Type of Article	Abbreviated Journal Name	Publisher Name	Year	Country	Citation
99	[158]	Adaptive equivalent consumption minimum strategy, equivalent factor, PHEV	Article	IJERD	John Wiley & Sons Ltd	2021	China	0
100	[159]	DC–DC converter; EV; intelligent controller; BSS; modulation techniques; metaheuristic optimization	Review	Electronics	MDPI AG	2021	Malaysia	0

AB = Automotive Batteries, ANN = Artificial Neural Network, BMS = Battery Management Systems, BP = Battery Pack, BSOC = Battery State of Charge, BESS = Battery Energy Storage Systems, CA = Cost Analysis, CR = Cost Reduction, CS = Control System, DP = Dynamic Programming, EB = Electric Batteries, EE = Energy Efficiency, ED = Electric Discharges, EM = Energy Management, EMC = Electric Machine Control, EP = Energy Planning, EPTN = Electric Power Transmission Networks, EV = Electric Vehicle, EMS = Energy Management Systems, ES = Energy Storage, ESS = Energy Storage Systems, EU = Energy Utilization, FC = Fuel Cells, FE = Fuel Economy, FL = Fuzzy Logic, HESS = Hybrid Energy Storage Systems, HV = Hybrid Vehicles, HEV = Hybrid Electric Vehicles, LIB = Lithium-ion Batteries, MPC = Model Predictive Control, NN = Neural Networks, OCS = Optimal Control Systems, OC = Optimal Control, PCS = Predictive Control Systems, PHEV = Plug-in Hybrid Electric Vehicles, PHV = Plug-in Hybrid Vehicles, PM = Power Management, REM = Real-time Energy Management, RL = Reinforcement Learning, SC = Solar Cells, SOC = State of Charge, SM = Storage Management, SS = Stochastic Systems, SB = Secondary Batteries, SC = Supercapacitor, TC = Temperature Control, VA = Vehicle Applications, V2G = Vehicle-to-grid.

3. Analytical Discussion

The analysis of the most relevant article in any specific field of study is critical for understanding and categorizing current research trends and providing an overall idea about the influential journals and publications. We aimed to provide transparent information about the most important fields of research manuscripts and recent research developments in EMSs for EV applications with this study.

3.1. Citation Analysis of the Selected Most Relevant Manuscripts

Table 2 shows the 100 most relevant articles in the field of EMSs for EV applications, as extracted from the Scopus database and analyzed to deliver further information for future researchers. It can be observed that Table 2 illustrates the number of citations for the 100 manuscripts, whose citation numbers range between 0 and 673; the first 6 manuscripts received more than 200 citations, while the first 11 manuscripts had more than 100 citations. Hannan et al. generated the manuscripts with the highest citations in 2017.

The most cited article in the field of EMSs for EV applications is “A review of lithium-ion battery state of charge estimation and management system in EV applications: Challenges and recommendations” [62] produced by Hannan et al., which received 673 citations and was published in the journal “Renewable and Sustainable Energy Reviews” in 2017. This study estimates the lithium-ion battery state of charge (SOC) and examines its management system in the context of future EV applications. Moreover, the need for a lithium-ion battery management system (BMS) is discussed, ensuring a dependable and safe operation while also assessing the battery’s state of charge (SOC). The SOC is a critical statistic, according to the study, since it indicates the remaining available energy in a battery, which gives an indication of charging/discharging strategies and protects the battery from overcharging/over-discharging. According to the citation, “Battery management system: An overview of its application in the smart grid and EVs” is a review paper by Rahimi-Eichi et al. that evaluates battery management issues based on smart grids and EV [63]. In 2013, the work was published in the journal “IEEE Industrial Electronics Magazine”, and it received 487 citations. “Review of energy storage systems for EV applications: Issues and challenges” [6] was the third most cited manuscript published in the “Renewable and Sustainable Energy Reviews” journal in 2017. Hannan et al. authored the manuscript, which

received 384 citations. This manuscript examines energy storage system (ESS) technologies in detail, including classifications, features, structures, power conversion, and assessment procedures, as well as their benefits and drawbacks in EV applications. Furthermore, this article examines several classes of ESS based on their energy forms, composition materials, and methodologies in terms of the average power delivery overcapacity and overall efficiency displayed within their life expectancies. Articles with an average citation per year (ACY) of 21.6 or higher are considered the most important in the EMS field. Those included in Table 2 provide a more profound knowledge of the topic.

3.2. Allocation of the Selected 100 Manuscripts over the Year

In Figure 3, the allocation of the 100 stated articles in EMSs for EV applications between 2010 and 2021 is illustrated. The numbers of papers published in the years 2010 and 2011 are 1 and 2, respectively. Based on Figure 3, the number of manuscripts published in 2020 was the highest, while it was the lowest in 2010; the figures are 22 and 1, respectively. With 12 manuscripts each, the number of papers generated in 2018 and 2019 is the same. Overall, the articles published from 2019 to 2021 indicate an increasing trend, but those—published from 2010 to 2016 show a fluctuating trend.

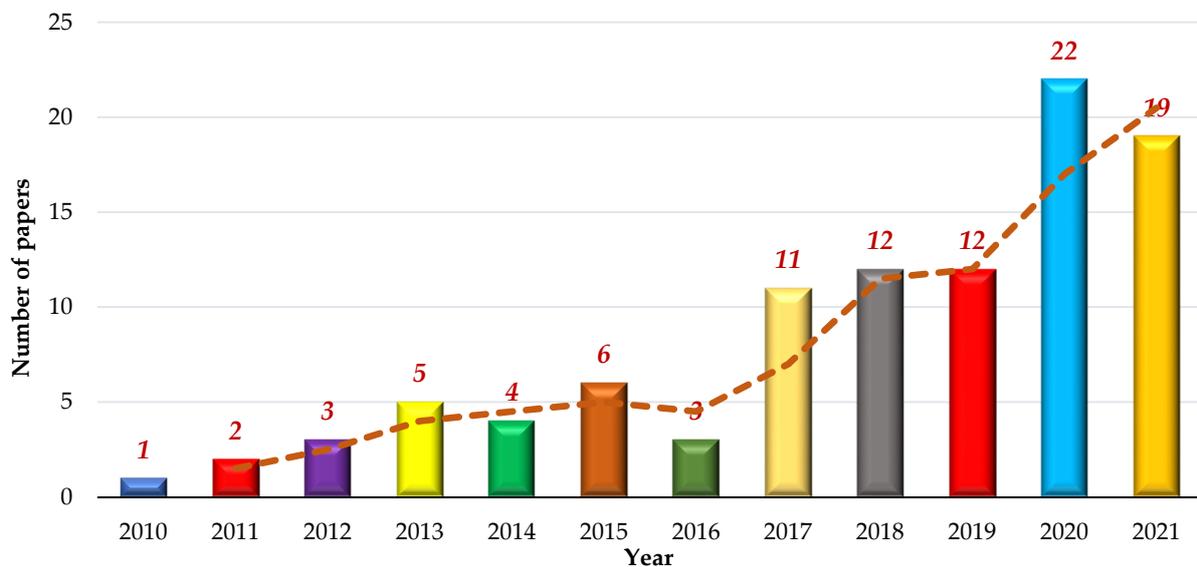


Figure 3. Distribution of elected manuscripts over the years 2010 to 2021.

3.3. Co-Occurrence Keyword Analysis

Table 2 delivers a broad notion of the selected research area, while Figure 4 shows co-occurrence keywords from the most relevant manuscripts picked from the selected database. Figure 4 demonstrates the internal network among all keywords, which is generated by using the VOSviewer software. The influence of the keywords controls the volume of the circle and label, while the connecting line among the keywords is revealed as a conjunctive connection. Different colors are used to describe different clusters depending on the area of expertise. The adaptive controller, battery, battery degradation cost model, battery management system, charge equalization controller, coolant, cost estimation, deep neural network, dual droop control, EV, energy storage, genetic algorithm, home energy management system, hydrogen fuel consumption, integrated energy management strategy, integrated optimization, isolated power grids, Jaya algorithm, optimization, parameter match, risk management strategy, sector-coupling, smart grid, state of charge, temperature monitoring, thermal management, thermal runaway, transport decarbonization, and variable perception horizon are in the red cluster, which illustrates the strong bond among them. The blue cluster represents different sorts of energy management strategies such

“Electric Vehicles” are 42 and 35, respectively, while “Secondary Batteries” have a figure of 31. “Energy Management Systems”, “Electric Vehicles”, “Optimization”, and “Controllers” were also the most popular terms in the recent two years, reflecting the growing interest in EMSs for EV applications. The total allocation of keywords and the graphical depiction of Table 3 are depicted in Figure 5. Based on the analysis of Table 3 and Figure 5, the following conclusions can be made:

- Scholars are now concerned about energy storage efficiency and minimizing carbon’s impact on the climate while enhancing the system’s efficiency.
- There has been a tremendous rise in EMS and EV application research.

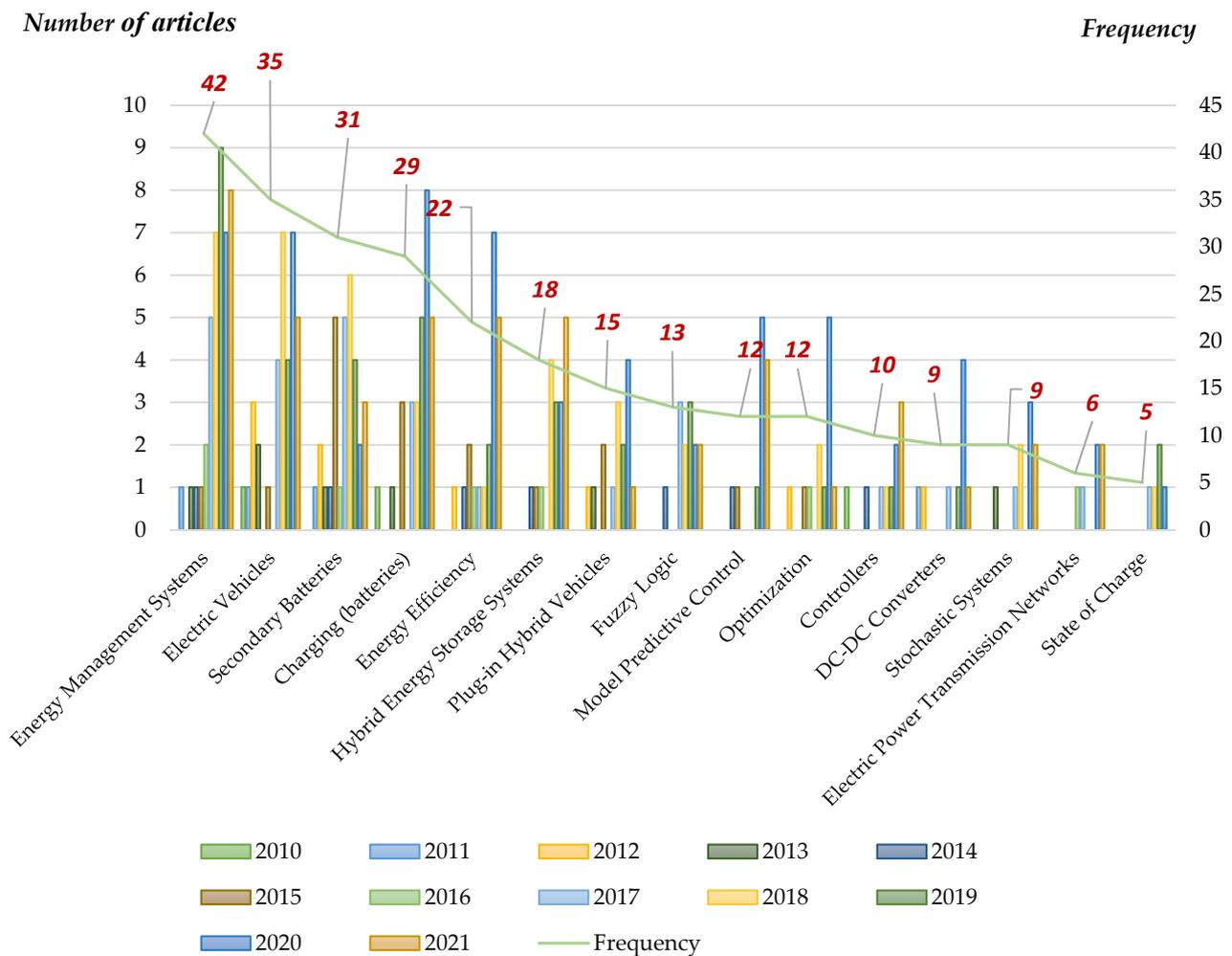


Figure 5. Distribution of topmost 15 keywords over the year 2010 to 2021.

According to Tables 2 and 3, it is clear that the scholars are currently interested in EMSs for EV application development, particularly in control and optimization technologies, topics that have received a lot of citations in the last 5 years and have a lot more ACY than the topic of general energy efficiency in storage systems.

Table 3. Top-most 15 keywords from the selected 100 manuscripts between 2010 and 2021.

Top Keywords	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Frequency
Energy Management Systems		[79]		[69]	[66]	[105]	[68,95]	[61,62,75,77,85]	[64,65,73,84,100,114,125]	[82,88,94,97,105,109,118,124,134]	[89,107,123,132,133,138,140]	[142,145,148,149,151,154–156]	42
Electric Vehicles	[141]	[143]	[71,92,119]	[80,86]		[76]		[91,103,106,135]	[64,73,84,100,112,114,129]	[88,94,109,124]	[89,122,123,128,131,133,139]	[142,149,152,153,155]	35
Secondary Batteries		[143]	[71,92]	[86]	[66]	[76,80,81,105,130]	[95]	[61,62,85,91,103]	[64,73,84,104,116]	[88,109,118,134]	[123,140]	[142,149,151]	31
Charging (batteries)	[141]			[86]		[80,81,130]		[62,91,103]	[84,104,129]	[74,88,93,109,115]	[98,99,107,111,120,122,128,138]	[142,146,149,157,158]	29
Energy Efficiency			[119]		[66]	[80,81]	[68]	[91]	[64]	[88,110]	[89,99,122,131,133,138–140]	[144,149,150,150,158]	22
Hybrid Energy Storage Systems					[66]	[130]	[68]		[64,73,84,116]	[109,110,118]	[90,99,102]	[136,142,149,151,156]	18
Plug-in Hybrid Vehicles			[92]	[86]		[72,76]		[135]	[64,104,116]	[82,118]	[108,111,113,120]	[158]	15
Fuzzy Logic					[66]			[85,91,135]	[96,116]	[88,109,118]	[90,99]	[142,144]	13
Model Predictive Control					[101]	[81]				[94]	[98,108,113,120,131]	[126,146,152,157]	12
Optimization			[92]			[80]	[68]		[73,96]	[118]	[89,122,127,131,133]	[144]	12
Controllers	[141]				[66]			[61]	[114]	[109]	[102,120]	[142,144,154]	10
DC–DC Converters		[143]	[71]					[106]		[118]	[90,102,123,139]	[154]	9
Stochastic Systems				[117]				[77]	[100,114]		[107,120,132]	[146,148]	9
State of Charge								[62]	[84]	[74,93]	[120]	[160–162]	8
Electric Power Transmission Networks							[83]	[77]			[132,138]	[145,146]	6

3.4. Bibliometric Analysis of Average Citations per Year and Study Type

Table 4 shows the top ten manuscripts with the greatest ACY in the last five years. Moreover, Table 4 also demonstrates the contributions, achievements, research gaps, and future directions in the top ten selected manuscripts. The most frequent research gaps include a lack of working capability in the real-world environment, a lack of accurate and robust SOC estimation under real-time EV drive cycles, short lifetime and limited load capacity, high cost, marginal safety, small voltage, and low energy density. In line with this, numerous key factors were identified including expenses, safety measures, sizing, power electronics interfaces, energy and power management, proper disposal, recycling, and material support. To overcome the above-mentioned knowledge gaps from different studies related to EMS in EVs, further investigation is required. The article by Hannan et al. has the highest ACY of 133.6, which is also ranked first in the total number of citations, followed by the second article by Rahimi-Eichi et al., which has an ACY of 73.8. As the research interests of scholars change over time, the ACY rank varies in relation to the overall citation rank.

Table 4. “Average citation per year (ACY)” of top 10 articles.

Rank	Ref.	ACY	Citation Rank Based on Table 2	Abbreviated Keywords	Contributions	Research Gaps/Future Directions
1	[62]	133.6	1	BMS, EV, LIB, SOC	This research examines the estimation of Li-ion battery SOC and its EMS in the context of future EV applications.	<ul style="list-style-type: none"> Lack of working capability in real applications. SOC estimation is only possible when the EVs are not moving.
2	[63]	73.8	2	BMS, BT, Charge/discharge, EV, SOC, SOH	This study evaluates the performance of BMS concerning reliability, safety, and cost.	<ul style="list-style-type: none"> Various batteries have distinct constraints on the charge receiving due to their different chemistries and architectures.
3	[6]	76.2	3	EV, ESS, Hybridization, Power electronics	This research assesses the different composition materials and methodologies of ESS based on average power delivery, capacity, and efficiency within their lifetime.	<ul style="list-style-type: none"> Crucial factors such as expenses, safety measures, sizing, power electronics interface, energy and power management, proper disposal, recycling, and material support are not considered.
4	[65]	52.5	5	EV, EMS, LIB, SOC	The reinforcement learning (RL)-based real-time power-management approach is used to achieve the optimal power distribution between the battery and SC.	<ul style="list-style-type: none"> As the outcomes of this paper are satisfactory and efficient, this technique can be implemented for practical purposes.
5	[67]	46.25	7	CC, EV, LIB, TD, TMS	This article presents a thorough examination of the current status of Li-ion battery technology, covering basics, architectures, and overall performance evaluation.	<ul style="list-style-type: none"> Short battery life and limited load capacity. High cost and marginal safety. Small voltage and low energy density.

Table 4. Cont.

Rank	Ref.	ACY	Citation Rank Based on Table 2	Abbreviated Keywords	Contributions	Research Gaps/Future Directions
6	[64]	44.4	4	EL, Forgetting factor, Kullback–Leibler divergence, PM, RL	A dynamic degradation model for the LiFePO ₄ battery is developed to quantitatively examine the impact of different control techniques in terms of minimizing battery deterioration.	<ul style="list-style-type: none"> The calculation of the number of battery cells and SC modules in obtaining accurate HESS sizing is challenging.
7	[66]	34.8	6	EV, EMS, HESS	This research explores the available literature on two levels: the cell level and the level of the battery module.	<ul style="list-style-type: none"> Heat transfer enhancement is not always the greatest option for dealing with temperature inconsistency.
8	[68]	30.4	8	EV, EM, ES, Optimization, Real-time	The study discusses real-time EMS for EVs with HESS that includes a battery and supercapacitor.	<ul style="list-style-type: none"> λ-control is better-suitable for a high supercapacitor voltage range.
9	[74]	26	15	BMS, ES, EV, LIB, SOC	The paper develops a hardware prototype to execute building energy management and an EV-charging scheduling algorithm.	<ul style="list-style-type: none"> The effects of PV output and electricity consumption forecast errors along with the vehicle-to-grid performance should be addressed in future research.
10	[70]	21.6	10	Eco-driving, EV, Optimal control	This study investigates EMS issues in EVs that conform with online standards for eco-driving.	<ul style="list-style-type: none"> In future research, this method can be implemented in real-time EV applications to provide online assistance to the driver.

Table 5 demonstrates the categories of the manuscripts that were selected as the most relevant. The category of experimental works, development studies, and performance assessments has the most articles (62.62%), followed by systematic and non-systematic reviews (16.16%), and problem formulations and simulation analyses (9%). There is a correlation between research categories, year ranges, and citation ranges. The largest number of publications (62) from the specified Scopus database of the most relevant articles, with a citation range (1–222), are focused on experimental work, development, and performance assessment-based analysis during the eight-year period up to 2021. From 2016 through 2021, the most common types of articles were technical overviews, observational articles, problem-formulation articles, and simulation analyses.

Table 5. Types of the most relevant 100 manuscripts in Scopus database.

Study Types	Numer of Manuscripts	Year Range	Citation Range
Experimental work, development, and performance assessment	62	2010–2021	1–222
Review (systematic/nonsystematic)	16	2011–2021	0–673
Problem formulation and simulation analysis	9	2016–2021	0–187
State of the art technical overview	7	2014–2021	0–384
Case study, meta-analysis, and survey	4	2016–2019	7–163
Technical and observational overview	3	2012–2018	11–212

The most common keywords from the selected 100 most relevant papers are listed as follows, along with most recent articles using these keywords: Energy Management Systems [79,163–165], Electric Vehicles [166,167], Secondary Batteries [168,169], Charging (batteries) [170], Energy Efficiency [171,172], Hybrid Energy Storage Systems [84,167,173], Plug-in Hybrid Vehicles [167], Fuzzy Logic [174], Model Predictive Control [175], Optimization [159,176], Controllers [61,109], DC–DC Converters [177], Stochastic Systems [178], Electric Power Transmission Networks [179,180], and State of Charge [181–183].

3.5. Bibliometric Evaluation of Journals, Publishers, and Countries

Figure 6 shows the proportion of papers published by thirteen individual publishers. Elsevier published the greatest proportion of articles among the selected papers (42%). IEEE occupy the second position with 21%, followed by Multidisciplinary Digital Publishing Institute with 17%, the John Wiley & Sons, Inc. with 7%, and Inderscience Publishers with 2%. The remaining papers were published by SAGE Publishing (1%), Oxford University Press (1%), ASME (1%), Emerald Group (1%), SAE International (1%), IOS Press (1%), Springer (1%), and the Korean Institute of Power Electronics (1%). Researchers are attempting to create new technologies and techniques that may be an alternative for the existing conventional fossil-based vehicle system because of their significant potential positive environmental impacts as well as the current research emphasis focusing mostly on EVs. Refs [77,85,88,108,134,152,163] investigate models based on EMSs for EV applications.

The numbers of manuscripts published in the various journals and their impact factors (IF) are shown in Figure 7. All 100 of the most popular articles were published in 42 different publications. The top five journals with the largest number of publications published 46.46% of the 100 most relevant articles, with impact factors ranging from 0.975 to 14.982. The “Energies” journal published the most papers (16), followed by “Applied Energy” with 10 articles; nevertheless, “Energy” and “International Journal of Energy Research” both published nine and six articles, respectively. The Renewable and Sustainable Energy Reviews journal contained five articles from the selected database. The journals “IEEE Access”, “IEEE Transactions on Control Systems Technology”, and “Journal of Power Sources” each contained four manuscripts. The impact factors of these journals ranged from 0.975 to 14.982, according to the Journal Citations Report 2020. The journal “Renewable and Sustainable Energy Reviews” had the highest IF of 14.982. In comparison, with the same rate of publishing, the “IEEE Transactions on Vehicular Technology” journal had the lowest IF of 5.978.

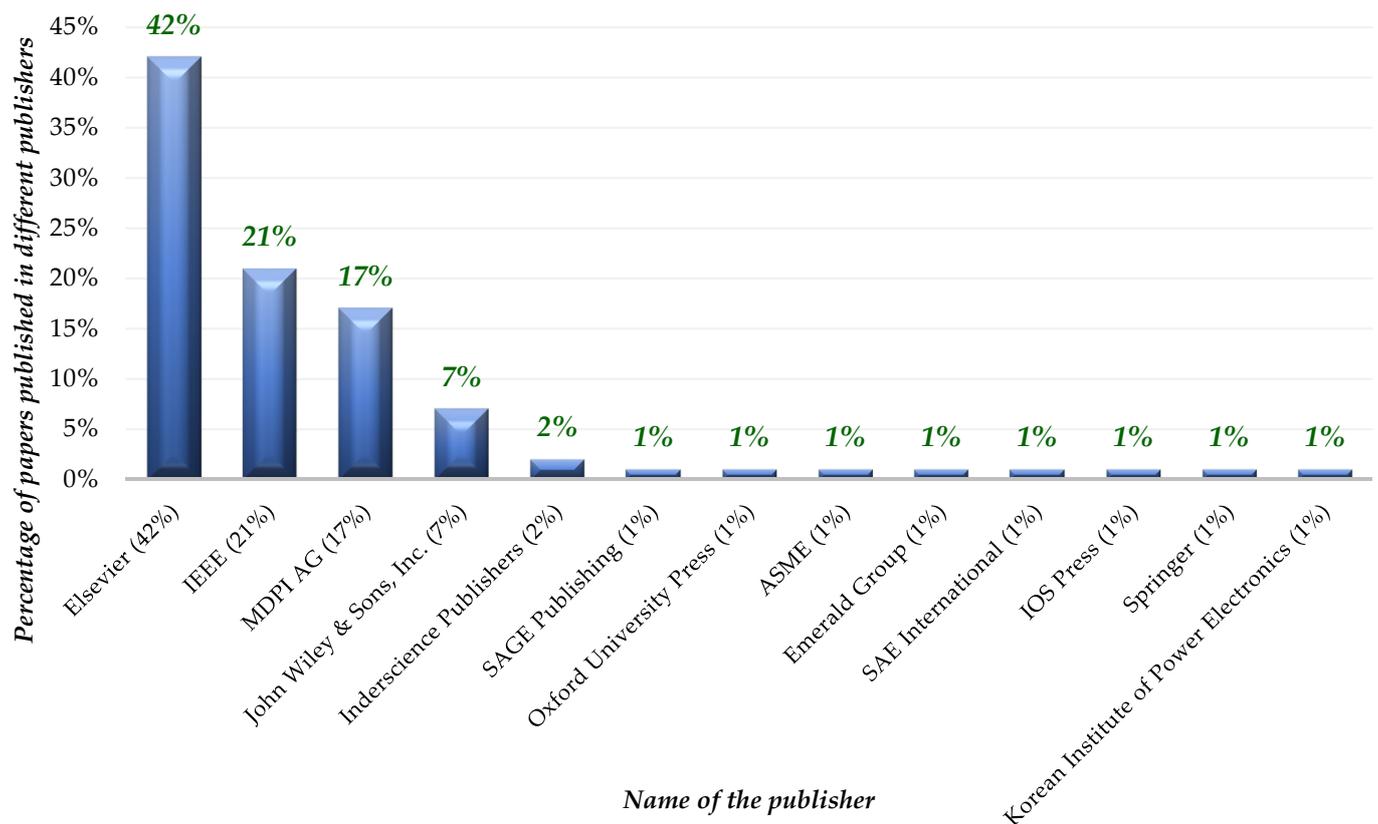


Figure 6. Distribution of 100 manuscripts across the different publishers.

3.6. Document Authorship Analysis

Table 6 represents the details of authors who published three or more papers. From the top 100 most relevant papers, 10 authors contributed more than three articles. With five manuscripts from the 100 most relevant manuscripts retrieved from the Scopus database, Zheng Chen of the Queen Mary University of London, United Kingdom, is the author with the most publications. Zheng Chen has an h-index of 25 with a total of 2687 citations. With four manuscripts, M.A. Hannan placed in the second position. His current affiliation is Universiti Tenaga Nasional, Malaysia, with an h-index of 40. With the same number of articles, Yonggang Liu, whose current affiliation is Chongqing University, China, gained the third position. The rest of the authors—Hongwen He, Md Murshadul Hoque, Guang Li, Jiangqiu Li, Azah Mohamed, Minggao Ouyang, and Yuanjian Zhang—produced three articles. China has the most authors ($n = 5$), whereas the United Kingdom and Malaysia have three and two, respectively. Minggao Ouyang of the Tsinghua University, China, has the most citations (19,265) and the highest h-index (68), followed by Jiangqiu Li and Azah Mohamed with 10,896 and 10,056 citations, respectively. They are from Tsinghua University, China, and Universiti Kebangsaan Malaysia, respectively. In contrast, the lowest citation (209) number was obtained by Yuanjian Zhang from Queen’s University Belfast, United Kingdom, with an h-index of 9. Figure 8 represents the co-authorship analysis conducted using VOSviewer. The highest number of authors who participated in these selected manuscripts are from China, followed by the USA.

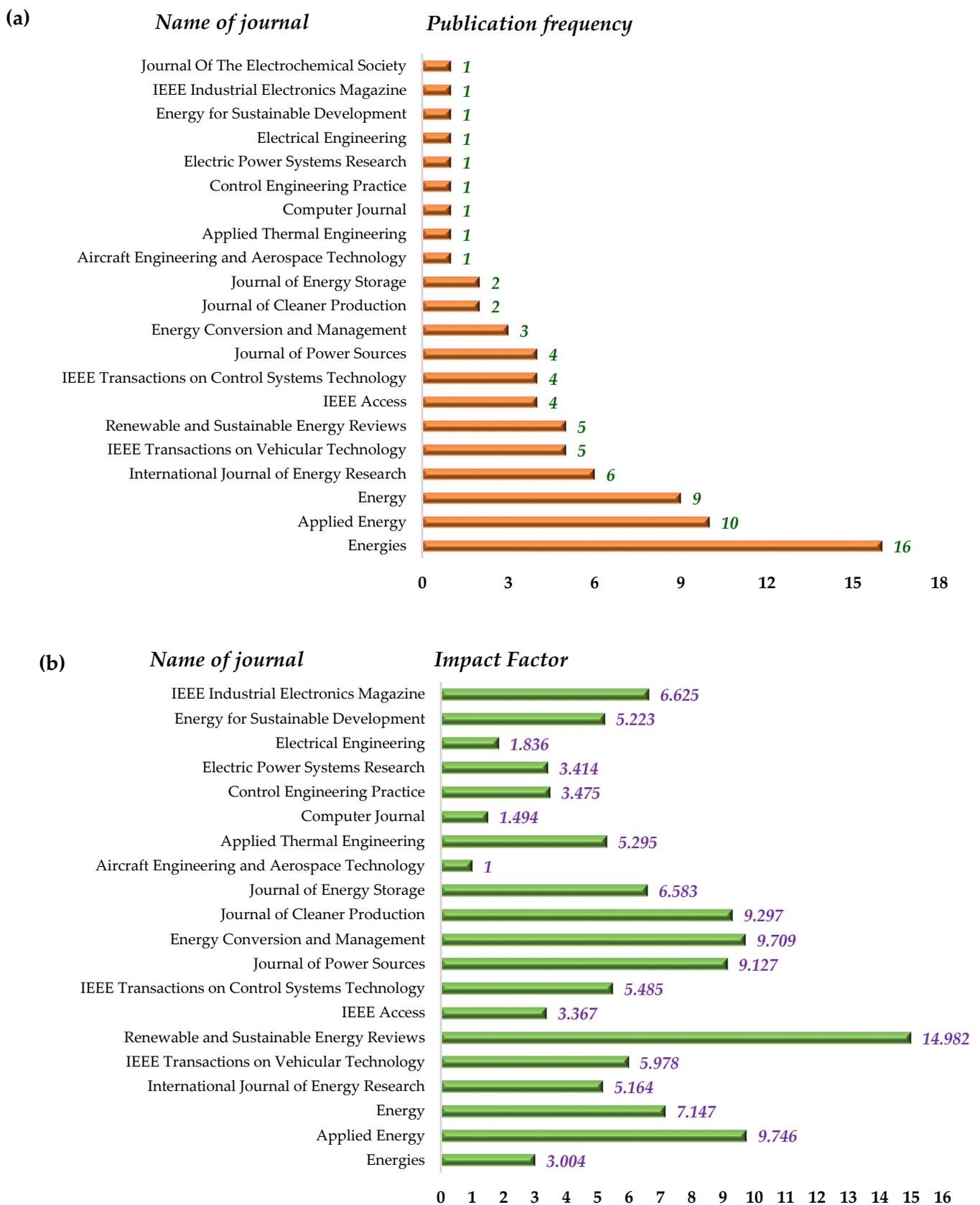


Figure 7. Distribution of manuscripts in terms of (a) journal evaluation and (b) journal impact factor.

Table 6. Topmost 10 author profiles based on the number of manuscripts.

Rank	Author Name	Current Affiliation	Country Name	Number of Manuscripts	Total Number of Citation	h-Index	Authors Position
1	Chen, Zheng	Queen Mary University of London	United Kingdom	5	2687	25	First author = 2 Senior author = 1 Co-author = 2
2	Hannan, M. A.	Universiti Tenaga Nasional	Malaysia	4	7192	40	First author = 3 Co-author = 1
3	Liu, Yonggang	Chongqing University	China	4	1061	18	First author = 2 Senior author = 2
4	He, Hongwen	Beijing Institute of Technology	China	3	8708	42	Co-author = 3
5	Hoque, Md Murshadul	Monash University	Australia	3	1163	11	First author = 1 Co-author = 2
6	Li, Guang	Queen Mary University of London	United Kingdom	3	1219	21	Co-author = 3
7	Li, Jiangqiu	Tsinghua University	China	3	10,896	53	Co-author = 3
8	Mohamed, Azah	Universiti Kebangsaan Malaysia	Malaysia	3	10,056	42	Senior author = 1 Co-author = 2
9	Ouyang, Minggao	Tsinghua University	China	3	19,265	68	Senior author = 1 Co-author = 2
10	Zhang, Yuanjian	Queen's University Belfast	United Kingdom	3	209	9	First author = 1 Co-author = 2

It was found that different authors have distinct fields of study. Zheng Chen of the Queen Mary University of London, United Kingdom, is primarily interested in Plug-in Hybrid Vehicles, Powertrains, and Energy Management [184–187]. He also wrote two manuscripts about EV applications, “Prediction of vehicle driving conditions with the incorporation of stochastic forecasting and machine learning and a case study in energy management of plug-in hybrid electric vehicles” [187] and “Stage of Charge Estimation of Lithium-Ion Battery Packs Based on Improved Cubature Kalman Filter with Long Short-Term Memory Model” [186]. M.A. Hannan from Universiti Tenaga Nasional, Malaysia, developed the following recent manuscripts on EMSs for EV applications: “Techno-Economic Analysis and Environmental Impact of Electric Buses” [188], “Fuzzy Based Charging-Discharging Controller for Lithium-ion Battery” [189], and “Energy Storage Integrated Microgrid Performance Enhancement” [190]. Yonggang Liu from Chongqing University, China, has a primary research interest in Plug-in Hybrid Vehicles, Powertrains, and Energy Management [191–193]. “A survey on key techniques and development perspectives of equivalent consumption minimization strategy for hybrid electric vehicles” [193] and “Prediction of vehicle driving conditions with the incorporation of stochastic forecasting and machine learning and a case study in energy management of plug-in hybrid electric vehicles” [187] are the manuscripts recently produced by Yonggang Liu.

Figures 9 and 10 represent a graphical representation of the top ten countries that dominate the EMSs for the EV applications, and co-occurrence country analysis performed using VOSviewer, respectively. China is in the leading position based on the number of manuscripts in EMSs for EV applications, with a total of 44, followed by the USA, with 16. With 12 manuscripts, France is in third place. Figure 10 also demonstrates that China has

the highest number of collaborations with other countries. Regarding funding sponsors, the “National Natural Science Foundation of China” is in the first position with 22 sponsors, whereas the “National Key Research and Development Program of China” and the “China Scholarship Council” sponsored 8 and 7 manuscripts, respectively.

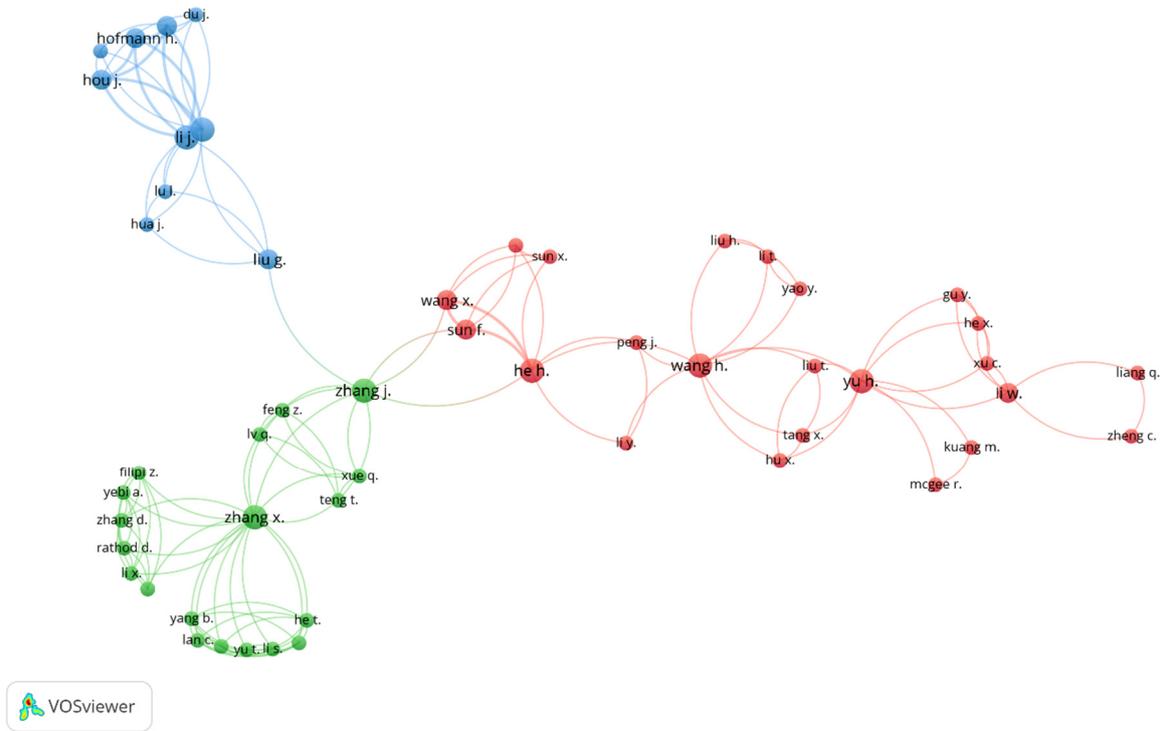


Figure 8. Co-authorship analysis by VOSviewer from the Scopus database.

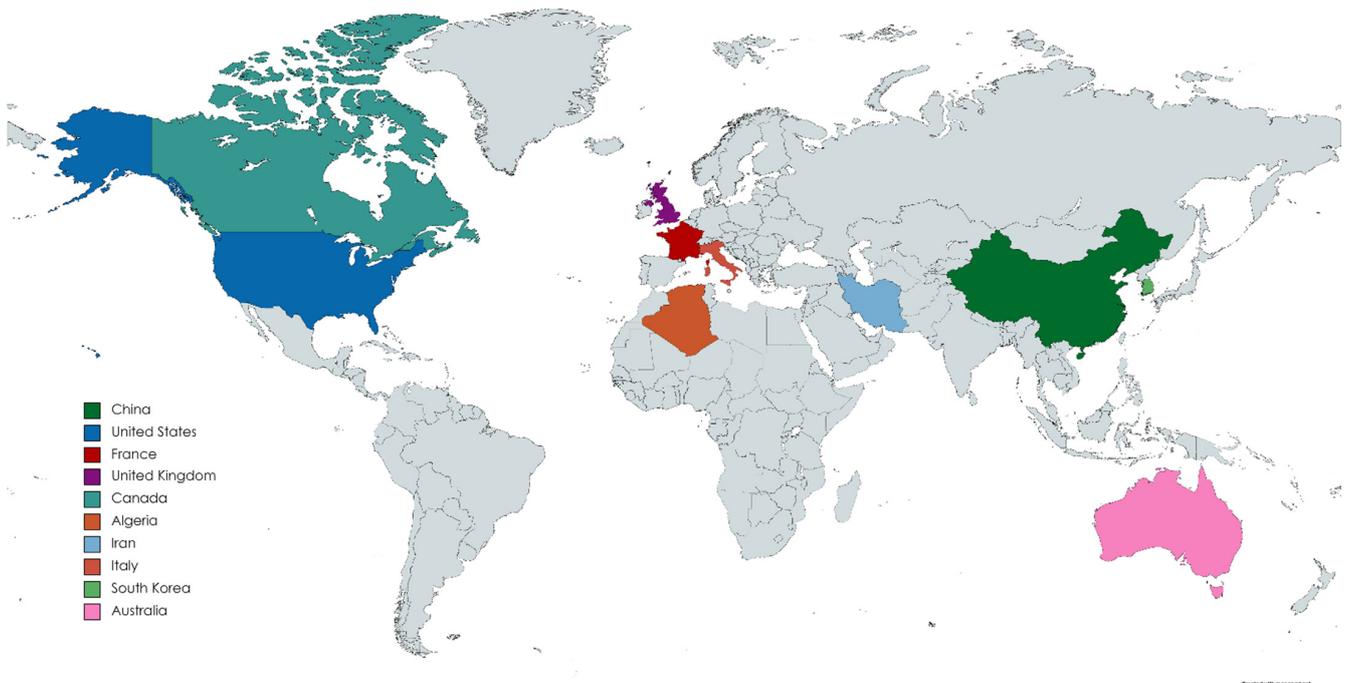


Figure 9. Graphical representation of top ten countries that dominate the EMSs for EV application.

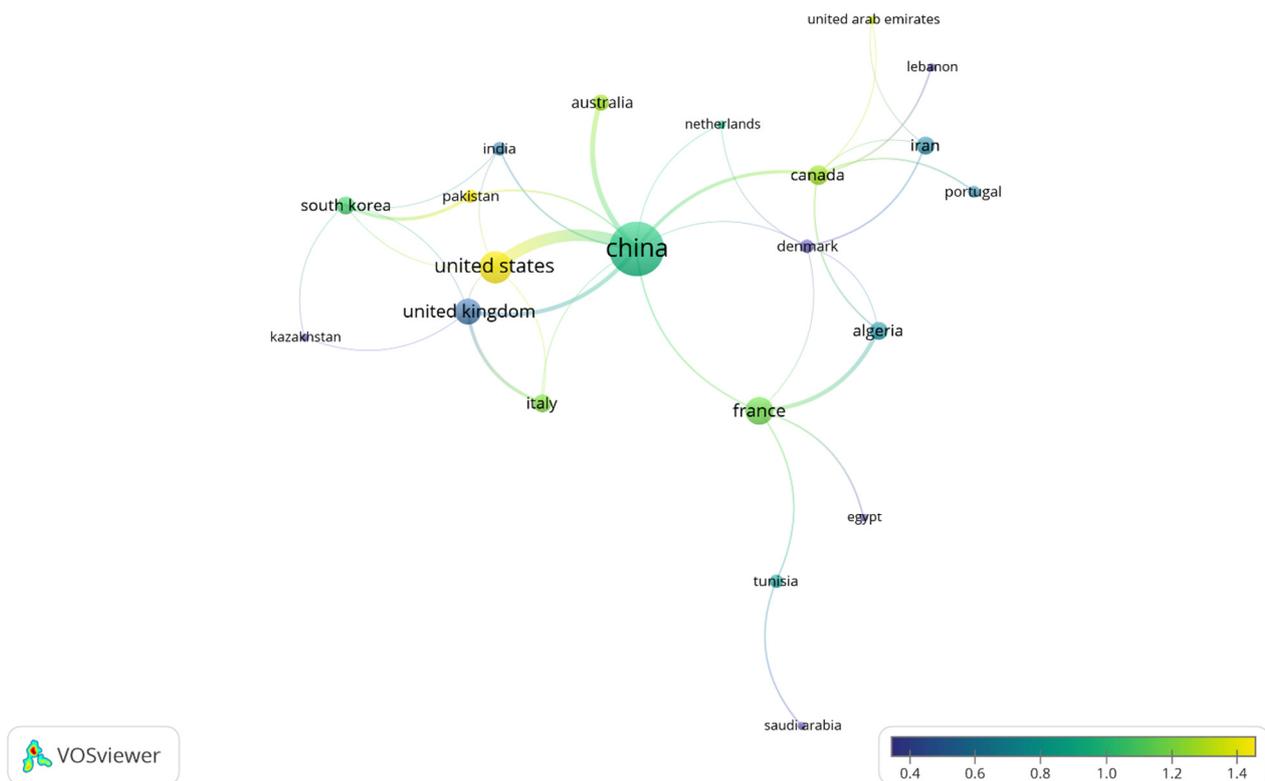


Figure 10. Co-occurrence country analysis of the Scopus database conducted using VOSviewer.

Following the discussion and analysis of the topmost 100 most relevant manuscripts from the chosen database, it was discovered that there had been a trend toward publishing both “review” and “technical” papers in recent years. “Energy Management Systems”, “Electric Vehicles”, “Secondary Batteries”, “Energy Efficiency”, “Hybrid Energy Storage Systems”, and “Plug-in Hybrid Vehicles” are six areas of study that are gaining high interest. Different researchers have performed various types of literature evaluations and techniques in the fields of economic advantages of EV applications, EMSs, optimization and control for cost reduction, the flexibility of system operations, and the reducing of carbon emissions [77,85,88,108,134,141,144,152,163,194,195].

4. Issues and Challenges of EMSs in EVs

The EV applications have many key components that influence the EMS’s dependability and efficiency. However, to overcome the problems of HEV EMS reliability and efficiency, several factors must be solved. The difficulties and challenges on EMSs for EV applications are split into the following categories and explored in the following sub-sections.

4.1. Optimal EV Design and Power Distribution Challenges

In ref [142,149,152,153,155], the authors explored various issues related to optimal EV design and power distribution. However, the power flow and EV design need further improvement. Managing the power flow and satisfying the market’s high expectations are critical in vehicle energy management systems that use a hybrid or a mix of several energy sources. The configuration and controller design are two major issues because of the complexity and difficulty of the integration needed among the other current systems in the vehicle [196]. When the EMSs are intended to reduce hydrogen consumption and enhance the fuel cell’s life expectancy, which relates to design optimization, power distribution among various components becomes more difficult. Power splits have become a major worry due to frequent charging from the fuel cell to the battery and variations in fuel cell output power, both of which have an impact on the battery and fuel cell’s performance

and service life [197,198]. To ensure the dependability of EV applications, the EMSs must be further studied and improved in terms of hardware or real-time applications.

4.2. Battery Thermal Management Issues

In [142,146,149,157,158], various authors discussed the issues concerning the thermal management of batteries. High temperature is generated because of chemical reactions, and this is a major issue that affects all batteries. Unusual temperatures harm the chemical characteristics of batteries and cause significant reductions in their efficiency. The temperature control system is also crucial for secondary batteries. In most cases, the battery must function at both low and high temperatures. Due to the lowered rate of chemical reactions and the transformation of active chemicals due to temperature, the charging and discharging currents and the battery's power handling capabilities are reduced by the impact of the low temperature [199]. On the contrary, the higher temperature in the battery creates certain challenging circumstances that induce aberrant chemical behavior and eventually lead to the battery exploding. Although some power may be saved by stimulating processes with the Arrhenius effect, a higher current creates a higher temperature, which leads to thermal runaway owing to positive temperature feedback. To avoid the battery's thermal runaway, specific measures must be implemented. Compared to other popular batteries, the capacity of the Li-ion battery increases as the temperature rises at the expense of the battery's life. Therefore, further attention is needed to address the battery's thermal issues to achieve better efficiency.

4.3. Battery Storage Life Cycle and Aging Issues

In [142,145,148,149,151,154–156], numerous authors investigated the battery storage life cycle and aging issues. The loss of battery cell function due to voltage and heat impacts has been studied; nevertheless, this loss reduces the battery's longevity. It's worth noting that running a battery cell outside its normal working range results in irreversible capacity loss. This anomaly has a cumulative impact, reducing battery life and possibly causing total and irreversible loss of usage [200]. Owing to anode plating, the lifespan reduces slowly at low temperatures (below 10 °C), but it drops dramatically at high temperatures (over 60 °C) due to chemical breakdown. As a result, the optimal operating temperature range should neither be too large nor too narrow. Hence, further investigation is suggested, particularly the conducting of feasibility studies to reduce the impact of cell function on battery life.

4.4. Power Electronic Controller and Converter Issues

In [90,102,123,139], different authors examined power electronics controller and converter issues including switching loss, high ripple current, voltage stress, high voltage gain, high impedance, optimization integration, and complex control techniques. The fuel cell generates low DC voltage by regulating the fuel cell to a level with the DC bus voltage through an appropriate DC–DC converter [201] with three distinct energy sources. As a result, in an EV, a power electronic interface is required. Open circuit failures pull increments of fuel cell stack ripple currents and add additional stress to inductors; thus, precautions must be taken before its growth. Driver failure, improper gate voltage, device damage, and excessive voltage, current, and transients are possible problems [202]. The DC–DC converter in the fuel cell system must be boosted, and the storage device requires a bidirectional DC–DC converter [203]. As a result, for the battery and SC, buck-boost converters are commonly employed [204]. Therefore, further studies are required to develop an efficient controller and converter for EV applications.

4.5. Environmental and Decarbonization Issues

In [145], Torabi et al. focused on the environmental and decarbonization issues for EVs. Further research should be conducted on the impacts of EVs in terms of reducing carbon emissions. Automobile electrification, such as EVs, HEVs, and PHEVs, is becoming

more popular as oil costs rise and the demand for large amounts of energy for sustainable transportation grows. Toyota estimated that by 2020, EVs would account for more than 7% of global transportation [205]. Li-ion batteries generate CO₂ and GHGs during their manufacturing and disposal, despite their positive influence on the environment by lowering the number of oil-based cars [206]. In a previous study, the US EPA examined Li-ion batteries for their use of nickel- and cobalt-based cathodes, as well as solvent-based electrode processing, and found significant environmental impacts, such as resource depletion, global warming, ecological toxicity, and human health effects, among other things [207]. According to this study, people involved in the manufacturing, processing, and use of cobalt and nickel metal compounds may be at risk for respiratory, pulmonary, and neurological disorders [207]. This danger can be mitigated by using a Li-ion battery recycling method to save natural resources and minimize the usage of nickel and cobalt [207,208]. Thus, the impact of EVs on the environment and towards achieving sustainable development goals (SDG) needs to be further enhanced.

4.6. Standard Regulation and Policy Issues

Policy and regulation are important issues in EV industries. In [82], Liu et al. discussed various regulations and policy-related issues. Clean development mechanisms (CDM), carbon trading (CT), and joint implementation (JT) are the three main elements within the Kyoto Protocol that the UN has defined to cost-effectively meet their emission reduction objectives [209]. Many measures have been implemented to decarbonize Europe's electricity industry. By utilizing a linear dynamic optimization model, the economic implications of the alternative energy strategy for Europe's power sector to cut greenhouse gas emissions by 80 to 95% by 2050 as compared to 1990 were calculated [210]. By 2050, Europe will convert to a 100% renewable energy system using the energy system transition model developed by Lappeenranta University of Technology [211]. Although a few effective initiatives have been undertaken to promote EVs, the long-term planning of EV use, including standardization, laws, enforcement, regulation, financial incentives, and policies, needs further attention.

5. Future Trends of EMSs in EV Applications

Based on a rigorous review of the existing notable articles, this bibliometric study delivered several major and selective proposals for future research towards the advancement of EMSs in EV applications.

- The global acceptance of EMSs in EV applications was discussed in terms of achieving SDG in the transportation sector. Nonetheless, various issues related to EMSs in EV applications, such as short driving ranges, battery lifetimes, long charging times, high initial costs, poor vehicles, and ineffective EV-based policies, need to be carefully examined. Further research is recommended to develop an efficient EMSs design with better operational mechanisms, encouraging market regulations and global collaborations for efficient EV operations.
- The existing converter designs implemented in EMSs suffer from various issues such as current stress, low impedance, high ripple current, and sensitive duty cycles. In this regard, further investigations are needed to optimize the converter design to achieve high frequency and low losses. Additionally, optimization based on mechanical design is suggested to obtain high robustness, mechanical strength, and power density.
- The application of enhanced control techniques towards achieving various benefits such as bidirectional power management, fast-tracking, and high efficiency can be observed in EMSs. Nevertheless, the implemented control technique suffers from various disadvantages such as lengthy training durations, computational complexity, and suitable hyperparameter adjustment. Therefore, further exploration is required to address control technique issues.
- Due to the implementation of EMSs in EV application for controlling battery heating and cooling, the reliability and stability of battery operation are improved significantly.

However, the efficiency of EVs is reduced due to the existence of thermal issues and deep-diving range loss. Additionally, the occurrence of thermal effects due to the electrochemical process results in poor EMSs accuracy and stability. To minimize the dynamic instability issues, the utilization of super capacitors in the battery storage system can be observed. Additionally, the optimization scheme in EMSs technology could effectively reduce battery aging and power curtailment issues.

- The performance of EMSs in EV applications can be improved by accurately estimating various states of batteries, such as SOC, SOH, and RUL, respectively. The inaccurate measurement of battery SOC would result in charging issues. Further, the inappropriate measurement of SOH and RUL would lead to early replacement of batteries, delays in battery replacement, explicit failure events, and further increases in cost. Therefore, further investigation should be conducted regarding the application of deep learning techniques for better estimation accuracy. Additionally, the application of multi-scale and co-estimation techniques in BMS technology would increase efficiency and minimize computational cost.
- The implementation of algorithm hybridization schemes was shown to be beneficial, with better accuracy and effectiveness than non-hybridized techniques. The development of the hybridization technique takes place by performing the integration of two or more intelligent techniques. The hybridized intelligent techniques may comprise an integrated intelligent algorithm with an optimization model or a combination of two intelligent models. However, hybridization schemes suffer from operational complexity and long training times, and they require human expertise and high computational processors to conduct the desired operations. Hence, further explorations, which aim to develop an efficient hybrid model while considering practicability issues, are needed.
- Even though substantial progress towards SDG and decarbonization has been accomplished with EMS-based EV applications, environmental issues such as soil and groundwater contamination need to be considered. Inaccurate battery disposal would result in health hazards from water as well as air. To prevent inappropriate disposal of batteries in the environment, adequate measures in terms of recycling and reusability should be carried out.
- To improve the performance capability and robustness of EMSs in EV applications, the implementation of real-time monitoring consists of sensors, data processors, and cloud-based technology. The performance of EMSs in EVs can be observed by acquiring real-time data in the form of voltage, current, impedance, temperature, etc. Additionally, the state estimation of the battery can be performed and stored in the cloud database. The effectiveness of the EMSs can be improved with suitable data extraction, data processing, and prediction in real-time applications.

6. Conclusions

The use of advanced EMSs in EVs is essential to achieve optimal power distribution and improve the cost, efficiency, lifespan, and effectiveness of EV batteries with regard to battery monitoring and management systems, charge and discharge controls, state estimation, energy storage safety, and protection. Thus, this study identified the 100 most relevant publications on EMSs for EV applications from the Scopus' database to assess the recent trends, performance, applications, issues, and problems. Many studies were also presented, including the distribution of 15 popular keywords—in terms of the most cited articles—by year, nation, publisher, and journal, and the grouping of studies by research field and study type. The primary goal of this article was to provide an overview of academic research trends and recognize the features and progress of EMSs in EV applications identified in high-impact research publications. Many challenges and possible solutions were also discussed for the EMSs for the EV applications related to this article in terms of the achievement of system flexibility and system cost reduction for EV applications.

The most relevant 100 articles were included in this bibliometric analysis to provide insights into the history, current approach of researchers in scientific investigation, and challenges related to EMSs for EV applications. There are several advantages to determining the characteristics of the most relevant publications, including:

- The systematic/non-systematic study and investigation of the most referenced manuscripts provide insights into the history and evolution that has shaped contemporary knowledge and practice.
- The characteristics of the most relevant articles in EMSs for EV applications can provide future researchers with a clear picture.
- The bibliographical analysis may give researchers an excellent perspective on a dynamic and expanding study area, inspiring various dedicated researchers to employ contemporary and new technologies to enhance a specific research field.
- Researchers and journal editors may use the most relevant article analysis to assist them in evaluating submitted manuscripts.

In conclusion, it is expected that valuable information, discussions, knowledge, and analysis on prominent EMS papers on EV applications between 2010 and 2021 would not only assist in enhancing EV operations but would also provide valuable guidelines and suggestions for automobile engineers and researchers towards achieving decarbonization targets and SDGs.

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