Review

A Bibliometric Survey of Research Output on Wireless Charging for Electric Vehicles

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Abstract: Wireless charging modules for electric vehicles are being increasingly studied. Previous research has focused on developing more effective wireless-charging modules for electric vehicles in order to pave the way for a more sustainable urban transportation. The objectives of the study were to identify the social structure of the field by mapping of research collaborations among authors and countries, measure the influence of authors and sources, identify the interactions between different researchers and the most influential authors, sources, documents and organizations. To achieve these objectives, a bibliometric search in the SCOPUS database was conducted using a combination of keywords and Boolean operators. The initial keyword search returned 2163 documents. The documents retrieved were manually filtered for further analysis. A scientometric analysis was carried out on the remaining 1367 documents using co-authorship, co-citation, and citation analyses for a number of measurement units. The results showed that “object detection” and “shielding effectiveness” were the most current research topics. Authors who were widely cited did not generally produce a large number of papers or collaborate with other authors. Authors from China, the United States, and the United Kingdom have all co-authored published works on the topic, indicating that they have all contributed considerably to the field’s achievements. This strongly highlighted the amount of funding localized in developed countries towards such technologies. The number of international co-authored studies conducted was low. This is most significant with no research conducted in this field in the less developed world. The most cited and influential scholars were G. A. Covic, J. T. Boys, and C. C. Mi. The most influential sources were IEEE Trans. on Power Electronics and IEEE Trans. on Induction Electronics, while the most productive sources were Energies and IEEE Access. The most influential documents were those by Covic G.A. (2013a) and Covic G.A. (2013b). Finally, emerging trends in charging and energy storage in electric vehicles were also discussed.

Keywords: wireless power transfer; inductive power transfer; wireless charging; structural batteries; solar electric vehicle; solar paint; bibliometric review

1. Introduction

Wireless charging modules for electric vehicles (EVs) are being increasingly studied. Two techniques of transferring power to EVs via charging systems can be used: conductive charging and wireless charging. Some notable studies, as presented in this work, focused on developing more effective wireless-charging modules for electric vehicles in order to pave the way for the creation of more sustainable urban transportation [1–3].

In 1891, Nikola Tesla developed the wireless power transfer (WPT) concept based on capacitive coupling [4]. There is no physical connection between the vehicle and the charger in wireless charging [5,6]. Coupling plates known as a transmitting end (at the roadside) and a receiving end (at the vehicle side) are used in most EV wireless chargers [7]. EV charging via an inductive power transfer (IPT) system is gaining a lot of attention [8,9].
in recent times, though it can also be done via capacitive power transfer (CPT), laser, microwave, and other methods.

In 1977, the Lawrence Berkeley National Laboratory demonstrated the very first IPT-based EV dynamic wireless charger [10]. Wireless charging systems are available in both mobile and fixed configurations. When using the dynamic (mobile) wireless charging technology, a vehicle can be charged while driving; when using the stationary (fixed) wireless charging technology, a vehicle must be parked. This was a revolutionary technology which begged for more research at the time. This was evenly met with numerous studies around the subject [11–14].

There are some benefits of wireless charging systems. First, it allows for convenient, adaptable, and safe EV charging without requiring direct human contact [15]. Second, the total cost of charging is considerably lower than the traditional conductive charging [15]. Third, the charging structure is practical, making it very suitable for residential use with minimal maintenance [16]. Finally, dynamic WPT technology allows for vehicle charging while moving [17, 18]. These merits make the WPT desirable technology for automotive applications towards the achievement of a more sustainable mobility in cities. Table A1 summarize some WPT technologies, along with their operations, benefits, drawbacks, and components. In Figure 1, Liang and Chowdhury [7] proposed an alternative classification based on the size of the air gap between the transmitter and reception units. The length of the air gap between the transmitting and receiving ends was used to classify EV wireless charging systems in the work of Liang and Chowdhury [7]. Also, various EV wireless charging strategies were reviewed. Each method was described, and the numerous topologies related to each method were reviewed and contrasted, with a special emphasis on power transfer efficiency. Liang and Chowdhury [7] proposed that a dynamic wireless charging system is created for improved output power efficiency during misalignments and lower installation costs for a sustainable electric transportation system. The paper further predicted that allowing vehicle-to-grid (V2G) technology and the development of dynamic wireless charging would usher in a new era of electric-vehicle based transportation with lower battery capacity and greater vehicle range.

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Figure 1. General Classification of EV Charging Systems (Adapted from [9]). CMR—Coupled Magnetic Resonance; CPT—Capacitive Power Transfer; IPT—Inductive Power Transfer; PMPT—Permanent Magnet Power Transfer; OLEVs—Online Electric Vehicles.
2. Literature Review

In a review conducted by Li and Mi [18] on wireless charging for electric vehicles, it was evident that vehicle electrification was unavoidable due to environmental and sustainable energy supply concerns. When contrasted with plug-in (cabled) charging, wireless charging offers numerous advantages. With highways electrified to provide wireless charging, it will lay the groundwork for mass-market adoption of electric vehicles, regardless of battery technology [19,20]. Researchers have conducted more research on topology [21], control [22–24], inverter design [25–27], and human safety [28–31].

Mohammed and Jung [32] carried out a comparable investigation. The report provided a good overview of contemporary EV wireless power charging research in a concise manner. It also included a small-scale experimental model for deeper comprehension of the wireless proposition. The inductive power transmission efficiency was significantly higher than that of the round coil, resulting in a more efficient total wireless power transfer system. Despite the fact that square coils were far more efficient than round coils, their efficiency remained low. To counter this, it was suggested by a study [33] that a larger diameter wire be used, as this would result in a longer coil. A longer coil length could significantly enhance inductance and magnetic field, resulting in a higher transfer efficiency.

The electromagnetic field (EMF) emission limitations mentioned in international guidelines and standards such as IEEE, ICNIRP, ACGIH, and SAE were examined and collated in a study by Asa et al. [34]. The authors asserted that EMF emissions can be significant, especially at high-power transfer levels and misalignment circumstances, and should be kept within the ICNIRP 2010 recommendations, which are more conservative and considered safer.

In the context of EV wireless charging applications, various WPT technologies were introduced and compared in the paper of Qiu et al. [35]. The fundamentals of inductive power transfer and strongly coupled magnetic resonance were discussed, with a focus on maximal power transmission and efficiency. A synopsis of current achievements in wireless EV charging was presented. The most up-to-date solutions for each issue were explored.

To eliminate mutual inductance fluctuation and provide output stability, including output power and efficiency, a crossed DD coil shape with double-coil excitation method was developed by Xiang et al. [36]. The system efficiency with the crossed DD geometry and double-coil excitation was nearly unchanged (from 89.2% to 88.7%) irrespective of the EV position, whereas the system efficiency with traditional DD coils was massively diminished (from 88.5% to 81.2%) when the pick-up coil moved from the non-switching area to the switching area, according to simulations and experimental results. In comparison with the conventional DD geometry, the proposed crossed DD geometry with double-coil excitation was found to considerably improve system output stability.

In a revised version, a DD geometry called DDQ pad was proposed, which contained a third D coil in quadrature with the other two to mitigate the null point problem [37]. The DDQ pad has boosted efficiency, but because of its high copper requirement in design, researchers have turned their attention to other pad structures. University of Auckland posited a version of the classic DD pad with some overlaps between the two coils that offers enhanced performance close to the DDQ pad with 25% reduced copper use [38].

Jiang et al. [39] examined safety implications for WPT applications on EVs in a study. Because of the broad region of electromagnetic field exposure between the vehicle and the primary coil, as well as the high electrical power involved in this operation, the system must be developed to fulfill the safety standard. In order to satisfy the customer’s expectations, safety must be improved, as well as the efficiency and charging cycle. Electrical shock, electromagnetic field exposure level, and fire danger should all be included in the standard test. Both computational and experimental tools were used to evaluate the near magnetic fields for the EV’s wireless charging system.

A quick review of the number of documents on WPT in the SCOPUS database showed a decline after a peak in 2020 (Figure 2). This is one of the motives that necessitated this investigation on the status of studies in the field. Furthermore, no study has been
undertaken to demonstrate the topology of the research field, as evidenced in the literature reviews to the best of our knowledge. The current study, therefore, attempts to answer the following research questions:

1. What is the social structure of the field among authors, countries and organizations?
2. What is the influence of authors and sources on the research domain?
3. Who are the most relevant authors, sources, documents and institutions on the topic?

Consequently, in answering the aforementioned questions, co-authorship, co-citation and citation analyses were employed. The evidence of collaboration and social structure among researchers were revealed with co-authorship analysis. The influence of sources and authors on works published was depicted in the co-citation analysis. It is worth noting that since new documents take time to receive citations, it was impossible to map documents that receive little or no citations in the current study [40]. However, this did not have any significant effect on the outcome of the analysis. A bibliometric coupling would have been suitable for acknowledging newly published documents but this technique has limited time interval for the data collected and does not necessarily show important works by citation counts. Hence making the co-citation analysis relevant. The citation analysis estimated the relevance of documents, sources, and authors in the research domain [40,41]. It must be pointed out that citation analysis is biased towards older published works but can quickly find the relevance of works in the research field.

Setting a threshold value for all studies involved a compromise between two competing goals: offering a broad picture of the visualization versus providing a more focused and clear depiction. If the threshold value is too high, there is a risk of missing certain smaller groups (clusters) of items that are below the threshold value but are nonetheless essential. We have a different set of issues if the threshold is set too low. It is more difficult to visualize larger sets of items. For citation analysis, less cited items have less information, which raises the likelihood of spurious links.

This study provides a bibliometric analysis of works published on WPT between 2011 and 2022. Specifically, this study conducted a bibliometric analysis on literature extracted from the SCOPUS database from 2011 to 2022. Figure 3 outlines graphically the various stages of the bibliometric study. In addition, some emerging trends in WPT electric vehicle applications were presented.
3. Methods
3.1. Bibliometric Data Extraction

Data collection from published studies was critical for achieving the objectives of this study since this would help in defining which scholarly publications would be used to draw any conclusions based on findings. SCOPUS was chosen as the database for this study because it has a wider variety of coverage of research than other databases including Web of Science (WOS), Google Scholar, and PubMed, among others [42]. SCOPUS is also a better alternative for inter-disciplinary areas of research, such as the one discussed in this [43]. However, it must be noted that, the WOS and SCOPUS have similar coverage when it comes to documents published in the engineering discipline [42].

In November 2021, a bibliometric search of WPT- and EV-based keywords through the SCOPUS database was completed to analyze published research in English Language. Using keywords like ‘Inductive Power Transmission’, ‘Energy Transfer’, ‘Electric Vehicles’, ‘Wireless Charging’, ‘Inductive Power Transfer’, ‘Magnetic Couplings’, and ‘Inductive Couplings’, the available literature relating to WPT application to electric vehicles in the SCOPUS database was retrieved. Two thousand, one hundred and sixty-three (2163) records were returned using Boolean logic operators (AND, OR) and an integrated list of targeted keywords. In order to retrieve all records matching the selected keywords in the title, abstract or selected keywords section, the keyword search in the SCOPUS database was configured to title/abstract/keywords. The search was limited to records from the past decade (2011 to 2022) on the subject under study.

3.2. Inclusion and Exclusion Criteria

The results of the preliminary keyword search were manually filtered to ensure that only relevant articles were used for the study. This was done by excluding documents without specific relevance to wireless power transfer application to electric vehicles. Other criteria for inclusion were the following:

1) Document type (articles, books, lecture notes etc.) was left to include every available documents on the topic.
2) Years under review was 2011–2022. Any document within the period was included. Any document published outside of this range was excluded.
3) Relevance of document title and content as outlined in the abstracts. This was necessary to eliminate any document with no relevance to the topic for the study.

After screening 2163 documents returned after the initial search, 1367 records from the SCOPUS database remained for evaluation. Table 1 depicts the distribution of document types of the data subjected to the bibliometric analysis.
Table 1. Distribution of Document Types for Bibliometric Analysis.

| Document Type       | Count |
|---------------------|-------|
| Article             | 1047  |
| Conference Paper    | 253   |
| Review              | 64    |
| Book Chapter        | 2     |
| Letter              | 1     |
| **Total**           | **1367** |

3.3. Scientometric Analysis

A scientometric analysis, including co-occurrence, co-authorship, co-citation, and citation analyses using several metrics (unit of measure), was conducted. Keywords, countries, and co-authors were used as units of measurement in the co-occurrence study. Co-authorship utilized authors, countries, and organization as units of measurement. Authors and sources were used as units of measurement for co-citation. Citation analysis included the usage of authors, documents, organization and sources. The scholarly topography was mapped and visualised using density maps and network visualizations.

4. Results and Discussion

4.1. Keyword Co-Occurrence Analysis

Keywords indicate the primary substance of published documents and show the scope of study within any domain’s bounds [44]. Keyword co-occurrence in the present study was gathered using VOSviewer to develop and map the knowledge domain between WPT and EVs. Fractional counting was used to count the items. This means that the link’s weight is fractionalized (for example, if one author co-authored a document with ten other authors, each of the ten co-authorship links has a weight of one tenth). To display the results of the bibliometric study of the literature, the visualisation of the keyword network was chosen. The VOSviewer software generates a distance-based map, in which the distance between two knowledge domains denotes the strength of the relationship [40]. A larger distance between the two nodes usually suggests a weaker relationship. The size of the item/node label is proportional to the number of articles that featured the word [45]. The minimal number of occurrences was set at five for each word, resulting in 698 out of 8053 items (keywords) meeting the requirements. This threshold was chosen after a series of cases with various parameters in order to obtain the optimal clusters. Figure 4 depicts the network of co-occurring keywords having eight clusters, 30876 links, and a total link strength of 6829.

Keyword co-occurrence networks are static depictions of the studied topic that do not take into account changes over time. VOSviewer, on the other hand, uses a time zone viewpoint to depict each node by the average year in which the keyword was used in literature. The evolution of WPT application in the EV industry has continued at a decreasing rate in recent years, as shown in Figure 4. General terms like “inductive power transmission”, “wireless charging”, “electric power systems”, and “electric vehicles” are all represented in the middle of the spectrum (around 2018). This outcome could be attributable to a focus on such themes during that time period (2014–2022) or to the fact that the topic was thoroughly explored over that time period. The most recent study subjects were “object detection” and “shielding effectiveness” possibly signaling a shift in the research focus in this field. Earlier contributions considered the various WPT as a viable target area of application for wireless charging applications; however, later publications focused on more specific problems in inductive power transfer and electromagnetic shielding effects for safety, with the other WPT methods and technologies relegated to second place. Keywords relating to novel methodologies, such as “compensation topology” or “internet of things”, were the exception.
4.2. Co-Authorship Analysis on Author, Countries and Organizations

The bibliographic records contain information about the document authors, countries and organizations of affiliation, allowing for the identification of the prominent scholars in the field as well as the mapping of research collaborations. After that, co-authorship networks and density visualizations can be created.

VOSviewer can create co-authorship networks because it can analyse scientific knowledge in order to capture the idea of a logically and cohesively organized body of knowledge [46]. A strategy like this has been regarded as a useful scientometric method for uncovering the hidden significance of a large amount of data. VOSviewer excels at mapping knowledge domains by creating a variety of easily accessible graphs [46]. Consequently, it was used to create and analyse co-author networks.

The author co-authorship network and density visualisation network for co-authorships was depicted in Figure 5, where each node represents an author and the links between the authors reflect collaboration developed through author co-authorships in publications. For the author co-authorship analysis, C. C. Mi had the highest citation count, but one of the lowest link strength scores. V. P. Galigekere had the strongest links, but had the lowest citation count. More documents had been produced by O.C. Onar. This indicates that authors who were often cited do not generally publish a large number of documents or collaborate with other authors. Authors like J. L. Afonso, M. Ghovanloo, J. Miles, and D.-W. Seo had no collaborations but high citation and document count, as seen in Figure 5C. A density visualisation in Figure 5B strongly depicted the intensity of collaboration among the scholars.
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Figure 5. Largest set of connected items for network (A) and visualization density (B) of author co-authorships. This network and visualization density map ((A) and (B) respectively) depicted the 163 items with 844 links and 11 clusters. 202 out of 3074 authors met the criteria of at least five documents to be published by an author and minimum citations was set at zero. The network (C) depicted some clusters/items that were not connected.

Similarly, a network was created based on research contributions from countries to explore the distribution of research articles on WPT applications in EVs. This network has 47 nodes and 240 connections, divided into seven clusters, with a total link strength of 567. Table 2 showed that China (428 records and 5020 citations), the United States (237 records and 8341 citations), the United Kingdom (128 records and 2914 citations), Italy (87 records and 912 citations), and Australia (44 records and 1372 citations) all made significant contributions to the field’s publications. In contrast to the prior co-author network, the country network (Figure 6A) is rather uniform and consistent. Table 2 details cross-national collaborations in detail. China had the most collaborations, followed by the United States, according to the network (Figure 6A) and density visualizations (Figure 6B) of country collaborations. Others have a limited number of partnerships.

It can be deduced from Figure 7 that research organizations/institutions rarely collaborate on topics in this research domain (depicted in Figure 7A). The only collaborations among research institutes were shown in Table 2 and Figure 7B,C. Notable collaborations were between Beijing Jiaotong University’s School of Electrical Engineering, San Diego State University’s Department of Electrical and Computer Engineering, and Northwestern Polytechnical University’s School of Automation. This means that fewer international co-authored research papers have been published. It should be noted, however, that some of these international co-authored works have garnered widespread recognition, such as the 632 citation counts on publications created by Northwestern Polytechnical University’s School of Automation. As a result, more collaboration between research institutes should be encouraged in order to develop more valuable works.
Table 2. List of Co-authorships with Author, Country and Organization as Measures for Top 10 Items Sorted According to Highest Link Strength Value.

| Author          | Documents | Citations | Total Link Strength |
|-----------------|-----------|-----------|---------------------|
| Galigekere V.P. | 34        | 151       | 138                 |
| Onar O.C.       | 38        | 1083      | 126                 |
| Su G.-J.        | 21        | 110       | 105                 |
| Pries J.        | 20        | 135       | 94                  |
| Huang X.        | 28        | 120       | 76                  |
| Onar O.         | 22        | 82        | 76                  |
| Ozpineci B.     | 22        | 48        | 73                  |
| Zhang Y.        | 27        | 314       | 64                  |
| Wilkins J.      | 11        | 86        | 64                  |
| Tan L.          | 21        | 88        | 63                  |

| Country         | Documents | Citations | Total Link Strength |
|-----------------|-----------|-----------|---------------------|
| China           | 428       | 5020      | 133                 |
| United States   | 237       | 8341      | 90                  |
| United Kingdom  | 128       | 2914      | 60                  |
| Italy           | 87        | 912       | 40                  |
| Australia       | 44        | 1372      | 33                  |
| Hong Kong       | 28        | 760       | 20                  |
| South Korea     | 104       | 1570      | 20                  |
| Spain           | 50        | 509       | 20                  |
| Germany         | 44        | 301       | 18                  |
| New Zealand     | 24        | 1641      | 17                  |

| Organization    | Documents | Citations | Total Link Strength |
|-----------------|-----------|-----------|---------------------|
| School of Electrical Engineering, Southeast University, China | 12 | 24 | 7 |
| Key Laboratory of Smart Grid Technology And Equipment In Jiangsu Province, China | 8 | 26 | 6 |
| Department of Electrical and Computer Engineering, San Diego State University, United States | 15 | 892 | 5 |
| School of Automation, Northwestern Polytechnical University, China | 6 | 632 | 3 |
| School of Electrical Engineering, Beijing Jiaotong University, China | 10 | 75 | 2 |
| Department of Electrical and Electronic Engineering, Imperial College London, United Kingdom | 7 | 752 | 1 |
| Department of Electrical and Electronic Engineering, University of Hong Kong, Hong Kong | 5 | 241 | 1 |
| School of Automation, Nanjing University of Science and Technology, China | 5 | 7 | 1 |
| College of Automation, Chongqing University, China | 7 | 26 | 0 |
| College of Electric and Information Engineering, Zhengzhou University of Light Industry, China | 5 | 57 | 0 |
Figure 6. Co-authorship analysis for countries network (A) and density visualization (B). This network and visualization density maps ((A) and (B) respectively) depicted the 47 items with 240 links and 7 clusters. 47 out of 77 countries met the criteria of at least five documents to be published by a country and minimum citations was set to zero.

Figure 7. Co-authorship analysis for organization network (A) and density visualization (C). These network and visualization density maps ((A) and (C) respectively) depicted three items with two links and two clusters. Eighteen out of 2292 organizations met the criteria of at least five documents to be published by an organization and minimum citation count was set to zero. The network visualization (B) shows only the connected organizations.

4.3. Co-Citation Analysis on Authors and Sources

Author co-citation analysis can uncover linkages between authors whose work is cited in the same publications. Seven clusters were created in the author co-citation network, as illustrated in Figure 8A. This represented seven intellectual knowledge frameworks with several collaborations. The size of the nodes represented the number of co-citations each researcher had received, while the links between authors represented indirect collaboration based on co-citation frequency. The most frequently co-cited scholars were G. A. Covic...
(frequency = 1467), J. T. Boys (frequency = 1051), C. C. Mi (frequency = 899), S. Li (frequency = 602), and J. Kim (frequency = 544). It is indeed worth noting that the total link strengths show a large number of partnerships by G. A. Covic, J. T. Boys, C. C. Mi, and S. Li. G. A. Covic is clearly the leading researcher in the field, as seen in Figure 8. Furthermore, it appears that G. A. Covic is responsible for the dissemination of concepts through literature. More details are shown in Table 3.

![Figure 8](image)

**Figure 8.** Co-citation analysis for authors. Network (A) and density visualization (B) showed 1170 out of 38,915 authors that met the minimum citation count of 20 per author. The maps consist of 1170 items, 7 clusters, and 472,247 links.

**Table 3.** Co-citation Analysis: Top Cited Authors and Sources based on Total Link Strength.

| Author                        | Citations | Total Link Strength |
|-------------------------------|-----------|---------------------|
| Covic, G.A.                   | 1467      | 172,038             |
| Boys, J.T.                    | 1051      | 126,423             |
| Mi, C.C.                      | 899       | 107,426             |
| Li, S.                        | 602       | 70,078              |
| Rim, C.T.                     | 537       | 67,877              |
| Kim, J.                       | 544       | 66,500              |
| Li, Y.                        | 510       | 61,978              |
| Zhang, Y.                     | 521       | 59,465              |
| Li, W.                        | 394       | 55,312              |
| Zhang, H.                     | 437       | 53,440              |

| Source                          | Citations | Total Link Strength |
|---------------------------------|-----------|---------------------|
| IEEE Transactions on Power Electronics | 2572     | 42,398              |
| IEEE Transactions on Induction Electronics | 1856     | 34,544              |
| Energies                        | 1206      | 20,016              |
| J. Power Sources                | 257       | 17,040              |
| IEEE Access                     | 730       | 14,423              |
| IEEE Transactions on Vehicular Technology | 430       | 10,289              |
| Applied Energy                  | 290       | 10,018              |
| Proceedings of IEEE             | 399       | 8583                |

For source co-citation analysis, a minimum citation count per source for the full counting approach is 200. As a result, the network and density visualizations for the sources are shown in Figure 9. It should be emphasized that *IEEE Trans. on Power Electronics* and *IEEE Trans. on Induction Electronics* were the most relevant sources on the topic. Table 3 demonstrates the relevance of sources.
4.4. Citation Analysis on Authors, Sources, Documents, and Organization

C. C. Mi (19 documents, 1975 citations), J. T. Boys (4 documents, 1517 citations), and G. A. Covic (4 documents, 1517 citations) were the most relevant authors (shown in Figure 10A). C. C. Mi, O. C. Onar, and S. Li had the highest citation strengths. This is an indicator of the researchers’ influence. With 28 documents published, X. Huang in cluster #7 had more influence, as seen in Figure 10A,B. This does not, however, imply that X. Huang is among the top five most prominent researchers in the field. O. C. Onar was displayed as the centroid of a map with unconnected authors (Figure 10C). This could be due to the large number of collaborative papers published.

Figure 9. Co-citation analysis for sources. Network (A) and density visualization (B) showed 33 out of 15,095 sources met the threshold of 200 citation counts. The maps had three clusters and 243 links.

Figure 10. Citation network for authors (A), density (B) and non-connected author map (C). The maps (A, B) show 300 connected authors (334 unconnected authors in C) out of 3074 authors that met the threshold of 1 document and 50 citations per author. There were 9 clusters and 6224 links.
The relative relationship between cited sources was highlighted by the density map (Figure 11B) and network map (Figure 10A). The linkages in the maps show that authors who referenced documents from *Energies* also cited materials from other sources. As indicated in Figure 11, most documents were published in *Energies* and IEEE Access. In terms of significance, *IEEE Transactions on Power Electronics* and *IEEE Transactions on Induction Electronics* outperformed *Energies* and IEEE Access in terms of citation count, despite having more documents.

![Image](image_url)

**Figure 11.** Citation Network for Sources. Network visualization (A) and density map (B) show 11 out of 289 sources that met the threshold of 1 document and 300 citations per source. There were four clusters and 44 links.

Each cluster, as indicated in Table 4 is made up of closely connected papers. There was a strong association between the two most cited documents Li S. (2015) and Miller J. M. (2015a) in cluster #1. Cluster #2 was dominated by Bi Z. (2016) and Li W. (2015). Other influential documents are available in Table 4 with their link strengths. In general, the three most relevant documents were Covic G. A (2013a), Covic G. A (2013b) and Forouzesh M. (2017). The network and density visualizations for the cited documents is presented in Figure 12.

![Image](image_url)

**Figure 13** depicts a map of significant research institutions. The top four important institutes for research in wireless power transfer for electric vehicles were also listed in Table 5. Although San Diego State University’s Department of Electrical and Computer Engineering produced the highest number of documents in this domain, it fell short of becoming the most relevant university with the most collaborations. The most relevant affiliation was the Department of Electrical and Computer Engineering, University of Michigan, United States with four documents receiving 893 citations. It is important to note that only one document was produced by the Department of Electrical and Computer Engineering at the University of Auckland in New Zealand, however that document received an appreciable number of citations which stood at 774.
Table 4. Citation Analysis—List of Cited Documents and Their Citation Counts with Number of Links Formed in the Network.

| Clusters | Document | Citations | Link Strength |
|----------|----------|-----------|---------------|
| Cluster #1 | Lu F. (2017) [47] | 101 | 2 |
| | Jawad A.M. (2017) [48] | 105 | 4 |
| | Lu F. (2016) [49] | 139 | 3 |
| | Li S. (2015) [50] | 502 | 4 |
| | Miller J.M. (2015a) [51] | 176 | 3 |
| | Kalwar K.A. (2015) [52] | 108 | 2 |
| Cluster #2 | Vu V.-B. (2018) [53] | 111 | 4 |
| | Kan T. (2017) [54] | 158 | 2 |
| | Bi Z. (2016) [55] | 207 | 8 |
| | Deng J. (2015) [56] | 138 | 2 |
| | Colak K. (2015) [57] | 145 | 1 |
| | Li W. (2015) [58] | 191 | 2 |
| Cluster #3 | Ponnimbaduge Perera T.D. (2018) [59] | 348 | 2 |
| | Zeng Y. (2017) [60] | 266 | 3 |
| | Lu X. (2016) [61] | 497 | 5 |
| | Zhong W.X. (2015) [62] | 243 | 2 |
| | Kim J. (2015) [63] | 102 | 2 |
| | Covic G.A. (2013b) [11] | 774 | 9 |
| Cluster #4 | Zhang W. (2015) [64] | 133 | 4 |
| | Berger A. (2015) [65] | 189 | 2 |
| | Wei X. (2014) [66] | 139 | 3 |
| | Covic G.A. (2013a) [12] | 774 | 9 |
| | Kiani M. (2012) [67] | 325 | 3 |
| Cluster #5 | Aldhaher S. (2014) [68] | 104 | 1 |
| | Miller J.M. (2015b) [69] | 282 | 1 |
| | Pinuela M. (2013) [70] | 270 | 2 |
| Unconnected | Khaligh A. (2019) [71] | 102 | 0 |
| | Min M. (2019) [72] | 172 | 0 |
| | Wang C. (2018) [73] | 108 | 0 |
| | Forouzesh M. (2017) [74] | 722 | 0 |
| | Un-Noor F. (2017) [75] | 209 | 0 |
| | Chen Z. (2016) [76] | 106 | 0 |
| | Wu J. (2015) [77] | 115 | 0 |
| | Onar O.C. (2013) [78] | 173 | 0 |

Table 5. Citation Analysis—List of Top Four Most Relevant Research Institutions.

| Organization | Documents | Citations | Total Link Strength |
|--------------|-----------|-----------|---------------------|
| Department of Electrical and Computer Engineering, University of Michigan, United States | 4 | 893 | 32 |
| Department of Electrical and Computer Engineering, San Diego State University, United States | 15 | 892 | 61 |
| Department of Electrical and Electronic Engineering, University of Auckland, New Zealand | 1 | 774 | 10 |
| Department of Electrical And Electronic Engineering, Imperial College London, United Kingdom | 7 | 752 | 11 |
Cluster #4 Zhang W. (2015) [64] 133
Berger A. (2015) [65] 189
Wei X. (2014) [66] 139
Covic G.A. (2013a) [12] 774
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Wu J. (2015) [77] 115
Onar O.C. (2013) [78] 173

Figure 12. Citation network for documents. Network visualization (A) and density map (B) show 23 out of 1367 sources that met the threshold of 100 citations per document. There were five clusters and 41 links. The connected cited documents surrounded by unconnected cited documents are depicted in (C).

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Figure 13. Citation network for research institutions. Network visualization (A) and density map (B) show 23 out of 2292 organizations that met the threshold of one document and 300 citations per organization. There were three clusters and 75 links. Network map (C) showed unconnected organizations surrounding a central cluster of connected organizations.

5. Outlook for WPT Application in EVs

5.1. Overview

Researchers have welcomed the progress made in WPT applications in EVs thus far, but are skeptical about the current technology's capacity to sustain the charging infrastructure for EVs at the requisite efficiency [79–81]. The ability to lower gross vehicle weight by employing a smaller battery (energy storage device) [82,83] and the energy storage device's ability to keep charge over extended charge and discharge cycles [84,85] are at the heart of the problem. The focus of this discourse, however, is mostly the technologies that may aid in reducing battery size. The current efficiency of wireless charging in...
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5.1. Overview

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5.2. Solar PV Roofed Vehicle

Traditionally, researchers have only looked at the long-term viability of solar PV in the construction of electric vehicle charging stations [87–90]. However, only a few authors/institutions have looked into the possibilities of combining solar PV technology with electric vehicles that have solar PV cells mounted on them. Some institutes conducted experiments but most of the published documents were reviews [91,92].

The experiments done by NEDO, Sharp Corporation (Sharp), and Toyota Motor Corporation (Toyota) on public roads from 2019 were an example of an institute’s work [93]. The purpose of the trials was to assess effective increment in cruising range and fuel efficiency of electrified vehicles with high-efficiency solar batteries.

Toyota built a demonstration car with solar panels on the roof, bonnet, rear hatch door, and other elements of the “Prius PHV” for public road trials. Toyota was able to obtain a rated power generation output of around 860 W by improving the solar battery panel’s efficiency and enlarging the on-board area, which is roughly 4.8 times higher than the commercial model Prius PHV (equipped with a solar charging system). This demo car, in addition to significantly increasing its power generation throughput, uses a system that charges the driving battery both while the vehicle is parked and while it is being driven, a progress that is expected to result in significant increases in electric-powered cruising range and fuel efficiency.

With research being done in this area and solar PV technology increases, it is expected that electric vehicles would use a solar PV charging system in conjunction with other charging technologies such as WPT that use a clean energy source. The solar charging system could also be used to provide direct energy to the drivetrain, which eliminates the requirement for an energy storage device (battery) or reduces the battery’s size as done in [94].

5.3. Structural Composite Batteries

The recent breakthrough in technology by researchers at Chalmers University in Sweden [95] has brought structural batteries into the spotlight and given them a fresh viewpoint. Integration of lithium-ion batteries into fiber-polymer composite constructions to carry mechanical stresses [96,97] while also storing electrical energy has a lot of promise for reducing total system weight [98,99]. When compared to existing commercial battery systems, energy storage composites with integrated lithium-ion pouch batteries achieve a better mix of mechanical performance and energy density [99]. Automotive, aircraft, spacecraft, marine, and sports equipment are all potential uses of energy storage composites with integrated lithium-ion batteries [100]. As a result, it is in the best interests of researchers to devote their efforts toward investigating the viability of structural batteries with WPT technologies, particularly for city transportation solutions. This is due to the fact that structural batteries considerably lessen the weight reduction challenge.
5.4. Solar PV Paints

Solar paint that generates electricity from water vapor has been developed by a team of researchers from the Royal Melbourne Institute of Technology (RMIT) [101]. The paint works by taking moisture from the air and breaking the water molecules into hydrogen and oxygen utilizing solar energy. After that, the hydrogen can be used to generate renewable energy. Titanium oxide, which is already present in normal paint, is also present in this solar paint. The titanium oxide aids the paint in breaking down absorbed moisture into hydrogen and oxygen particles using sun energy. After that, the hydrogen can be used to generate renewable energy. A hybrid vehicle (hydrogen powered internal combustion and electric drive) can greatly benefit from this solar PV paint, especially with certain automakers pursuing the net zero emission dream via hydrogen combustion vehicles. The demand for battery on-board the vehicle would be expected to be substantially reduced as a result of the additional energy provided by the WPT technology.

The University of Toronto also produced quantum dots, often known as photovoltaic paint [102]. They are nanoscale semiconductors that can absorb light and convert it to electricity. To use the full scientific phrase, ‘colloidal quantum dot photovoltaics’ are not only cheaper to make, but also substantially more efficient than typical solar cells. These dots have the potential to outperform regular solar panels by up to 11% [102]. In principle, we will be able to paint quantum dots on our roofs and other surfaces in order to convert sunlight into power at some point in the future. This can easily be applicable to automobile painting [103,104]. When properly integrated with WPT, a significant reduction in weight could be attained.

Finally, perovskite solar cells are especially compelling since they can take on a liquid state, making them a perfect option for solar paint. Spray-on solar cells, for example, were developed by researchers as a technique to spray liquid perovskite cells on surfaces [105,106]. In 2014, the University of Sheffield developed the world’s first spray-on solar cell [107]. To create a sun-harnessing layer, a perovskite-based combination was sprayed over a surface.

6. Conclusions

A bibliometric analysis of documents in the SCOPUS database has been presented. There has been a decrease in overall contribution on wireless charging for electric vehicles. This can be seen in the decrease in studies in 2019/2020 (Figure 2). A scientometric study has been conducted to investigate the current state and global trends in wireless charging studies for electric vehicles. Despite the fact that some literature reviews have already been published, this is the first bibliometric analysis of the subject as a whole, with 1367 papers examined using a ‘science mapping’ technique.

Recent research has focused on ‘object detection’ and ‘shielding effectiveness,’ according to the findings. Early contributions looked at all aspects of wireless charging, but later research focused on specific aspects of inductive power transfer and electromagnetic shielding effects. Novel strategies including ‘compensation topology’ were investigated as well.

For the author co-authorship analysis, C. C. Mi had the highest citation counts, but one of the lowest link strength scores. V. P. Galigekere had the strongest links but had the fewest citations. More documents had been produced by O.C. Onar. This indicates that authors who are often cited do not generally publish a large number of documents or collaborate with other authors. China, the United States, the United Kingdom, Italy, and Australia have all made important contributions to the field’s publications. It was inferred that the more publications a country has, the more advanced it is, because more money may be spent for advanced research. It can also be determined that research organizations/institutions rarely collaborate on this study domain’s topics. Only three research institutes collaborated: Beijing Jiaotong University’s School of Electrical Engineering, San Diego State University’s Department of Electrical and Computer Engineering, and Northwestern Polytechnical University’s School of Automation. Only three of the 2292 research organizations had collaborations in this area. This means that fewer international co-authored research papers
have been published. It should be noted, however, that some of these international co-authored works have garnered widespread recognition, such as the 632 citation counts on publications created by Northwestern Polytechnical University’s School of Automation. As a result, more collaboration between research institutes is encouraged in order to develop more valuable works.

The most often mentioned scholars were G. A. Covic, J. T. Boys, C. C. Mi, S. Li, and J. Kim. As seen in the total link strengths, there were a lot of collaborations between G. A. Covic, J. T. Boys, C. C. Mi, and S. Li. G. A. Covic is the field’s leading researcher. Furthermore, G. A. Covic appears to be the source of thought spread through literature. In terms of sources, it should be noted that IEEE Trans. on Power Electronics and IEEE Trans. on Induction Electronics are preferred by the scientific community.

C. C. Mi, J. T. Boys, and G. A. Covic were the most influential authors according to citation analysis. C. C. Mi, O. C. Onar, and S. Li had the highest citation strengths. This is an indicator of the researcher’s importance. The connections in the maps show that authors who referenced documents from Energies also cited materials from other sources. As indicated, Energies and IEEE Access appear to have published the majority of documents, however IEEE Transactions on Power Electronics and IEEE Transactions on Induction Electronics outperformed Energies and IEEE Access in terms of impact. Covic G. A. (2013a), Covic G. A. (2013b), and Forouzesh M. (2017) were the three most significant documents. Although San Diego State University’s Department of Electrical and Computer Engineering produced the most research in this discipline, it fell short of becoming the most relevant institution with the most collaborations. Only one document was generated by the Department of Electrical and Computer Engineering at the University of Auckland in New Zealand, but that document made the department immensely relevant.

Certainly, a better understanding of wireless charging methods, particularly the use of renewable energy technologies, may cultivate industry support for more in-depth and narrowly focused research in the field, which in turn may aid policy-makers’ and practitioners’ research planning and funding efforts. Furthermore, this research presents experts with crucial insights into the current lack of drive in the sector when it comes to wireless charging and renewable energy research. Besides, the trend toward wireless charging in electric vehicles, with an emphasis on reducing battery size by employing renewable energy sources, appears promising. The required battery size and charging infrastructure will be minimized when WPT is combined with these technologies. As a result, the environmental footprint associated with the transportation industry will be reduced.

Despite the study’s significance, the findings must be seen in the context of certain constraints. The findings are constrained by the initial keyword selection, which limits the scope of the published studies. Furthermore, given the study’s aims, delving into the “why” and “how” research has been undertaken thus far is outside the scope of this work. As a result, while various difficulties within the research domain have been dis-covered, tracing these problems to their source and proposing solutions are research areas that could be tackled in the future. Furthermore, performing such studies at future critical times will help to address the shifting complexity of the examined topic and track its progress.

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## Appendix A

### Table A1. Summary of Some Wireless Power Transfer Technologies.

| Power Transfer System | Magnetic Induction Coupling | Microwave | Capacitive Coupling | Magnetic Resonance Coupling |
|-----------------------|-----------------------------|-----------|---------------------|-----------------------------|
| **Operation**         | To charge an electric vehicle wirelessly, it employs the principle of electromagnetic induction. [108–110] | The use of radio waves to transmit power is involved, with the wavelength of the radio wave being reduced to the one produced by a microwave. [52] | The inverter converts a direct current voltage to an alternating current voltage with a high frequency, which is then given to two primary metallic sheets. [111]. | It works on the idea of a transmitting coil that generates the magnetic field and a receiving coil that induces current in the coils inside the magnetic field. By channeling the electromagnetic field to the receiving coil resonating at a corresponding frequency, resonance is employed to dramatically improve efficiency. [112] |
| **Merit**             | Environmental circumstances have little effect on the systems. [91,97]. Because it requires ferrites for flux guidance, it operates at low frequencies; as a result, the size is reduced due to core losses. In general, it is safe, requires little maintenance, is long-lasting, conserves energy, is dependable, and does not emit magnetic field radiation. [18,113–115] | A relatively innovative concept that outperforms others. [116] | This is useful for EV charging because the electric field penetrates through metal barriers with minimal power loss. [117,118] There are no ferrites required for flux guiding, making it ideal for use at high frequencies and resulting in higher efficiency and power transfer densities than inductive coupling. Because of the large potential difference across metal plates, the devices on the charging pad are generally positioned freely, with flat metal plates, low rise in electrode temperature, and reduced power and frequency use. [117–120] | In comparison to other techniques, the charging distance has been increased. Power is only transferred to items that operate at the same frequency as it has no influence on objects that operate at almost the same frequency. [112,121] |
| **Demerit**           | The transmitting and receiving coils must be in close proximity and accurately aligned. Because of the large air gap, the electrical characteristics’ charging cycles differ (charging is only efficient on short distances; less than the coil diameter). Only one-phase or three-phase input can be used. [18,113–115] | Because the power transferred is so high, it is harmful to human health, has a low efficiency, and is limited to just straight-line propagation. [116] | The coupling capacitance is small, and the efficiency is low. [117–120] | To eliminate the large inductance leakage and the small coupling, resonant compensation should be applied. [121] |
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