

Review

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Aircraft Electrification: Insights from a Cross-Sectional Thematic and Bibliometric Analysis

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Posted Date: 12 August 2024

doi: 10.20944/preprints202408.0757.v1

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Review

Aircraft Electrification: Insights from a Cross-Sectional Thematic and Bibliometric Analysis

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Abstract: Electrifying aircraft, a crucial advancement in the aviation industry, aims to cut pollutive emissions and boost energy efficiency. Traditional aircraft depend on fossil fuels, which contribute significantly to greenhouse gas emissions and environmental pollution. Despite progress in electric propulsion and energy storage technologies, challenges such as low energy density and integration issues persist. This paper provides a comprehensive thematic and bibliometric analysis to map the research landscape in aircraft electrification, identifying key research themes, influential contributors, and emerging trends. The study applies natural language processing to unstructured bibliographic data and cross-sectional statistical methods to analyze publications, citations, and keyword distributions across various categories related to aircraft electrification. The findings reveal significant growth in research output, particularly in energy management and multidisciplinary design analysis. Collaborative networks highlight key international partnerships, with the United States and China being key research hubs, while citation metrics highlight the impact of leading researchers and institutions in these countries. This study provides valuable insights for researchers, policymakers, and industry stakeholders, guiding future research directions and collaborations.

Keywords: aviation technology; co-authorship networks; bibliometric analysis; electric propulsion; energy management; electric machines; thermal management; sustainable aviation; multidisciplinary design

1. Introduction

Aircraft electrification, a pivotal development in the aviation industry, aims to reduce pollutive emissions and enhance energy efficiency. Traditional aircraft depend on fossil fuels, which contribute significantly to greenhouse gas emissions and environmental pollution. However, unlike electric cars, the transition from conventional fossil-fuel-powered engines to efficient and reliable electric propulsion and energy management aircraft systems is still not feasible [1]. Nevertheless, this transition is crucial to meet global sustainability goals and reduce the aviation sector's environmental footprint. Electrified aircraft promise lower operational costs, reduced noise pollution, and increased energy efficiency [2]. Achieving these benefits requires significant advancements in energy storage, power distribution, electric propulsion, and thermal management technologies [3].

Current research in aircraft electrification has made considerable strides, particularly in the development of electric propulsion systems and energy storage solutions such as lithium-ion batteries and hydrogen fuel cells [4]. Despite these advancements, several limitations and gaps remain. Existing energy storage technologies suffer from low energy density, limited lifespan, and safety concerns [5]. Electric propulsion systems, while efficient, require further optimization to meet the enormous power demands of commercial aviation [6]. Additionally, the integration of these systems into existing aircraft designs poses significant engineering challenges.

The **goal** of this paper is to provide a comprehensive thematic and bibliometric analysis of the current research landscape in aircraft electrification. This study aims to identify key research themes, influential contributors, and emerging trends within this field. To achieve this goal, this study applies natural language processing to unstructured bibliographic data and cross-sectional statistical

methods to analyze publications, citations, and keyword distributions across various categories related to aircraft electrification. Specifically, the study:

1. Examines publication trends over time to understand the growth and evolution of research in this area.
2. Identifies the most frequently researched topics and themes through keyword analysis.
3. Analyzes citation metrics to determine the impact and influence of key contributors.
4. Maps co-authorship networks to highlight collaborative efforts and international partnerships.

This work provides several valuable **contributions**:

1. *Insight into Research Trends*: Analyzing publication trends offers insights into the evolution of research in aircraft electrification, highlighting periods of significant growth and the emergence of new research areas.
2. *Identification of Key Themes*: Keyword analysis identifies the dominant research themes and topics, providing a clear picture of the current focus areas within the field.
3. *Assessment of Research Impact*: Citation metrics analysis reveals the most influential contributors and institutions, offering a benchmark for future research and collaboration efforts.
4. *Mapping Collaborative Networks*: Co-authorship network analysis highlights key collaborative efforts and international partnerships, suggesting potential areas for enhanced cooperation.

The organization of the remainder of this paper is as follows: Section 2 presents a literature review of current challenges and opportunities in aircraft electrification, and reviews related studies that applied bibliometric analysis to the field of sustainable aviation. Section 3 describes the analytical methods used for data collection, cleaning, and visualization. Section 4 presents the findings from the thematic and bibliometric analysis, including publication trends, keyword distributions, citation metrics, and co-authorship networks. Section 5 interprets the results, discusses their implications, highlights the limitations of the study, and proposes future research directions. Section 5 summarizes the key findings and contributions.

2. Literature Review

The following two subsections examine recent literature on the challenges and opportunities in aircraft electrification and applications of bibliometric analysis to the field of sustainable aviation.

2.1. Aircraft Electrification

Aircraft electrification involves various technologies and systems, including electric propulsion, advanced energy storage technologies, and hybrid-electric configurations. The subsections that follow explore the recent literature on opportunities and challenges associated with aircraft electrification.

2.1.1. Opportunities

All-electric and hybrid-electric aircraft can potentially achieve zero-emissions and quieter flights [5]. By replacing conventional jet fuels with electric power, aircraft can decrease nitrogen oxide emissions, contributing to improved air quality [6]. The literature suggests that, in general, electric propulsion systems are more efficient than traditional combustion engines. The higher efficiency of electric motors, combined with advancements in energy storage technologies, enables better energy utilization and lower operational costs [7]. Integrating energy management systems further optimizes energy consumption, enhancing the overall efficiency of aircraft operations [8].

Recent progress in battery technology, fuel cells, and superconducting materials has accelerated the development of electric aircraft. High specific energy batteries and advanced fuel cell systems can provide the necessary power density and endurance for longer flights [9]. Additionally, superconducting materials enable more efficient power transmission and lighter electrical systems [10]. The lower number of moving parts in electric propulsion systems reduces cost and maintenance needs while increasing reliability. The industry expects that the cost per kilowatt-hour will decrease as battery and fuel cell technologies advance, making electric aviation more economically competitive [2].

2.1.2. Challenges

One of the primary challenges in aircraft electrification is the energy density of current battery technologies, which is a measure of the amount of stored energy per unit weight. While manufacturers have made progress, batteries still fall short in providing the required energy density for long-haul flights. The current state-of-the-art energy density is 350 watt-hours per kilogram (Wh/kg) for commercial grade lithium-ion rechargeable batteries [9]. Researchers estimate that a battery specific energy of 800 Wh/kg can extend the range of electric aircraft to cover a significant portion of flight operations [5]. Additionally, the adoption of electric aircraft necessitates the development of supporting infrastructure, including charging stations, maintenance facilities, and supply chains for battery materials and hydrogen [8].

Integrating various components of electric propulsion systems, such as batteries, fuel cells, electric motors, and power electronics, requires sophisticated engineering solutions to keep size and weight at a minimum [11]. High-power-density electric motors and batteries generate substantial heat, requiring advanced cooling systems to prevent overheating and ensure operational reliability [12]. Ensuring seamless interaction between these components is crucial for the efficient and safe operation of electric aircraft [13]. Furthermore, the regulatory landscape for electric aircraft is still evolving [14]. Ensuring safety and reliability through rigorous testing and certification processes poses a significant challenge [15].

Despite significant advancements, the existing literature often lacks comprehensive solutions for integrating electric propulsion systems with current aircraft designs, highlighting a critical **gap**. While significant opportunities exist in terms of environmental benefits, energy efficiency, technological advancements, and economic potential, stakeholders must address several challenges. Overcoming limitations in energy storage, developing infrastructure, managing thermal loads, navigating regulatory frameworks, and integrating complex technologies are critical steps toward realizing the full potential of electric aviation.

2.2. Bibliometric Analysis

Bibliometric analysis has emerged as a powerful tool to help understand the landscape of a field and guide future research directions. Donthu et al. (2021) observed that although bibliometric analysis is not new, its proliferation is fairly recent [16]. Bibliometric methods are particularly valuable in fields characterized by rapid technological change and interdisciplinary research, such as aircraft electrification. This method involves the quantitative assessment of academic publications and citations to provide insights into the structure and dynamics of research areas.

Only a few studies employed bibliometric analysis in the field of sustainable aviation. Ullah, et al. (2023) employed bibliometric analysis to identify the current state-of-the-art and future prospects of electric vehicles [17]. They found that China, the United States (U.S.), and the United Kingdom (UK) are leading in electric vehicle research and large-scale applications. Additionally, they found that the Multidisciplinary Digital Publishing Institute (MDPI) journal *Energies* is the most prominent publication related to battery-management systems, energy storage, charging infrastructure, and their associated environmental concerns. Utilizing keyword analysis of trends in sustainable aviation, Dinçer et al. (2024) found that “sustainable aviation fuel” was the most prominent term [18]. Similarly, in their bibliometric analysis of advanced air mobility and drones, Purtell et al. (2024) found that the terms “drone technology” and “image” appeared together most frequently [19]. Utilizing citation analysis in their study of gas turbine aero-engines for more electric propulsion, Mohammadi (2021) found that the journal *IEEE Transactions on Industrial Electronics* and author-affiliated organizations in the U.S. received the most citations [20]. In mapping co-authorship networks of literature on environmental management in aviation, Uzgör, Ateş and Kafalı (2024) commented on the global nature of research efforts in this field by noting collaborations between leading countries and organizations.

3. Methodology

Figure 1 illustrates the analytical workflow employed for the thematic and bibliometric analysis.

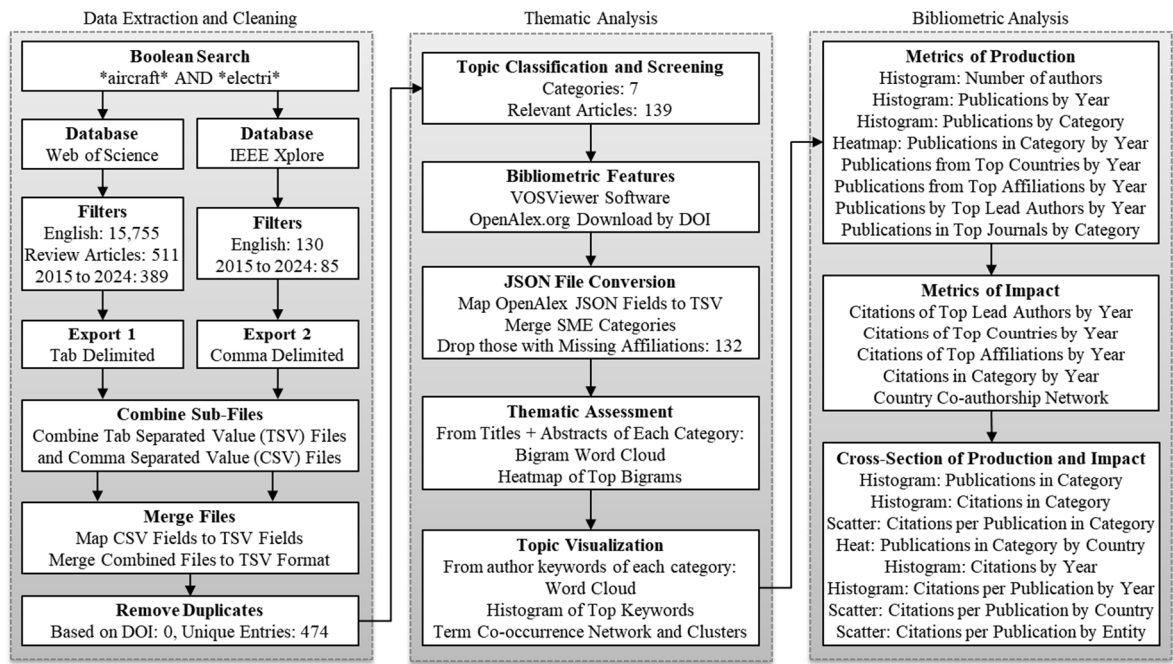


Figure 1. The analytical workflow developed in this study.

It consists of three distinct sections to extract and clean data, categorize and visualize topics, and perform cross sectional analysis of bibliographic metrics. The initial phase of the data extraction and cleaning section involved a Boolean search that applied the query (“*aircraft*” AND “*electri*”) on the titles and abstracts across two primary academic databases: Web of Science and IEEE Xplore. The authors selected these databases because of their comprehensive coverage of articles in the social, engineering, and computer sciences. These databases also feature advanced search functionalities that enable precise query building. The wildcard search character (*) ensured that retrieved documents include word variations of “electri” such as “electric,” “electrified,” “electrification,” “all-electric,” and “more-electric.” The search constrained the results to English-language articles published in the past decade, between 2015 and 2024. The Web of Science search identified 15,755 articles, with 511 being review-type articles and, of those, 389 from the specified timeframe. IEEE Xplore yielded 130 articles, with 85 from the specified timeframe. The search capability of both databases also retrieved articles that contained related words and synonyms like “drones,” “aviation,” “airplane,” “airport,” “aerial vehicles,” “aerospace,” “space craft,” “flying robots,” and “UAS.”

Subsequently, the workflow exported these articles, with Web of Science data supporting the tab-separated values (TSV) format and IEEE Xplore data supporting the comma-separated values (CSV) format for bulk download. A software procedure in Python separately combined the sub-files from each database, followed by merging the combined files. Another Python procedure mapped the CSV fields to the TSV fields to ensure uniformity, resulting in a comprehensive TSV file. The software then removed duplicates based on the document identification (DOI) numbers, resulting in 474 unique entries.

In the second part of the workflow, the author, a subject matter expert (SME), identified seven primary categories of relevant articles. Excluding the irrelevant articles resulted in 139 articles. The author then utilized the VOSViewer software (version 1.6.20) to download bibliographic features from OpenAlex.org in JSON format based on their unique DOI numbers [21]. Another Python procedure converted the JSON file output from OpenAlex to TSV format, with specific fields mapped

accordingly, and merged the SME-identified categories for further processing. Removing articles with missing affiliation data resulted in 132 articles for final bibliometric analysis.

The thematic analysis involved natural language processing methods to preprocess titles and abstracts to remove “stop words,” identify bigrams, and generate word clouds and heatmaps of top bigrams. For topic visualization, the author utilized the Seaborn graphics library (version 0.13.2) to extract author keywords from each category to create word clouds, histograms of top keywords, term co-occurrence networks, and term clusters.

In bibliometric analysis, the number of articles published, and the number of citations received are metrics of production and impact, respectively [16]. The workflow assessed various metrics of production through visualizations, including histograms of publications by year and category, top journals, and publications from top lead authors including their countries and affiliations. The workflow evaluated metrics of impact or influence with a parallel examination of, as well as constructing, a country co-authorship network. Finally, the workflow conducted a cross-sectional analysis of production and impact using scatter plots and heatmaps to provide a comprehensive overview. This multifaceted approach ensured a thorough bibliometric analysis of the field.

4. Results

The following subsections discuss the results of the thematic and bibliometric analysis.

4.1. Thematic Analysis

4.1.1. Category Identification

Table 1 summarizes the categories identified by the SME and notable articles on the topic.

Table 1. Categories identified and their representative literature.

Category	Description	Notable Articles
Electric Machines	The electrification of various moving parts on an aircraft, such as flaps, ailerons, rudders, landing gears, brakes, generators, rotors, and hydraulic pumps.	[22], [23], [24], [25], [26], [27], [28], [29]
Electric Propulsion	The use of electric power for aircraft propulsion, including all-electric, hybrid-electric, and distributed electric propulsion systems. Includes the development of electric motors, power electronics, and integration for improved efficiency and reduced emissions.	[30], [31], [32], [33], [34], [35], [36], [37], [38]
Electrical Power Distribution	The design and implementation of electrical systems to efficiently distribute power throughout the aircraft. Includes high-voltage DC systems, power electronics for conversion and control, and smart power management strategies to optimize energy use across various aircraft systems.	[39], [40], [41], [42], [43], [44], [45], [46]
Energy Management	Strategies and technologies for optimizing the use, storage, and generation of electrical energy onboard aircraft. Encompasses battery systems, fuel cells, energy harvesting techniques, and intelligent algorithms for balancing power demands across different flight phases.	[47], [48], [2], [49], [9], [50], [51], [52]
Multi-disciplinary Design Analysis	The integrated approach to aircraft design, considering the complex interactions between electrical systems, aerodynamics, structures, and propulsion. Includes computational tools and methodologies for optimizing aircraft performance while incorporating electrification technologies.	[53], [14], [11], [13], [3], [15], [6], [7]
Novel Aviation Materials	The development and application of new materials specifically suited for electrified aircraft. Includes lightweight composites for structural components, advanced conductors for electrical systems, and innovative materials for insulation and electromagnetic shielding.	[54], [55], [56], [10], [57], [58], [59], [60]
Thermal Management	Technologies and strategies for managing heat generated by electrical systems in aircraft. Includes cooling systems, heat exchangers, thermal materials, and design approaches to ensure optimal performance and safety.	[61], [62], [63], [64], [65], [66], [67], [12]

4.1.2. Thematic Thrusts

Figure 2, Figure 3, and Figure 4 collectively present a view of the research landscape in aircraft electrification by highlighting keyword prominence, frequency, and author emphasis across the various categories identified.

Electric Machines: Characterized by keywords like “power density,” “synchronous motor,” “permanent magnet,” and “Flux Modulated Permanent Magnet (FMPM) machine.” The word cloud (Figure 2) visually emphasizes these terms, indicating a strong research focus on the design and optimization of electric machines. Figure 3 quantitatively confirms this focus, showing an even distribution among top keywords, with “FMPM machine” slightly leading. Author keywords in Figure 4 further support these insights, emphasizing “motor” and “optimization,” indicating a broad interest in enhancing efficiency in electric machines.

Electric Propulsion: The terms “high power,” “power density,” “motor drive,” and “electronic converter” dominate this category. The word cloud (Figure 2) highlights the critical focus on propulsion efficiency and power output. Figure 3 supports this by showing a pronounced skew toward these keywords, while author keywords (Figure 4) add terms like “EMI” and “systems,” suggesting a comprehensive approach to addressing propulsion system integration and performance challenges.

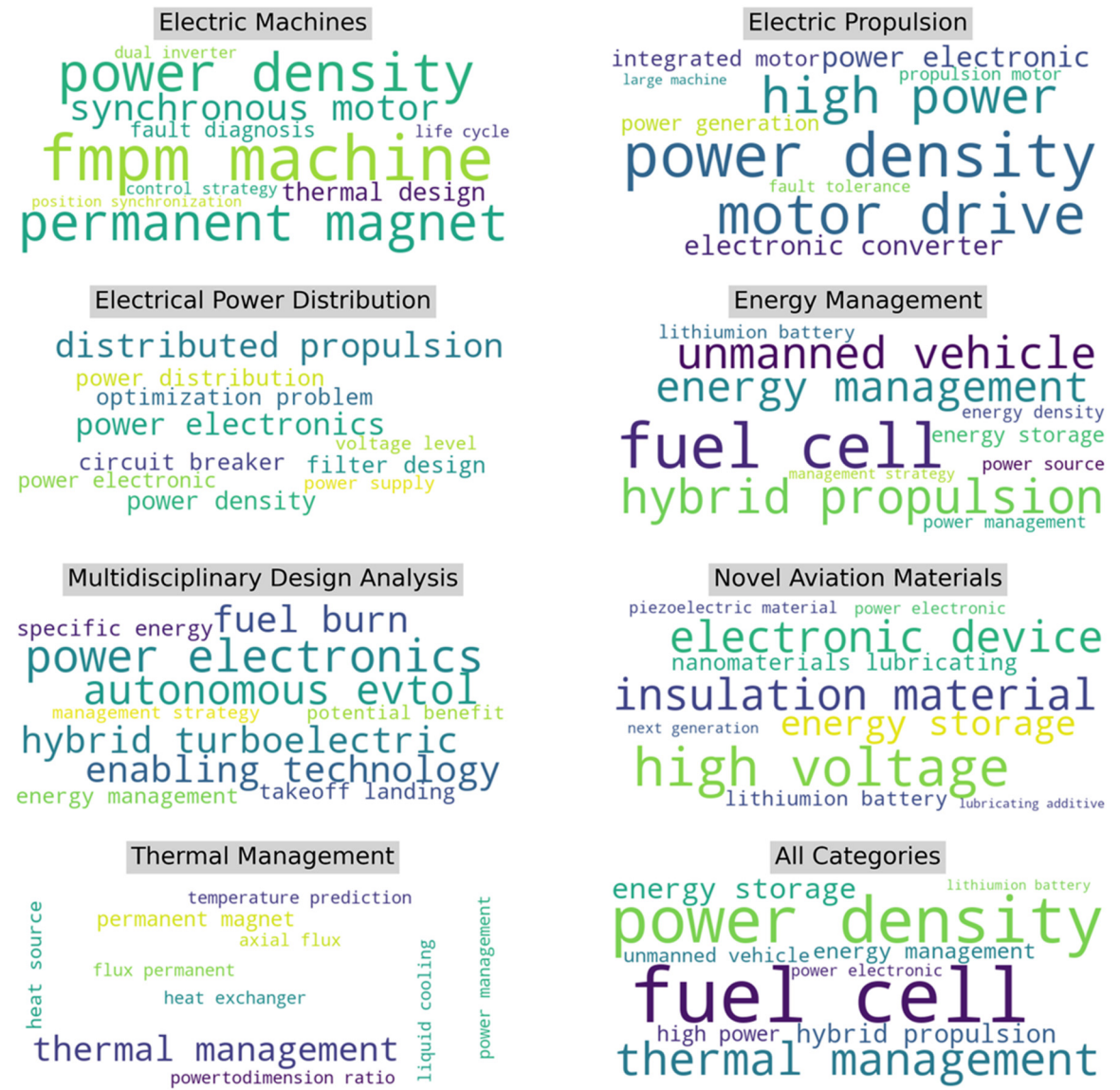


Figure 2. Bigram word cloud within categories.

Electrical Power Distribution: Keywords such as “distributed propulsion,” “power electronics,” “circuit breaker,” and “filter design” are prevalent in the word cloud (Figure 2). The bar chart (Figure 3) shows a concentration around these terms, indicating their significance in research priorities in this category. Author keywords (Figure 4) emphasize “power,” “DC,” “propulsion,” and “optimization,” aligning with research focus in this category.

Energy Management: Terms like “fuel cell,” “hybrid propulsion,” and “energy management” dominate the word cloud (Figure 2), reflecting a major research focus in advancing onboard energy management. Figure 3 quantitatively highlights the dominance of the term “fuel cell,” confirming its importance as a rechargeable battery alternative. Author keywords (Figure 4) consistently emphasize “fuel cell,” “battery,” “hydrogen,” and “energy,” highlighting their critical role in this category.

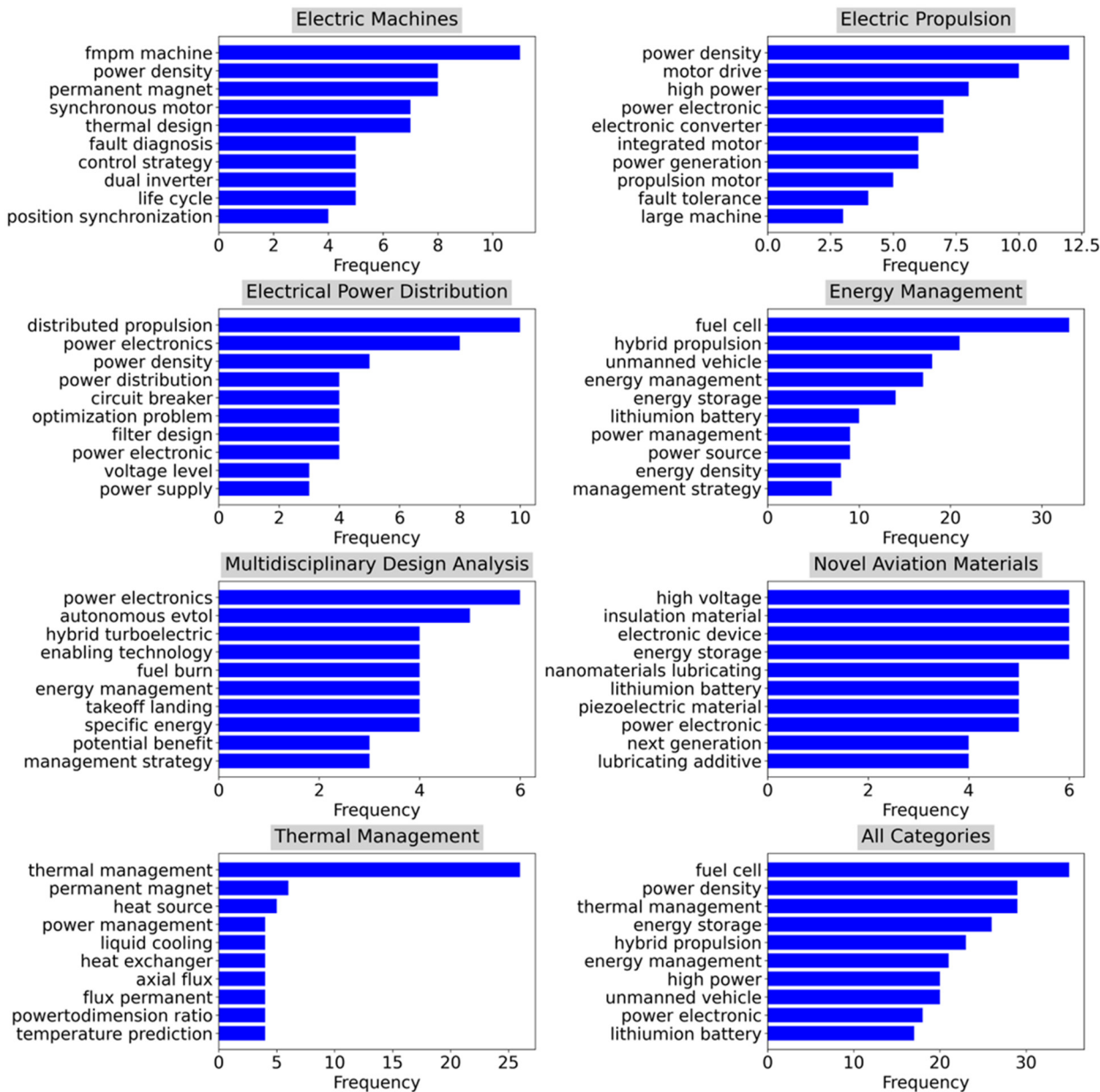


Figure 3. Bigram word frequency within categories.

Multidisciplinary Design Analysis: Important word cloud (Figure 2) terms include “autonomous eVTOL,” “fuel burn,” “power electronics,” and “hybrid turboelectric,” highlighting a broad, integrated research focus. Figure 3 shows a balanced spread among these keywords, aligning with the word cloud’s depiction of a multidisciplinary approach. Author keywords (Figure 4) such

as “urban air,” “transit,” “propulsion,” and “sustainability,” further validate the focus on comprehensive design solutions and their practical implications.

Novel Aviation Materials: Keywords like “insulation material,” “high voltage,” “electronic device,” and “nanomaterials” dominate this category in the word cloud (Figure 2). Figure 3 confirms this concentration, emphasizing the development of materials for environments undergoing high electrical stress. Author keywords (Figure 4) like “electrical,” “materials,” “piezoelectric,” and “wiring” reflect ongoing research into advanced materials to reduce weight and power various electrical systems.

Thermal Management: The word cloud (Figure 2) for this category highlights terms such as “thermal management,” “permanent magnet,” “heat source,” and “liquid cooling.” Figure 3 shows “thermal management” leading in frequency by a wide margin, followed by related terms, emphasizing the focus on temperature regulation. Author keywords (Figure 4) include “management,” “heat,” “motor,” and “battery,” indicating specific technical challenges related to heat transfer and cooling.

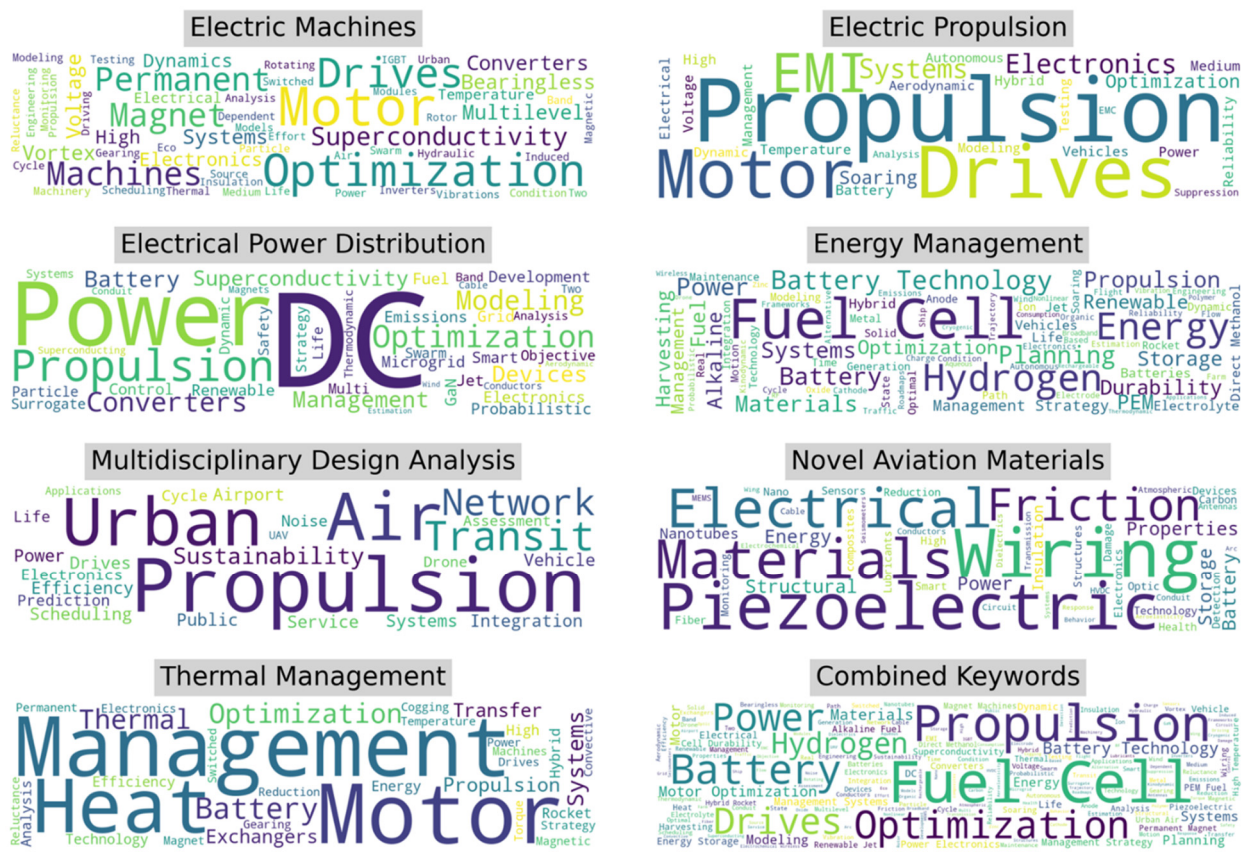


Figure 4. Author keyword cloud within categories.

All Categories: The aggregated views in Figure 2 and Figure 3 show universally important terms like “power density,” “fuel cell,” “thermal management,” “energy storage,” and “hybrid propulsion.” This comprehensive view highlights interconnected research areas, with the combined keywords further validating the primary focus areas and interconnected nature of these efforts.

Overall, the visual emphasis of the word clouds, combined with the numerical insights from bar charts and the detailed author keywords, offer a comprehensive picture of the thematic landscape, illustrating dominant trends and research focus areas within the field.

4.1.3. Thematic Cross Sections

Figure 5 provides a heatmap that illustrates the top five author keywords across the various categories identified. The number in each cell reflects the number of articles in which they appear.

This heatmap offers cross-sectional insights into how specific research topics intersect across multiple categories, highlighting the multidisciplinary nature of the field and the nuanced focus areas within each category. The color code aids in identifying clusters of frequent keywords and the topic category of those articles.

Electric Machines: Prominent keywords are “motor optimization” and “permanent magnet machines.” The term “motor optimization” also appears in other categories such as “electric propulsion” and “thermal management,” suggesting a shared focus on optimizing motor performance and efficiency.

Electric Propulsion: Keywords like “propulsion” and “motor optimization” are most prominent. “Propulsion” also appears in the categories of “electrical power distribution,” “multidisciplinary design analysis,” and “thermal management,” highlighting their co-relevance and inter-relatedness of integrated system designs.

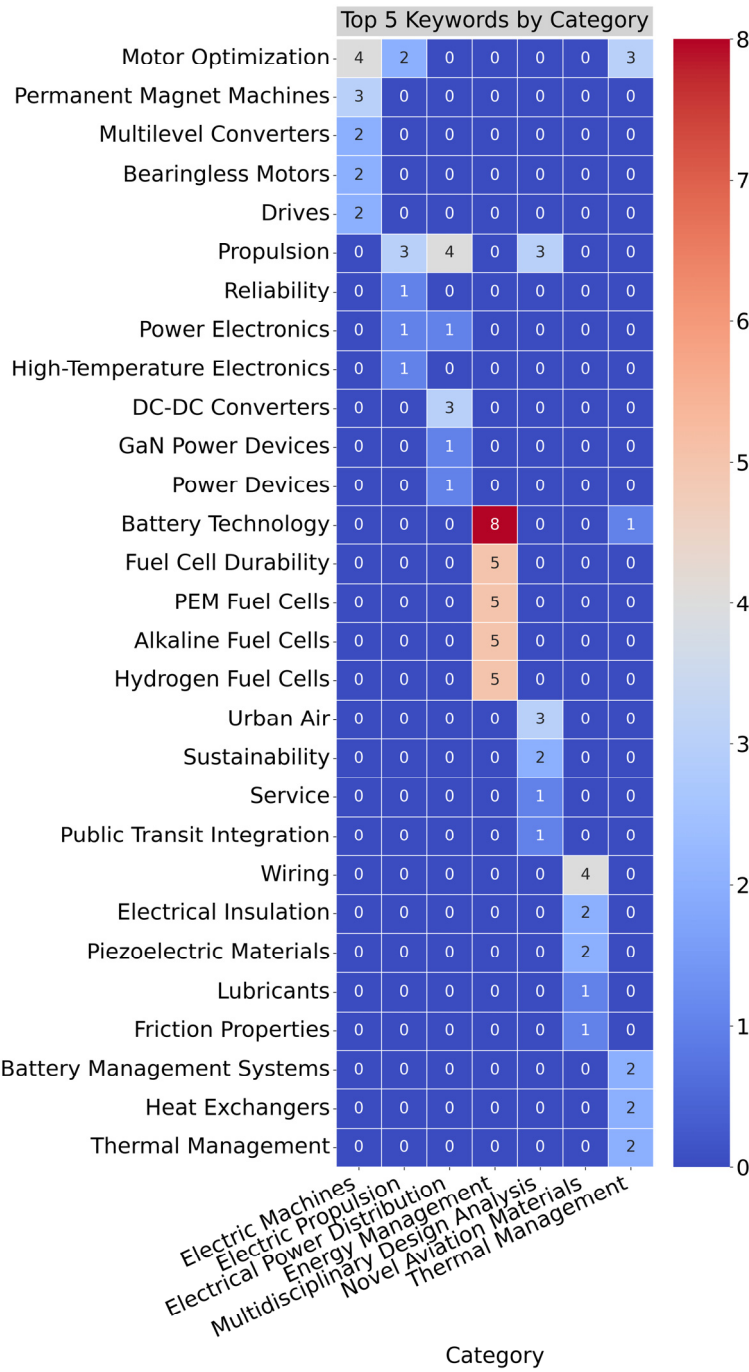


Figure 5. Top 5 author keyword within categories.

Electrical Power Distribution: This category emphasizes “DC-DC converters” and “propulsion,” with the latter also intersecting with “electric propulsion” and “multidisciplinary design analysis,” reflecting their inter-relatedness in designing complex aircraft systems.

Energy Management: “Battery technology” is the most frequent keyword followed by topics on fuel cells (“fuel cell durability,” “PEM fuel cells,” “alkaline fuel cells,” “hydrogen fuel cells”). The lack of intersection of these top keywords across the other categories suggests an independent focus on the advancement of energy storage technologies like different types of batteries.

Multidisciplinary Design Analysis: Keywords such as “urban air” and “sustainability” are most prominent, indicating a broader system-oriented focus on integrating urban air mobility solutions as a sustainable practice in future aviation.

Novel Aviation Materials: This category features keywords like “wiring,” “electrical insulation,” and “piezoelectric materials.” In the word clouds, these keywords also appear in “electric machines” and “thermal management,” suggesting a cross-disciplinary approach to improving performance and reliability in electric machines.

Thermal Management: The top keywords of “thermal management,” “heat exchangers,” and “motor optimization” indicate focused research on motor performance relative to thermal management. In the word cloud, these keywords also intersect with “electric machines” and “energy management,” reflecting the importance of effective thermal regulation across different components and systems in aircraft electrification.

Overall, the heatmap provides a detailed and nuanced view of the research landscape, highlighting key focus areas and their intersections across the research categories. This cross-sectional analysis emphasizes the complexity and interconnectedness of research efforts in the field, providing valuable insights for guiding future research and development initiatives.

4.1.4. Term Co-Occurrence Network

Words that appear frequently together in documents (co-occurrence) provide a framework for understanding the thematic structure and relationships among topics within the research corpus. Figure 6 shows the co-occurrence network where the size of the bubbles (Figure 6a) correlate with the overall frequency in the corpus, and the thickness of the connecting lines correlate with the number of co-occurrences of these terms. The distance between bubbles reflects the degree of term relatedness. The distinct colors represent clusters based on the similarities of their distribution in documents.

The term frequency distribution (Figure 7) helped to identify the core set of terms displayed, ensuring that the co-occurrence network focuses on the most relevant terms without accumulating clutter by less significant ones. Figure 7 illustrates a distribution of the number of terms that meet the threshold of minimum number of occurrences. The plot reveals an inverse relationship that follows the power law model

$$y = 9120.7 \times x^{-1.58} \quad (1)$$

with an R^2 value of 0.96, indicating a strong fit. Out of 13,829 terms, only 92 terms appeared at least 20 times.

The author chose this threshold as a balancing point to ensure a meaningful yet manageable set of terms for further analysis. After excluding 75 stop words, 60 terms met the selected threshold of appearance frequency, providing a focused vocabulary for examining the co-occurrence relationships in the corpus.

Figure 6a presents the term co-occurrence network representing 60% of the terms with the strongest links. The network consists of 36 terms, organized into three distinct clusters with a total of 533 links, visualizing the interconnectedness and thematic clustering within the research corpus.

- Cluster 1 (Red): Terms that appeared together frequently in this cluster included “analysis,” “algorithm,” “optimization,” “model,” and “data.” These terms indicate a research emphasis on computational and analytical methodologies within the field of aircraft electrification.

- Cluster 2 (Green): Centered around terms like “efficiency,” “development,” “power,” and “safety,” this cluster highlights key themes in transforming stored energy into aircraft propulsion. The inclusion of “battery” and “electric propulsion” further highlights their importance in the development of electrified aircraft.
- Cluster 3 (Blue): This cluster includes terms such as “structure,” “composite material,” “property,” and “sensor,” pointing to a strong focus on material science and structural engineering. The co-occurrence of “characteristic” suggests ongoing advancements in material properties to reduce weight and bulk while enhancing performance.

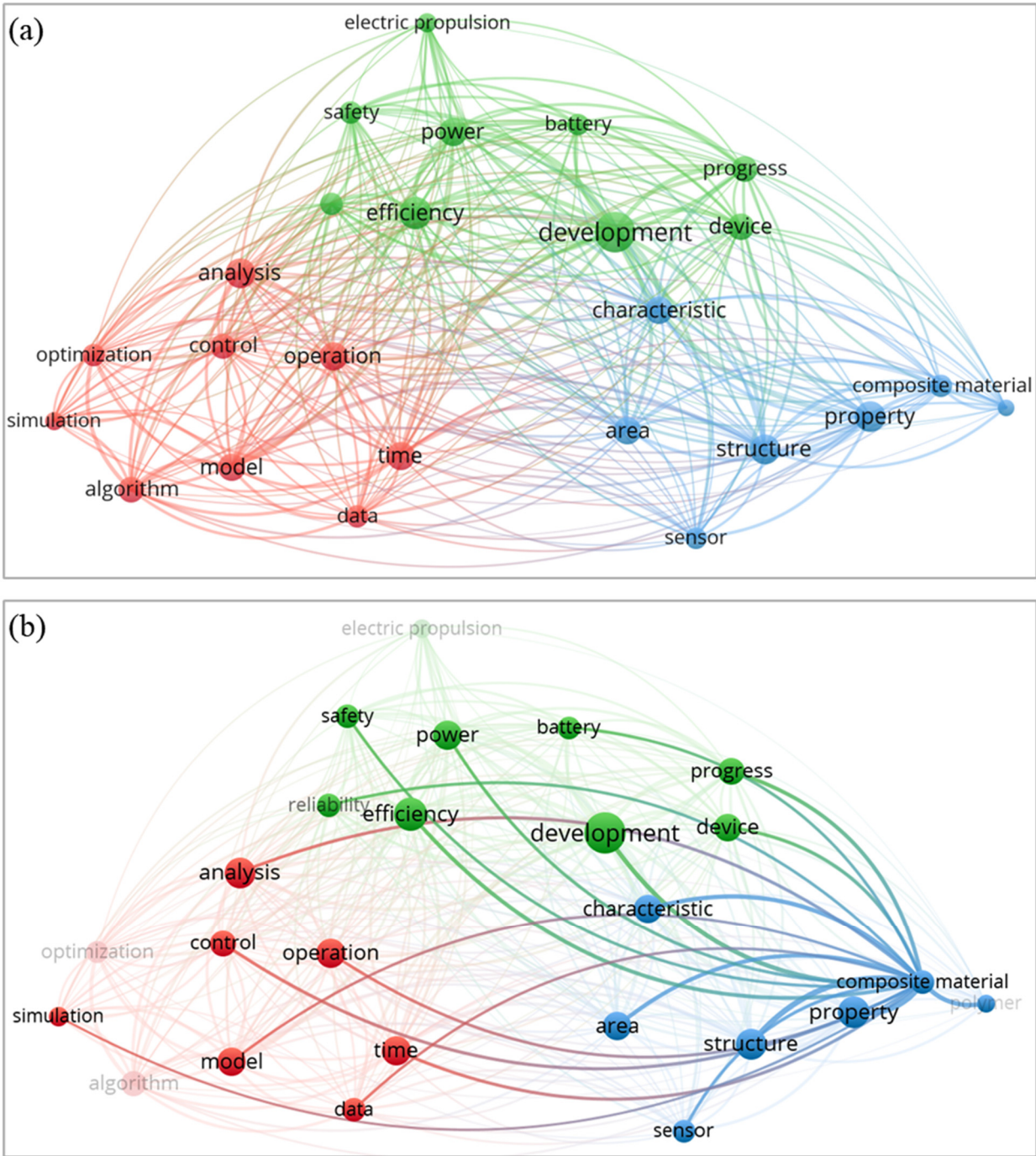


Figure 6. a) term co-occurrence and clusters, and b) highlighted example of “composite material”.

The insights from the term co-occurrence network complement the previous keyword frequency distributions and word clouds by providing a more nuanced understanding of the research topics. For instance, the emphasis on “efficiency,” “progress,” and “safety” in the green cluster aligns with

key research objectives in aircraft electrification, which are not immediately apparent in the word clouds. Similarly, the focus on “algorithm,” “simulation,” and “optimization” in the red cluster highlights the computational and analytical themes not seen in the word clouds.

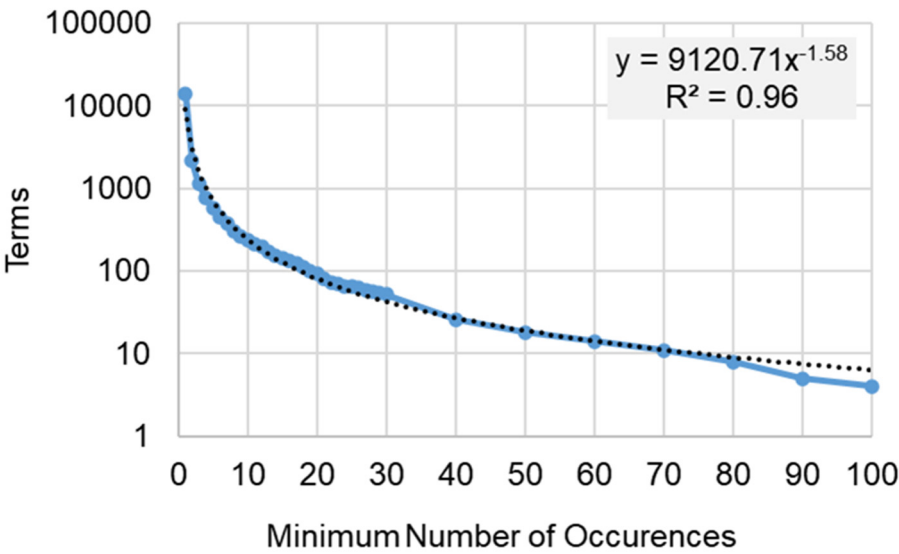


Figure 7. Number of terms as a function of their minimum number of occurrences in the corpus.

The term co-occurrence clusters also provide a visual representation of the interconnectedness of terms across various categories, reinforcing the interdisciplinary nature of the research. For instance, Figure 6b highlights an example of how the term “composite material” links to occurrences of terms within and across the other clusters. Hence, this analysis offered deeper insights into the key focus areas and interdisciplinary connections in the field.

4.2. Bibliometric Analysis

The next subsections present the results of the bibliometric analysis covering production metrics, impact metrics, and their bibliometric cross-sectional views.

4.2.1. Production Metrics

Figure 8 provides a comprehensive overview of the production metrics in the field, encompassing publications by year and category, author count distribution, and publications in category by year. The bar chart (Figure 8a) shows a significant increase in research output, with a peak in 2022. This trend indicates growing interest and advancements in the field, with 2021 and 2022 being particularly productive years. The slight drop in 2023 might suggest either a plateauing of interest or a delay in publication processes. The author conducted this research in mid-2024, which explains the small number of current publications relative to the previous four years.

The chart on publications by category (Figure 8b) shows that the Energy Management category is the most prolific, followed by Electric Machines and Multidisciplinary Design Analysis. This distribution highlights the primary focus on managing energy and optimizing machine performance within the research community.

The number of authors per paper histogram (Figure 8c) displays a right-skewed distribution, indicating that a moderate number of researchers author most papers, with a decreasing frequency as the number of authors increases. The mean number of authors per paper was 4.71, with a standard deviation of 2.66, highlighting a collaborative effort in the field. The minimum number of authors on a paper is one, while the maximum reaches 22, suggesting the presence of both individual and highly collaborative research efforts. The peak of the histogram lies between three and five authors per paper, suggesting that most research projects involved small- to medium-sized teams that require

multi-disciplinary expertise. The trend toward moderate-sized author teams aligns with the interdisciplinary nature of the field. The outlier papers with 14 and 22 authors were [65] and [68], respectively, highlighting their multi-university collaborations.

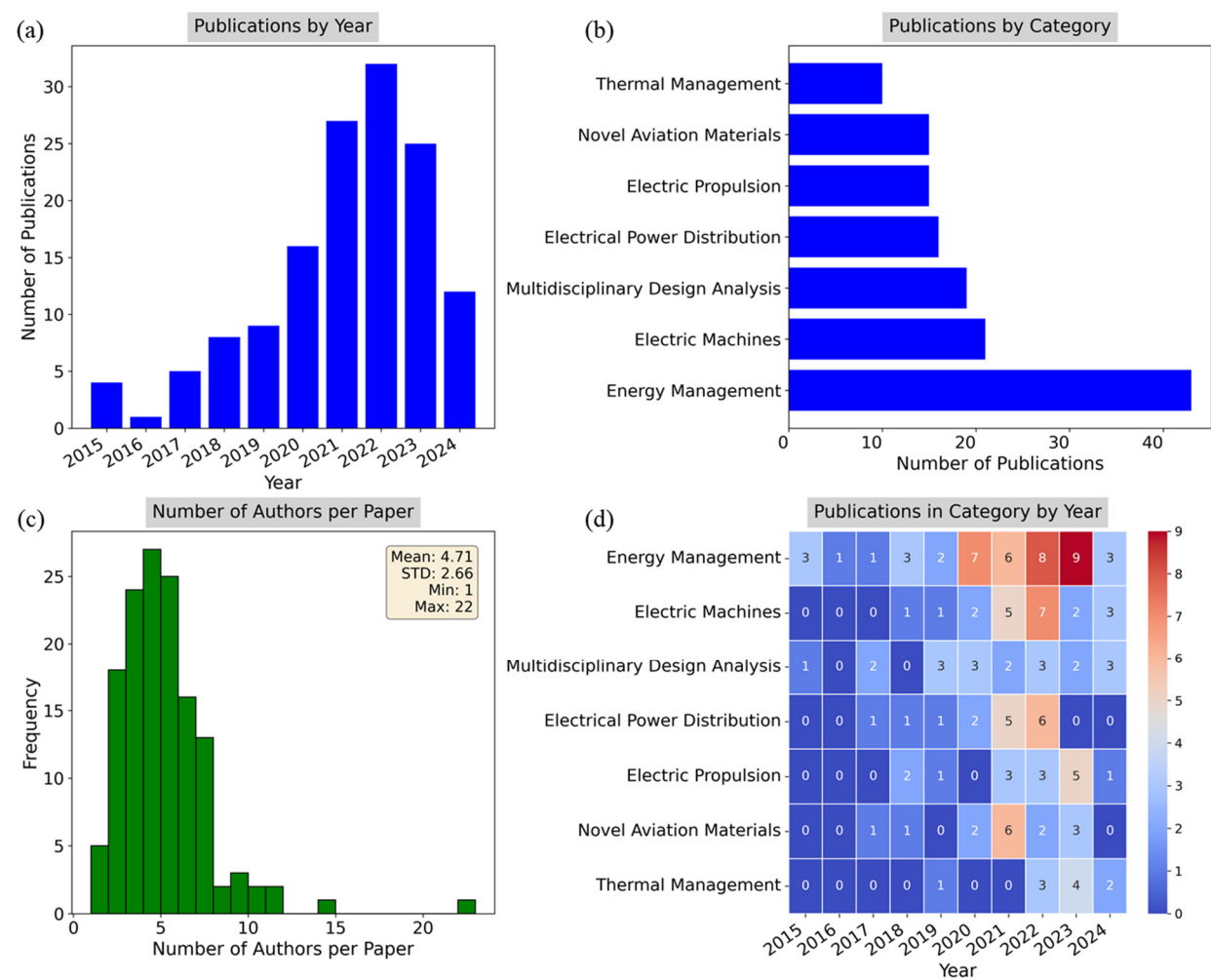


Figure 8. Publications by a) year, b) category, c) author count distribution, and d) category.

The publications in category by year heatmap (Figure 8d) provides a granular view of publication trends within each category over time. Energy Management shows a marked increase in publications from 2020 to 2022, reflecting heightened research activity in this area. Electric Machines also display a notable rise in recent years. Other categories, such as Multidisciplinary Design Analysis and Electrical Power Distribution, show steady contributions, while Novel Aviation Materials and Thermal Management have more sporadic publication patterns.

Figure 9 provides another view of the production metrics by focusing on the contributions of lead authors, their affiliation and country, and the journals publishing their work. This analysis highlights the key contributors and publication venues, offering insights into the collaborative and geographical distribution of research efforts.

The heatmap (Figure 9a) shows the publication activity of the top 10 lead authors from 2017 to 2023. The number in brackets indicates the number of unique co-authors in all of their works. The top three authors are notably productive, with consistent contributions over multiple years. Their most recent papers are [31], [69], and [70]. The latest article by the remaining top authors are [71], [72], [32], [49], [73], [74], and [75]. This distribution indicates a core group of researchers driving the field forward, with varying levels of activity across the years.

The heatmap on publications by top 10 countries of lead authors (Figure 9b) shows that China and the U.S. lead in publication output, with China showing a significant increase from 2019 onward. The UK, Germany, and Australia also contribute significantly, reflecting a strong international effort in aircraft electrification. The heatmap reveals that the majority of research output is from these leading countries, highlighting their pivotal role in advancing aircraft electrification technologies.

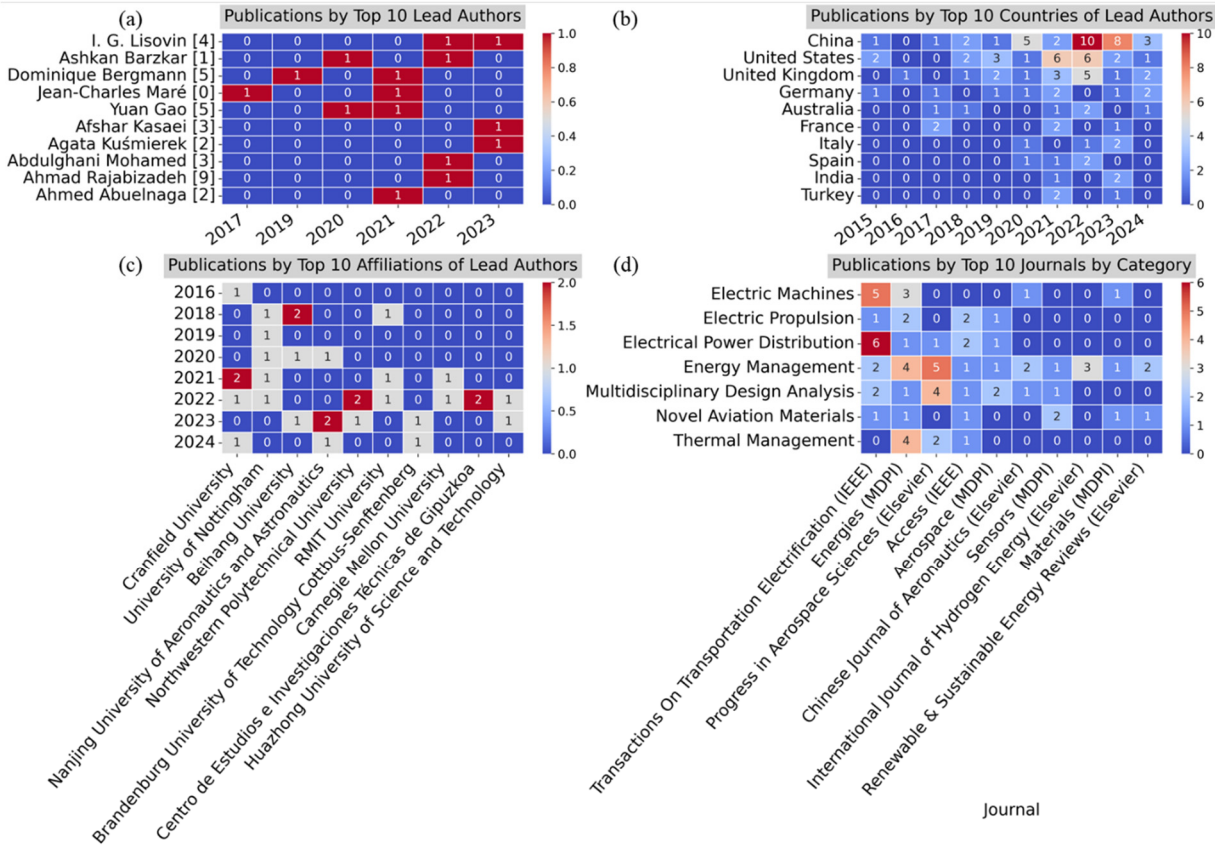


Figure 9. Publications by top 10 a) lead authors, b) countries, c) affiliations, and d) journals.

The heatmap on publications by top 10 affiliations of lead authors (Figure 9c) shows that universities such as Cranfield University (UK), University of Nottingham (UK), and Beihang University (China) are prominent contributors. The heatmap shows that Cranfield University and Nanjing University of Aeronautics and Astronautics (China) have been particularly active in recent years, while other institutions show sporadic contributions. This distribution highlights the academic institutions leading research in this field and their evolving roles over time.

The heatmap on publications by top 10 journals by category (Figure 9d) shows that the journals *Transactions on Transportation Electrification* (IEEE) and *Energies* (MDPI) are notable for publishing research across multiple categories. The categories of Electric Machines and Electrical Power Distribution are well-represented in these journals. The presence of specialized journals such as *Progress in Aerospace Sciences* (Elsevier) and *International Journal of Hydrogen Energy* (Elsevier) highlights the diverse range of publication venues catering to different aspects of aircraft electrification research.

4.2.2. Impact Metrics

Figure 10 provides a detailed analysis of the impact metrics in the field, focusing on citations of top lead authors, countries, affiliations, and categories by year. This analysis offers insights into the scholarly influence and recognition of research contributions, complementing the production metrics discussed earlier. The heatmap on citations of top 10 lead authors (Figure 10a) highlights the citation activity for that group from 2015 to 2024. The single paper by Sarlioglu and Morris (2015) from the

University of Wisconsin-Madison (U.S.) stands out with a consistently high number of citations over the years, peaking at 144 in 2023 [76]. Papers by other notable authors include Vincenzo Madonna [77], Benjamin J. Brelje [78], and Christopher Hendricks [79], each showing significant citation counts, particularly in recent years. The most recent papers by the remaining top 10 authors are [39], [80], [5], [81], [4], and [82]. This indicates their influential contributions to the field and the growing recognition of their work.

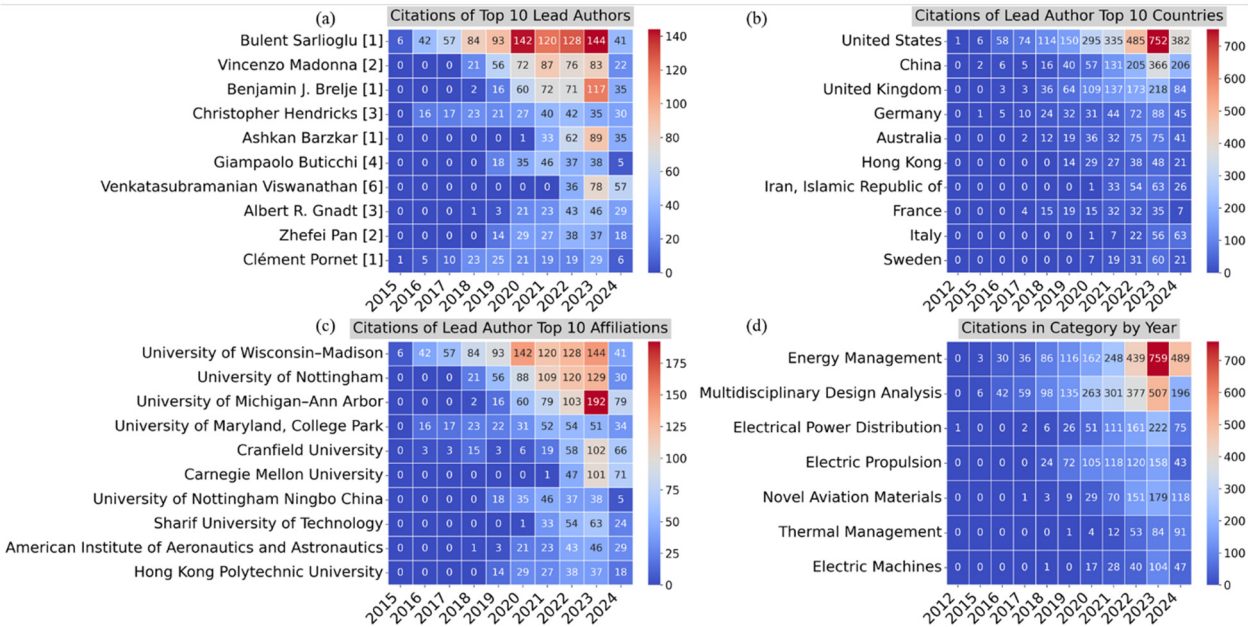


Figure 10. Citations a) of top 10 lead authors, b) of lead author in top 10 countries, c) of lead author in top 10 affiliations, and d) in category by year.

The heatmap on citations of lead author in top 10 countries (Figure 10b) shows that the U.S. leads with the highest citation counts, reflecting its dominant role in the research landscape. China and the UK follow, with substantial citations, particularly from 2018 onward. Germany, Australia, and Hong Kong also contribute significantly, highlighting the global nature of impactful research in the field. The increase in citations over the years indicates expanding research influence and recognition of developments across these countries.

The heatmap on citations of lead author in top 10 affiliations (Figure 10c) shows that the University of Wisconsin-Madison, University of Nottingham, and University of Michigan-Ann Arbor (U.S.) are prominent in citation counts. The University of Wisconsin-Madison shows the same citation counts for the single paper by Sarlioglu and Morris (2015). Other institutions like the University of Maryland (College Park, U.S.) and Cranfield University (UK) also show significant citation activity, reflecting their contributions to high-impact research. This distribution highlights the academic institutions at the forefront of impactful research in this field.

The heatmap on citations in category by year (Figure 10d) shows that the category of Energy Management leads in citation counts, peaking at 759 in 2022, highlighting its critical importance and research focus. The category of Multidisciplinary Design Analysis also shows high citation counts, particularly in recent years, indicating its growing relevance. Categories like Electrical Power Distribution and Electric Propulsion have substantial citation counts, reflecting ongoing research and innovation in these areas. The distribution of citations across categories shows the multifaceted nature of research in aircraft electrification and the varying impact of different research areas over time.

4.2.3. Co-Authorship Network

Figure 11 illustrates the co-authorship collaborations across countries in the field of aircraft electrification, focusing on countries with a minimum of five publications. Only 10 of 43 countries shown in the figure met this threshold. The bubble sizes represent the number of publications, while the lines between bubbles indicate collaborative links. The total link strength (TLS) for a country is the sum of its publications with all collaborating countries. Table 2 lists the 10 countries along with the publication, citation, and TLS statistics. With 39 publications, China is a leading country in aircraft electrification research. It has a TLS of 21, reflecting strong collaborative ties, particularly with the UK and Germany.

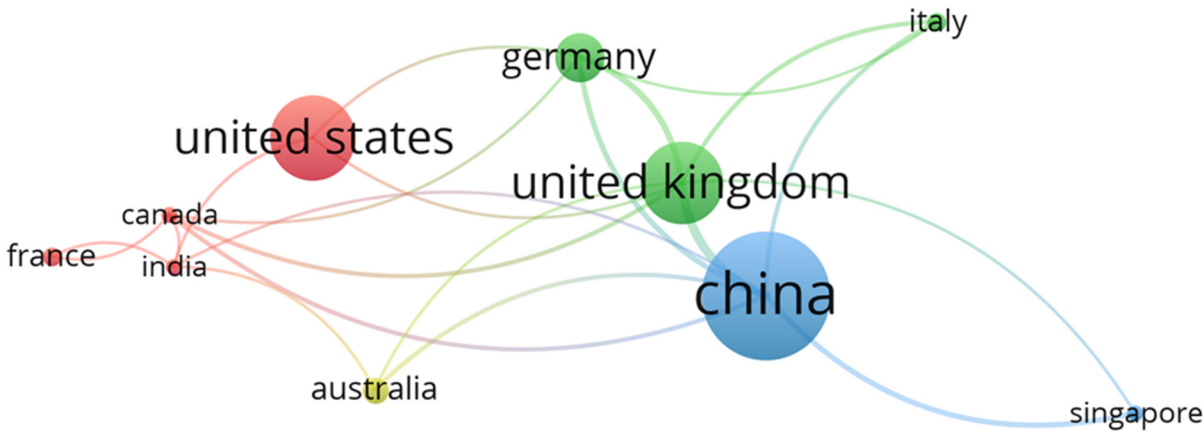


Figure 11. Authorship collaborations across countries.

Table 2. Countries with at least 5 publications.

Country	Pubs	Pubs %	Cites	Cites %	TLS
China	39	27.9%	1,724	21.0%	21
United Kingdom	25	17.9%	1,413	17.2%	19
Germany	15	10.7%	736	8.9%	10
Canada	5	3.6%	379	4.6%	7
India	5	3.6%	60	0.7%	5
Italy	6	4.3%	221	2.7%	5
Australia	8	5.7%	361	4.4%	4
Singapore	5	3.6%	172	2.1%	4
USA	26	18.6%	2,974	36.1%	3
France	6	4.3%	187	2.3%	2

Despite its significant output, there are no direct links with the U.S., highlighting a gap in Sino-American collaboration. The UK has 25 publications and a TLS of 19, indicating extensive collaborations, especially with China and Germany. This strong network highlights the central role of the UK in facilitating international research efforts. The U.S. has 26 publications, accounting for 18.6% of the total, with the highest citation count of 2,974 (36.1%). However, its TLS is comparatively low at 3, suggesting fewer international collaborations compared with China and the UK. With 15 publications and a TLS of 10, Germany has significant collaborative ties, particularly with the UK and China. Its research is well-recognized with 736 citations (8.9%). Despite having only 5 publications, Canada has a TLS of 7, indicating strong collaborative efforts, particularly with the U.S. and the UK. Australia, Singapore, and Italy have moderate publication outputs and varying levels of collaboration. Australia (8 publications, TLS 4) and Singapore (5 publications, TLS 4) show moderate collaborative efforts, while Italy (6 publications, TLS 5) has notable ties with Germany and the UK.

4.2.4. Bibliometric Cross-Sections

Figure 12 provides a cross-sectional analysis of both citations and publications in the field, focusing on trends over time, and by country and affiliation.

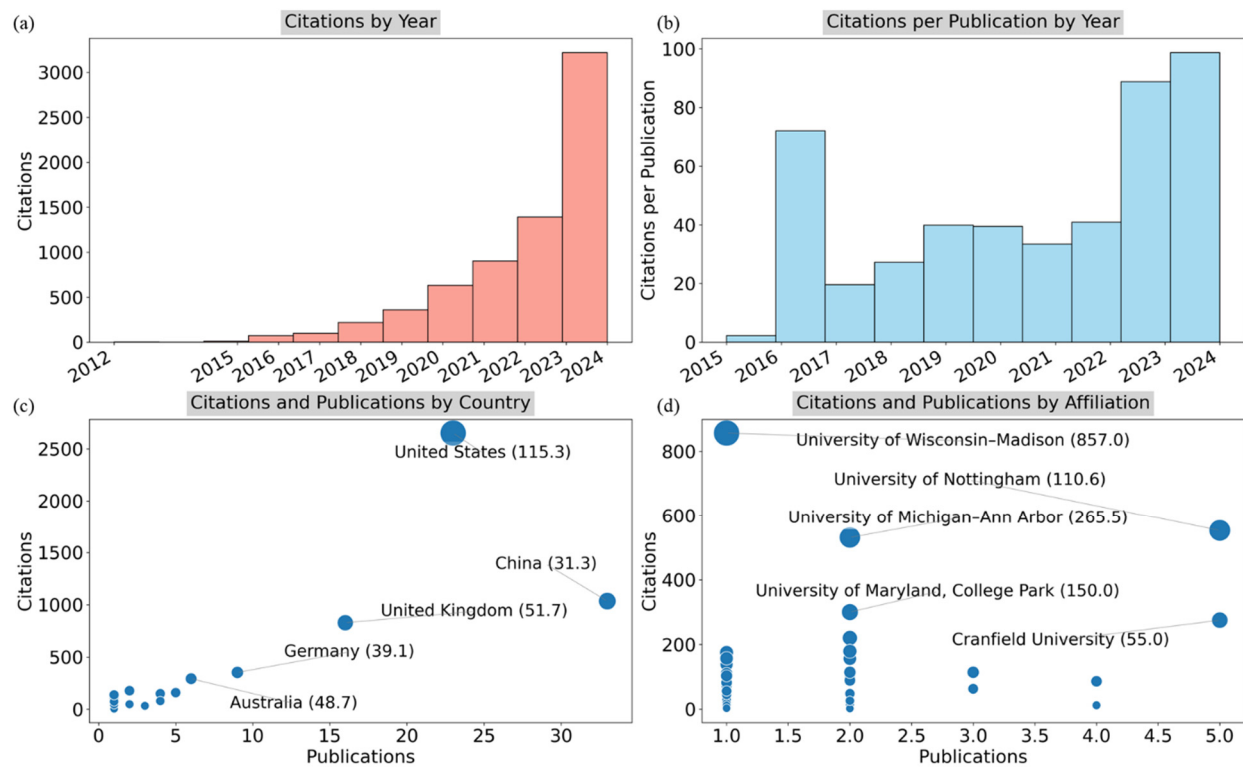


Figure 12. Citations a) by year, b) per publication by year, c) per publication by country, and d) per publication by affiliation.

This analysis offers insights into the impact and productivity of research efforts. Figure 12a shows a steady increase in citations from 2015 to 2023, with a sharp rise in 2022 and 2023. This trend indicates a compounded growth in recognition and influence of research in aircraft electrification, reflecting the field’s increasing relevance. The citations per publication (Figure 12b) have varied over the years, with notable peaks in 2016, 2023, and 2024. The increase in recent years suggests that more recent publications are receiving higher attention and impact, indicating a rising quality and relevance of research outputs. The scatter plot (Figure 12c) reveals that the U.S. leads in the number of citations, with a significantly high citations per publication ratio (115.3). China and the UK follow, with China having a high number of publications but a lower citations per publication ratio (31.3). The UK shows a balanced performance with a higher citations per publication ratio (51.7) compared with China. Germany and Australia also contribute significantly, though with fewer publications. The scatter plot of citations and publications by affiliation (Figure 12d) highlights the contributions of various universities. Once again, the single paper by Sarlioglu and Morris (2015) from the University of Wisconsin-Madison stands out as an outlier with the highest citations of 857. The University of Nottingham, University of Michigan-Ann Arbor, and University of Maryland also show strong performance with significant citations per publication ratios of 110.6, 265.5, and 150, respectively. Cranfield University, despite having more publications, shows a notable but lower citations per publication ratio (55.0), still indicating impactful research.

Figure 13 provides a cross-sectional analysis of publications and citations by category in the field, highlighting the number of citations, citations per publication, and the distribution of publications across top countries. The bar chart (Figure 13a) indicates that the category of Energy Management leads with the highest number of citations, followed closely by Multidisciplinary Design Analysis. The categories of Electric Propulsion and Electrical Power Distribution also show

significant citation counts, reflecting their impact within the field. Categories like Novel Aviation Materials, Electric Machines, and Thermal Management have fewer citations, suggesting they are emerging areas with potential for further research impact. The bar chart on citations per publication in category (Figure 13b) reveals that the category of Multidisciplinary Design Analysis has the highest citations per publication, indicating highly impactful research despite a moderate number of publications. The category of Energy Management also shows a high citations per publication ratio, followed by Electric Propulsion and Electrical Power Distribution.

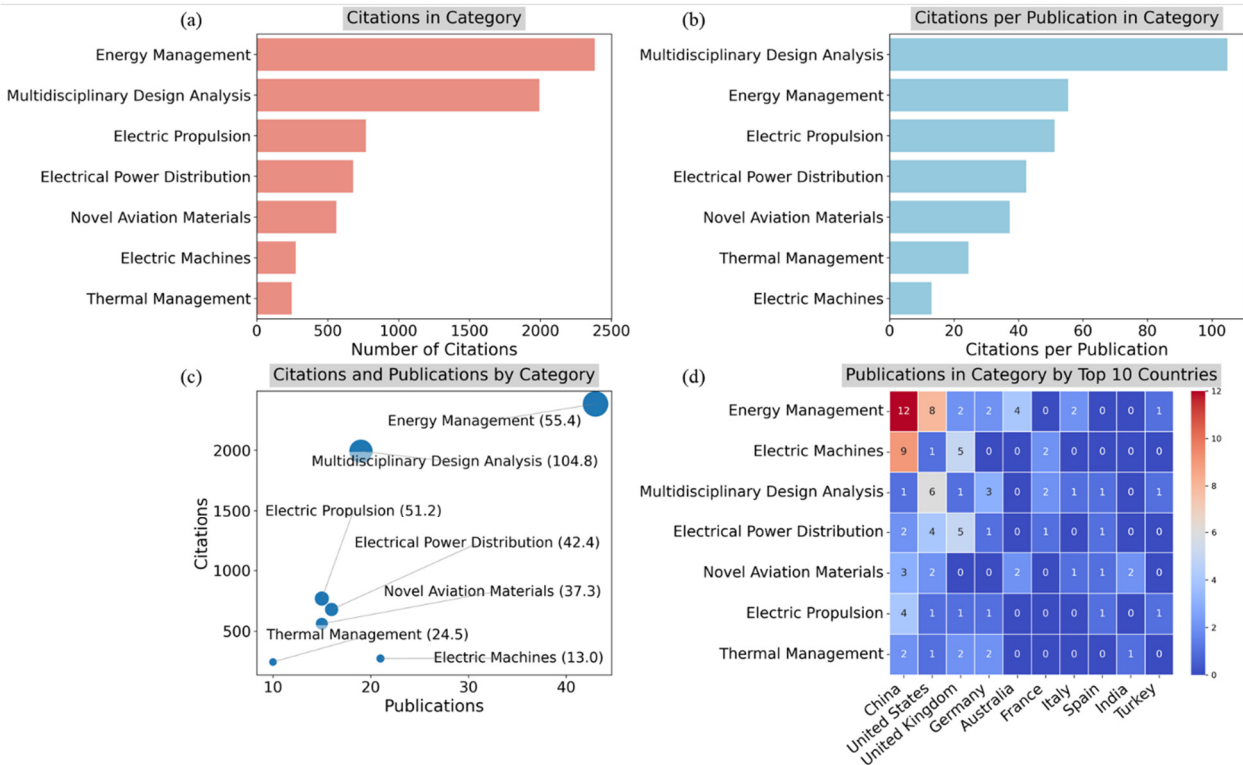


Figure 13. a) Citations in category, b) citations per publication in category, c) citations per publication in category, and d) publications in category by top 10 countries.

The scatter plot of citations and publications by category (Figure 13c) provides a complementary view for comparing citations versus publications across categories. The category of Energy Management stands out with both the highest number of citations and publications, but with fewer citations per publication than the category of Multidisciplinary Design Analysis. This indicates that these categories, while having different numbers of publications, both produce highly cited research. Other categories like Electric Propulsion and Electrical Power Distribution also show a balanced number of publications and citations, reflecting their significance in the field.

The heatmap of publications in category by top 10 countries (Figure 13d) shows the distribution of publications across the top 10 countries in various categories. China and the U.S. lead in publications focused on energy management, reflecting their significant contributions to this critical area. The UK, Germany, and other countries also contribute notably across different categories, indicating a global interest in aircraft electrification research.

5. Discussions

The following subsection (Section 5.1) discusses a sample of the literature focusing on each of the seven thematic thrusts identified. Section 5.2 interprets the results of the bibliometric analysis. Section 5.3 discusses implications for future directions; Section 5.4 acknowledges limitations of this research.

5.1. Thematic Thrusts

The subsections that follow elaborate on a sample of the literature that focuses on topics within each category identified.

5.1.1. Electric Machines

This section provides an overview of selected works that focused on significant contributions in electric machines for aircraft electrification. Lisovin et al. (2022) discussed the critical technologies required for developing more electric engines (MMEs), focusing on the transition from hydraulic and pneumatic systems to electric ones [28]. The integration of electric machines into aircraft engine shafts, such as embedded starter-generators and electric drives for fuel and oil systems, is a key trend in achieving higher efficiency and reliability in aircraft systems. She et al. (2024) presented a novel integrated design methodology for shimmy reduction subsystems in the nose wheel steering systems of all-electric aircraft [24]. They proposed a systematic approach combining systems engineering methods and morphological analysis to explore design solutions and optimize the subsystem's performance.

Jiao et al. (2023) examined the brushless wound-rotor synchronous starter-generator (BLWRSSG) technology for more-electric aircraft [25]. They detailed the key technologies necessary for high-performance BLWRSSG systems, such as brushless excitation, starting control, rotor position estimation, and fault diagnosis, providing a thorough understanding of the system's operation and potential improvements. Pei et al. (2022) provided a comprehensive review of bearing-less synchronous motors (BLSMs), highlighting their principles, topologies, and potential applications [29]. The integration of magnetic bearing functions with synchronous motor capabilities offers advantages such as frictionless operation and system simplification, making them suitable for applications like aviation systems. Zhao et al. (2023) focused on axial flux permanent magnet synchronous motors (AFPMSMs), widely used in renewable energy applications, including wind power and electric aircraft [26]. Their review covered design and control optimization strategies for AFPMSMs, highlighting the need for efficiency improvements and the development of advanced control methods to suppress torque ripples.

Paterson et al. (2024) addressed the sustainability challenges of permanent magnet electrical machines [23]. They discussed the environmental impact of the current linear life cycle of these machines and proposed alternative practices to enhance their sustainability, emphasizing the need for improvements across the entire life cycle to achieve true environmental benefits. Xu et al. (2022) reviewed segmented switched reluctance motors (SSRMs), noting their magnet-free construction and robustness, which make them suitable for high-reliability and fault-tolerant applications in aircraft systems [27]. They discussed the development of SSRM topologies, and the various methods employed to reduce torque ripples and enhance performance. Zhou et al. (2024) explored the reliability of insulation systems in low-voltage electrical machines used in transportation electrification. They reviewed the degradation mechanisms, lifetime modeling, and accelerated aging tests for insulation systems, emphasizing the importance of reliability-oriented design and remaining useful life estimation in achieving high-performance and reliable electric machines.

5.1.2. Electric Propulsion

This section synthesizes key contributions from the retrieved literature, focusing on the evolution and state-of-the-art developments in electric propulsion systems. Wang et al. (2023) analyzed the basic structure and principles of various motor types and compared their performance to determine the most suitable for propulsion applications [34]. Their review discussed methods to improve power density and fault tolerance, including redundant design and fault-tolerance capability enhancement. Liu et al. (2022) detailed the architecture, characteristics, and performance of MEEs, highlighting their potential benefits in terms of fuel consumption and emissions reduction [36]. Zhang et al. (2022) highlighted the advantages of integrated motor drives (IMDs), including compact size, high power density, and high efficiency [35]. Kasaei et al. (2023) highlighted the

principles and benefits of rim-driven fan (RDF) technology, which promises energy-efficient and eco-friendly air travel [32]. Alvarez et al. (2022) discussed the challenges associated with implementing electric motors, such as the need for high power density and the use of high-voltage systems at high altitudes [37]. Arabul et al. (2021) reviewed the evolution of aircraft power systems toward more electric aircraft (MEA), which aims to enhance safety, comfort, and environmental performance [38]. They emphasized the importance of onboard electrical systems, which involves significant changes in aircraft design and onboard power systems. Wang et al. (2023) discussed the challenges posed by electromagnetic interference (EMI) in achieving high power density and the various modeling approaches and suppression methods [33]. The review emphasized active EMI mitigation techniques due to their advantages over passive filters. Lisovin et al. (2023) focused on the control of MMEs, power transmission, integration of starter-generators and electric generators, heat recovery, and the training of personnel [31]. Phosung et al. (2024) applied the state-variables-averaging model to reduce computational time of controllers, and stability analysis based on the eigenvalue theorem to ensure stable operation [30].

5.1.3. Electrical Power Distribution

This discussion synthesizes the contributions of key studies that focused on electrical power distribution in aircraft. Ilić and Jaddivada (2021) presented a modeling and control approach to optimize turbo-electric distributed propulsion (TeDP) systems by integrating control and automation from the design stage [46]. Fard et al. (2022) discussed the differences in system structures and power generation stages of distributed electric propulsion (DEP) technologies, highlighting the need for their comprehensive optimization to improve aerodynamics, energy efficiency, and noise reduction [40]. Martinez et al. (2022) proposed semiconductor technology to create adaptable, bidirectional modules for decentralized electric power, and to enhance system redundancy and fault tolerance by increasing the number of paths for power distribution [43]. Nolan et al. (2022) examined the sizing of superconducting cables to find a balance between preventing equipment disconnection due to temperature rise following faults and minimizing weight and cost [42]. Gao et al. (2021) proposed using a genetic algorithm to optimize direct current (DC) filters to ensure low mass and power losses in point-of-load converters while maintaining output power quality [45].

Barzkar and Ghassemi (2022) discussed the limitations of current electrochemical energy units, circuit breakers, and electric drives. The review suggested that advancements in high-voltage wide bandgap circuit breakers, Li-air and Li-S batteries, and multimegawatt superconducting electric machines could make commercial passenger AEAs feasible within 20 to 30 years [39]. Wileman et al. (2021) examined failure modes in existing power electronics devices and highlighted the potential of wide bandgap (WBG) technologies like gallium nitride (GaN) and silicon carbide (SiC) for enhancing reliability [44]. Psaras et al. (2022) conducted a landscaping exercise to assess the impact of arc characteristics and identified the need for improved testing methods to facilitate the performance validation of new arc fault detection devices [41].

5.1.4. Energy Management

Articles within the category of energy management covered topics such as hydrogen storage, hybrid electric propulsion systems, battery management, and energy storage technologies. Yang et al. (2023) highlighted the importance of energy management strategies in achieving high fuel economy, low emissions, and low noise [51]. Raoofi and Yildiz (2023) emphasized the importance of effective battery state estimation for ensuring safety and reliability in electric propulsion systems while highlighting the potential for AI in this field [50]. Fakhreddine et al. (2023) found that hydrogen fuel cells have higher energy conversion efficiency and emit only water and heat, making them a promising alternative for reducing environmental and economic concerns in the transportation sector [9]. Massaro et al. (2023) identified hydrogen's low density and the need for large storage volumes and heavy tanks as significant challenges [52].

Kuśmierek et al. (2023) discussed the potential of hybrid gas-electric propulsion to reduce fuel consumption and emissions while highlighting challenges such as immature battery technology,

complicated power management systems, and cooling systems for high-power propulsion systems [49]. Aghmadi and Mohammed (2024) highlighted the benefits of hybrid energy storage systems for enhanced flexibility and resilience in an overview of recent advancements in high-power energy storage systems, including supercapacitors, superconducting magnetic energy storage, and flywheels [47]. Niri et al. (2023) discussed the role of explainable machine learning in optimizing battery structure, characteristics, and manufacturing processes, as well as monitoring battery states of health, charge, and energy [48]. Ansell (2023) found that bio-jet fuels, synthetic kerosene, liquid natural gas, and liquid hydrogen are technically feasible energy carriers that can contribute to improved environmental outcomes but emphasized the need for a transition to fully sustainable aviation fuels [2].

5.1.5. Multidisciplinary Design Analysis

This section reviews significant contributions in multidisciplinary aspects of the field, focusing on electric aircraft architectures, sustainable aviation, low noise aircraft, powertrain electrification, advanced air mobility (AAM), autonomous electric vertical take-off and landing (eVTOL), and unmanned aerial vehicle (UAV) avionics systems. Cano et al. (2021) presented a comprehensive analysis of all-electric aircraft architectures, emphasizing reliability, efficiency, and specific power density [7]. Kieseewetter et al. (2023) analyzed various aircraft designs and propulsion system architectures. They provided insights into the strengths, weaknesses, and gaps in design considerations for AAM applications [11]. Xiang et al. (2024) identified key technologies enabling autonomous eVTOL aircraft, including automated flight control, sensing, perception, safety, reliability, and decision-making [14]. Osmani and Schulz (2024) reviewed the electronic hardware and algorithms used for drone data processing, flight control, surveillance, navigation, protection, and communication [53].

Zhang et al. (2022) reviewed electrified aircraft propulsion architectures, energy management strategies, and control system design challenges [6]. Ciliberti et al. (2022) reviewed advances in propulsion, aerodynamics, and structures, emphasizing the need to integrate disruptive technologies from the preliminary design phase [15]. Greenwood et al. (2022) highlighted the challenges and opportunities in predicting and reducing noise generation for electric aircraft through advances in computational aeroacoustics, flight simulation, and autonomy [3]. Roboam (2023) discussed specific projects in powertrain electrification for greener aircraft that emphasize the integration of power electronics, electric machines, and cooling devices [13].

5.1.6. Novel Aviation Materials

This section reviews significant contributions to the development of novel aviation materials, including piezoelectric systems, energy storage structural composites, smart composite structures, insulation materials, superconducting propulsion, and high-temperature superconducting cables. Galos et al. (2021) discussed methods for embedding commercial lithium-ion batteries into fiber-polymer composite structures, which can simultaneously carry mechanical loads and store electrical energy, reducing overall system weight [59]. Janeliukstis and Mironovs (2021) emphasized the advantages of embedding sensors into smart composite structures, such as better sensor protection and real-time monitoring capabilities, over traditional surface-mounted technologies [58]. Vo et al. (2021) reviewed potential amplification mechanisms for piezoelectric materials, which can produce compact systems with fast responses and high power density despite their limited strain generation [60]. Lizcano et al. (2022) reviewed the needs for novel lightweight materials and system solutions to improve performance and safety in high voltage and extreme environments [56]. Jiang et al. (2023) highlighted the insulation challenges for power modules, electric machines, and aeronautical cables and summarized existing technical barriers and future prospects [55]. Borghei and Ghassemi (2021) discussed aging factors, such as internal discharges, arc tracking, and thermal degradation, and explored novel insulating materials to enhance performance and reliability [57]. Paramane et al. (2023) discussed the different aspects of high-temperature superconducting cables, including dielectrics, electrical insulations, superconductors, and cooling systems [54]. Ferreira da Silva et al.

(2021) reviewed the development of high specific power superconducting machines and ongoing projects, emphasizing the need for alternative materials and nonconventional designs to meet aeronautical application requirements [10].

5.1.7. Thermal Management

This section reviews significant contributions in thermal management, focusing on novel cooling methods, system architectures, and the integration of power and thermal management systems. Asli et al. (2024) emphasized the complexity of integrating efficient thermal management systems that adhere to weight limits and prioritize safety [62]. Deisenroth and Ohadi (2019) emphasized the need for innovative design topologies, materials, and manufacturing techniques to improve the thermal management of emerging synchronous machines, enabling higher efficiency and specific power [12]. Heerden et al. (2022) highlighted the challenges posed by increased onboard heat loads and the inefficiency of composites in transferring waste heat [67]. Lv et al. (2022) provided an overview of active and passive cooling methods, such as forced air cooling, cold plate cooling, heat pipes, and phase change materials [66]. Coutinho et al. (2023) identified liquid cooling loops integrated with ram air heat exchangers as a viable technology in thermal management [65]. Konovalov et al. (2023) highlighted the advantages of air and liquid cooling systems, noting that liquid cooling offers a high power-to-dimension ratio [64]. König et al. (2023) evaluated different cooling methods aimed at permanent magnet synchronous motors (PMSMs) and provided a review based on safety, weight, effectiveness, and integrability [63]. Ouyang et al. (2024) combined architecture design and power management optimization to address the challenges of integrated power and thermal management systems (IPTMS) in civil aviation [61].

5.1.8. Cross-Sectional Themes

The clusters and distribution patterns in the cross-sectional heatmap (Figure 5) reveal several nuanced insights:

- **Interdisciplinary Focus:** Keywords such as “motor optimization” and “propulsion” appear across multiple categories, highlighting their co-relevance in research thrusts. This suggests that advancements in one area will have implications for the other, necessitating a holistic approach to research and development.
- **Technological Priorities:** The prominence of specific keywords like “battery technology” and assorted topics relating to “fuel cells” highlights the independent focus on critical importance of energy storage solutions in this field.
- **Thermal and Battery Management:** Keywords related to thermal and battery management (“battery technology,” “battery management systems,” “heat exchangers,” “thermal management”) indicate their fundamental coupling in ensuring the safe and efficient operation of electrified aircraft.
- **Material Innovations:** The presence of keywords related to novel materials (“piezoelectric materials,” “electrical insulation”) across several categories highlights the ongoing search for advanced materials that can improve the performance, reliability, and sustainability of aircraft systems while reducing weight.

5.2. Bibliometric Analysis

The bibliometric analysis provides a comprehensive overview of the research landscape. The production metrics analysis complements the thematic findings by providing temporal and categorical context to the research trends in aircraft electrification. The subsections below discuss key insights and trends identified.

5.2.1. Increasing Research Output

The analysis of publications by year (Figure 8) reveals a significant increase in research output over the past decade, with a notable surge in publications from 2020 onward. This trend highlights the growing interest and investment in aircraft electrification technologies, driven by the global push

toward sustainable and environmentally friendly aviation solutions. The peak in 2022 and 2023 indicates that this field has been attracting substantial attention from the academic and industrial research communities.

5.2.2. Dominant Research Categories

The category Cross-section Analysis highlighted key focus areas, impactful research categories, and the contributions of various countries, offering insights into the factors driving research productivity and impact. The category of Energy Management emerged as the most prolific, with the highest number of both publications and citations (Figure 13). The surge in publications within that category in recent years indicates a strategic shift toward addressing energy challenges, aligning with global sustainability goals. This focus reflects the critical importance of developing efficient energy storage and management systems to support electric propulsion and hybrid aircraft. The high citation count in this category showcases its central role in addressing the technical challenges associated with energy density, battery reliability, and fuel cell technologies. The categories of Electric Machines and Multidisciplinary Design Analysis also feature prominently, indicating a strong emphasis on optimizing the performance of electric motors and integrating multidisciplinary approaches to aircraft design. The high citations per publication in the Multidisciplinary Design Analysis category suggest a holistic approach to addressing complex engineering problems is particularly impactful.

5.2.3. Key Contributors and Collaborative Networks

The analysis of publications and citations by top lead authors, institutions, and countries (Figure 9 and Figure 10) highlights the leading contributors to the field. The dominance of China and the U.S. in publication output correlates with global trends in technological advancements and research funding. This geographical concentration of research efforts reflects broader strategic priorities in these nations. The co-authorship network provided a visual and quantitative understanding of international collaborations, complementing the publication and citation metrics. The strong collaborative ties between the UK, China, and Germany highlight their pivotal roles in advancing research through international partnerships. The lack of direct links between the U.S. and China, despite their dominant roles, suggests potential areas for enhancing global collaboration.

The prominence of certain universities highlights their pivotal roles in fostering research and innovation. The results indicate that institutions with strong aerospace and engineering programs are key players in advancing aircraft electrification technologies. The distribution of publications across various journals highlights the interdisciplinary nature of research in this field.

Journals focusing on transportation electrification, aerospace sciences, and energy systems were primary publication venues, providing platforms for disseminating research across different sub-domains.

5.2.4. Emerging and Impactful Research Areas

The impact metrics provided a deeper understanding of the scholarly influence and recognition of research in aircraft electrification, complementing the production metrics. The high citation counts for top lead authors highlight the recognition of their work within the scholarly community. This complements the publication metrics by showing not only who is publishing but also whose work others widely cite and recognize.

The scatter plot of citations versus publications by category (Figure 13) provided insights into the relative impact of different research areas. The category of Multidisciplinary Design Analysis, with the highest citations per publication, stands out as a highly impactful area due to its comprehensive approach to integrating various technological and methodological advancements. The category of Energy Management, while having the highest number of publications, also shows a strong citations per publication ratio, reflecting its ongoing relevance and influence. Categories such as Electric Propulsion and Electrical Power Distribution, although having fewer publications, demonstrate substantial impact, indicating focused research efforts that yield significant

contributions to the field. Emerging areas like Novel Aviation Materials and Thermal Management, while less explored, showed potential for high impact, suggesting opportunities for further research and development.

The citation analysis by country highlighted the leading role of the U.S. and other key countries in producing high-impact research. This complements the earlier findings on publication outputs, showing how research from these countries is influencing the field globally based on recognition. The high citation counts in categories like Energy Management and Multidisciplinary Design Analysis emphasize the critical importance of these areas. This aligns with the keyword and term co-occurrence analyses, showing how these focus areas are not only frequently researched but also widely cited and impactful.

The analysis of citations per publication provided a nuanced understanding of research impact, complementing previous findings on publication outputs and collaboration networks. The increasing number of citations per publication over recent years indicates a rising impact of research outputs. This suggests that newer publications are addressing pertinent issues and contributing significantly to the field, enhancing the overall quality and influence of the research. These findings present a holistic understanding of the research landscape and its evolution over time.

5.3. Future Directions and Implications

The results of the thematic and bibliometric analysis indicate several key directions for future research in aircraft electrification. The emphasis on energy management and electric machines highlights the need for continued innovation in battery technologies, fuel cells, and electric motor design. The interdisciplinary nature of impactful research highlights the importance of integrating diverse engineering disciplines to address complex challenges. Enhancing international collaboration, particularly between leading countries like the U.S. and China, could further accelerate advancements in this field. Additionally, emerging areas such as novel materials and thermal management offer promising avenues for future exploration, with potential to significantly enhance the performance and reliability of electric aircraft systems. These findings can inform strategic decisions for researchers, funding agencies, and policymakers, guiding efforts to advance sustainable and efficient aviation technologies.

5.4. Limitations

The bibliometric analysis provides valuable insights into the research dynamics of aircraft electrification, highlighting key trends, influential contributors, and emerging areas. However, this study acknowledges several limitations. First, the bibliometric analysis relies on the accuracy and comprehensiveness of the databases used (Web of Science and IEEE Xplore). Any omissions or errors in these databases could slightly affect the findings. Second, the analysis primarily focuses on publications in English, potentially overlooking significant contributions published in other languages. Finally, while the study identifies key trends and contributors, it does not delve into the contextual factors driving these trends, such as funding policies, institutional support, and geopolitical considerations. Addressing these limitations in future research could provide a more comprehensive understanding of the field.

6. Conclusions

The thematic and bibliometric analysis conducted in this study offers a comprehensive and nuanced understanding of the current research landscape in aircraft electrification. By systematically examining publication trends, citation metrics, and keyword distributions, this analysis identifies key research themes, influential contributors, and emerging trends. Such insights are crucial for guiding future research efforts, fostering international collaborations, and informing policy decisions aimed at advancing sustainable aviation technologies.

The analysis reveals a significant increase in research output over the past decade, particularly in the areas of energy management and multidisciplinary design analysis. This growth highlights the

rising interest and investment in sustainable aviation technologies, driven by the global imperative to reduce emissions and improve energy efficiency. The prominence of keywords related to fuel cells, power density, and hybrid propulsion indicates a strong focus on developing efficient energy storage and management systems, optimizing electric machines, and integrating multidisciplinary approaches to aircraft design.

The distribution of authors per paper indicates a balanced collaborative effort, with most research projects involving small- to medium-sized teams. This collaborative approach is essential for addressing the complex challenges of aircraft electrification, requiring expertise from various domains, including electrical engineering, materials science, and thermodynamics. Collaborative research efforts are evident from the co-authorship networks, with countries like the U.S., China, and the UK leading in both publication output and citation impact. The analysis highlights the importance of international partnerships and interdisciplinary collaboration in advancing the field of aircraft electrification. However, the lack of direct links between major contributors such as the U.S. and China suggests potential areas for enhancing global cooperation.

To researchers, this study highlights the importance of interdisciplinary approaches and the need to address identified gaps, particularly in energy storage, electric propulsion, and thermal management. Policymakers should consider the findings of this analysis when formulating policies and funding strategies. Supporting research in the highlighted key areas and facilitating international partnerships can accelerate the development and adoption of electric aircraft technologies. Policies that incentivize innovation and address regulatory challenges will be vital in overcoming the current technological barriers. For industry stakeholders, the insights from this study highlight the potential for technological advancements and market opportunities in aircraft electrification. Investing in research and development, fostering partnerships with academic institutions, and participating in collaborative networks can drive progress and position industry players at the forefront of this transformative field. Overall, the thematic and bibliometric analysis not only maps the current state of research but also provides strategic direction for future efforts, ensuring that the aviation industry moves toward a more sustainable and efficient future.

Funding: This research received funding from the United States Department of Transportation, Center for Transformative Infrastructure Preservation and Sustainability (CTIPS), Funding Number 69A3552348308.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The author declares no conflicts of interest.

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