International Journal of Science & Advanced Technology
ISSN: 3083-9335

Bibliometric Analysis of Renewable Energy Technologies Using VOSviewer: Mapping Innovations and Applications

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Abstract
This study analyzes the interrelationships between critical topics in technology development using VOSviewer bibliometric visualization. Three main clusters were found: battery and energy storage technologies, catalysis and chemical reactions, and information and communication technologies. The first cluster highlights battery, energy density, and high energy density, indicating a strong focus on energy storage innovation. The second cluster includes catalyst and oxygen evolution reactions, emphasizing the importance of catalysis in hydrogen-based energy conversion. The third cluster is related to IoT, networks, and data, highlighting the role of innovative grid technologies and data management in digital transformation. These results demonstrate the synergy between renewable energy development, technological efficiency, and digital integration, key directions of modern technology research. This study provides important insights to support sustainable innovation in energy and information technologies.

Article Info
Received: 03 December 2024
Revised: 25 December 2024
Accepted: 15 January 2025
Available online: 05 February 2025

Keywords
Battery
Catalysis
IoT
Renewable Energy
VoSviewer
Digital Transformation

1. Introduction
The development of modern technology faces increasingly complex global challenges, especially in terms of the need for sustainable and efficient energy. The limitations of fossil energy resources and the environmental impacts they cause have encouraged various parties to seek renewable energy solutions and better energy storage technology innovations. On the other hand, rapid digital transformation, including adopting Internet of Things (IoT) technology and intelligent grids, introduces new data management and privacy challenges (Abir, Anwar, Choi, & Kayes, 2021; Bahagia, Nizar, Yasin, Rosdi, & Faisal, 2025; Esenogho, Djouani, & Kurien, 2022; Goudarzi, Ghayoor, Waseem, Fahad, & Traore, 2022). This study attempts to map and analyze the interrelationships between critical topics in developing these technologies using bibliometric visualization methods. One of the main focuses in research related to energy technology is the development of batteries and energy storage technology (Bulut & Özcan, 2024; Erdiwansyah et al., 2022; Zarate-Perez, Rosales-Asensio, González-Martínez, de Simón-Martín, & Colmenar-Santos, 2022; Zhao, Andersen, Træholt, & Hashemi, 2023). Batteries with high energy density support the energy needs of electronic devices, electric vehicles, and renewable energy systems. Along with the increasing demand for cleaner

and more efficient energy solutions, battery technology continues to experience significant innovation, especially in increasing capacity and energy efficiency (Chowdhury et al., 2018; Erdiwansyah, Mamat, Sani, & Sudhakar, 2019; Ong, Bhadbhade, Olsen, & Wellig, 2023). Therefore, this study finds that battery and energy density are key topics often discussed in energy technology development.

In addition, research in catalysis and chemical reactions also plays an important role, especially in hydrogen-based energy conversion (Kamran & Turzyński, 2024; Rolo, Costa, & Brito, 2023; Yilmaz et al., 2024; Yu et al., 2023). Hydrogen is considered one of the most promising renewable energy sources due to its low carbon emission potential. Innovations in catalysis technology, such as oxygen evolution reactions and oxygen reduction reactions, play an essential role in increasing the efficiency of this energy conversion (Ding, Liu, Chu, Wu, & Xie, 2021; Luo et al., 2021; Wen, Jiao, Xia, & Chen, 2023). The discovery of more effective and efficient catalysts is a significant focus in supporting the development of more reliable and affordable hydrogen energy technology. Beyond the energy aspect, information and communication technology development, especially IoT, is also a significant concern in the ongoing digital transformation (Li, 2024; Maroufkhani, Desouza, Perrons, & Iranmanesh, 2022; Massari, Nacchiero, & Giannoccaro, 2023; Yana, Mufti, Hasiany, Viena, & Mahyudin, 2025). With its ability to connect various devices through a network, IoT has significantly changed multiple sectors, including industry, health, and transportation. However, along with the increasing use of IoT, new challenges have also emerged related to data management and privacy (Gani et al., 2025; Rao & Deebak, 2023; Xia, Semirumi, & Rezaei, 2023; Yan, Li, Iliyasu, Salama, & Hirota, 2023). This study shows that network, data, and privacy often appear as interrelated topics, reflecting the importance of network technology and data management in the IoT ecosystem.

Furthermore, adopting IoT and innovative grid technologies improves operational efficiency and opens opportunities for broader integration with renewable energy technologies. Effective extensive data management and strong network security are essential foundations for ensuring the success of IoT implementation, especially in the context of energy infrastructure. Therefore, developing solutions combining energy and information technologies is central to creating a more sustainable future. In a broader context, this study shows that innovations in energy and information technologies are complementary and have the potential to generate significant synergies. Using bibliometric visualization tools, such as VOSviewer, provides in-depth insights into how these different research fields develop in parallel and interconnected ways. These results underscore the importance of a cross-disciplinary approach to drive sustainable innovation in the increasingly critical digital and renewable energy era.

2. Methodology

This study used a bibliometric approach to analyze the relationship between critical topics in technology development. This method identifies and visualizes the relationship network between terms frequently appearing in scientific literature on energy technology, catalysis, and the Internet of Things (IoT). The primary tool used in this analysis is the VOSviewer software, which can map and display the relationship network between terms based on bibliometric data.

Data Collection

The data used in this study were obtained from relevant scientific publication databases, such as journals covering energy technology, catalysis, and information technology. Data sources include publications from various disciplines, including chemistry, physics, engineering, and information technology. Key terms related to battery, energy density, catalyst, hydrogen, IoT, network, and data were used as the primary keywords in the data collection process. Articles published over the past few years were selected to ensure the analysis results cover the latest research trends.

Bibliometric Analysis
Bibliometric analysis was performed using VOSviewer after collecting publication data. This software allows for mapping relationships between terms based on co-occurrence or the frequency of occurrences in the same publication. This process produces a visualisation in the form of a network of nodes showing interrelated terms, with the node's size reflecting the frequency of occurrence of the term and the thickness of the connecting lines, depicting the strength of the relationship between terms.

Clustering and Network Interpretation
The results from VOSviewer were then grouped into clusters based on the relationships between terms. Each cluster represents a research field or topic closely related to each other. The researchers then analyzed each cluster to understand the main trends within each group. The clusters that emerged from this analysis included battery technology, catalysis and hydrogen reactions, and IoT technology and data management. Visualization interpretation was also performed by taking into account temporal changes in the relatedness of terms, which allowed for the identification of current research trends.

Temporal Analysis
In addition to analyzing the overall relationship between terms, the study used temporal analysis to see how research topics evolved. VOSviewer allows visualization based on specific periods, where the color of each node is represented when the term became the focus of research. With this analysis, researchers can see when topics such as battery technology and IoT began to increase in popularity, providing insight into the chronological development of each research field.

Validation of Results
The results were validated by comparing the findings of the bibliometric analysis with relevant secondary literature. The researcher reviewed various publications and reports related to the development of energy, catalysis, and IoT technologies to ensure that the trends and patterns found in the bibliometric analysis aligned with the existing literature findings. This aims to ensure that the results of this study are reliable and relevant in the context of broader technological development.

3. Result & Discussion

Table 1, taken from the document, displays various categories related to a particular theme, where each category is associated with several parameters, including clusters, links, total link strength, and occurrences. Analysis of this table can provide insight into the importance of each category in the context discussed. The clustered column divides categories into several main groups that indicate thematic relationships between more significant concepts. For example, the categories battery and electrolyte are in cluster 3, suggesting that these categories may be closely related to each other in the energy or battery technology discussion. In addition, activity and catalyst are in cluster 1, indicating a close relationship in catalysis or chemical reaction activity. The links column shows the number of relationships each category has with other categories. For example, a battery has 69 links, which means it has many connections with different concepts. This suggests that batteries are a central component in a broader discussion, which could involve energy storage technologies or innovations in energy technologies. Similarly, the catalyst category has 60 links, indicating that catalysts play a crucial role in the interactions between concepts.

Table 1
Parameters, including clusters, links, total link strength, and occurrences

Categories	Cluster	Links	Total link strength	Occurrences
Active site	1	41	146	20
Activity	1	77	366	70
Algorithm	2	39	119	35
Anode	3	48	187	38
Artificial intelligence	2	45	153	29
Battery	3	69	445	126
Blockchain	2	27	61	14
Carbon emission	4	37	70	22
Case study	2	25	48	11
Catalysis	1	44	115	19
Catalyst	1	60	389	67
Cathode	3	54	203	36
China	4	25	35	21
Climate change	4	36	74	23
Cloud	2	25	90	13
Co2 emission	4	35	61	17
Communication	2	38	271	59
Communication technology	2	28	99	23
Composite	1	38	82	23
Country	4	40	82	36
Current challenge	1	28	42	10
Current density	1	33	96	16
Data	2	57	265	68
Deployment	2	57	170	31
Durability	1	48	106	17
Electrocatalysis	1	39	144	21
Electrocatalyst	1	47	303	45
Electrochemical performance	3	33	99	21
Electrode material	3	24	71	17
Electrolyte	3	58	248	51
Energy conversion	1	39	122	30
Energy density	3	44	189	40
Energy efficiency	2	49	197	51
Energy storage technology	3	40	126	34
Energy technology	1	44	92	24
Evidence	4	15	32	22
Fuel	4	59	213	53
Fuel cell	1	46	147	30
Fundamental understanding	3	31	48	11
Global warming	4	24	46	10
Her	1	38	176	19
High Capacity	3	35	69	11
High energy density	3	28	91	19
Hydrogen	4	57	232	45
Hydrogen evolution reaction	1	41	220	28

Categories	**Cluster**	**Links**	**Total link strength**	**Occurrences**
Hydrogen production	4	37	85	18
Infrastructure	2	44	133	29
Internet	2	42	359	61
IoT	2	38	244	37
IoT device	2	28	83	11
Lib	3	21	90	15
Libs	3	21	82	14
Lithium	3	20	55	13
Lithium-ion battery	3	27	77	17
Lithiumion battery	3	24	86	18
Ma cm2	1	29	91	12
Machine	2	24	60	15
Management	2	63	239	60
Mof	1	19	34	10
Natural gas	4	26	48	12
Network	2	54	401	91
Oer	1	42	216	25
Orr	1	30	115	13
Oxygen evolution reaction	1	44	259	32
Oxygen reduction reaction	1	34	146	19
Photocatalysis	1	23	60	17
Photocatalyst	1	27	65	20
Policy	4	46	103	31
Practical application	3	52	134	28
Precursor	1	33	52	12
Privacy	2	24	86	11
Promising solution	2	30	42	10
Rational design	1	36	72	16
Reaction	1	57	332	70
Reliability	2	45	122	26
Renewable energy technology	1	31	52	17
Safety	3	52	187	36
Security	2	41	229	41
Selectivity	1	32	111	28
Service	2	33	187	35
Set	2	36	75	15
Supercapacitor	3	29	64	20
Survey	2	35	157	28
Teng	4	16	45	15
Thing	2	42	336	55
Triboelectric nanogenerator	4	16	45	19
User	2	40	113	23
Vision	2	40	99	16
Water electrolysis	1	34	101	16
Water splitting	1	40	192	31

The total link strength column measures the strength of the relationships between categories. For example, communication has a total link strength of 271, indicating significant connection strength with other categories, reflecting the critical role of communication technology in the context discussed. Similarly, the electrolyte has a total link strength of 248, indicating its strong relevance to other aspects of this table. The final column, occurrences, records the frequency with which each category appears in the data analysis. A category such as battery appears 126 times, indicating that batteries are a significant focus. This suggests that batteries and energy storage technologies are essential to the development or research discussed in this table. Other categories, such as activity and catalyst, also show high frequencies, indicating the importance of chemical activity and the use of catalysts in the context discussed.

Fig. 1 above shows visualization using VOSviewer, which shows a network's relationship between various concepts or categories. Each point or node in the image represents a term or category, with the node's size reflecting the term's frequency or importance. The relationship between nodes is depicted by lines, where the thickness of the line indicates the strength of the relationship between terms. This visualization is beneficial for understanding clusters and the relationship of concepts involved in a particular research or technology field. In the image, we can see several clusters distinguished by different colors. For example, the blue cluster at the top of the image focuses on terms related to battery technology, such as battery, energy density, and high energy density. The dense connections between nodes indicate that these terms are closely related to broader energy storage or battery technology discussion. The large size of the battery and energy density nodes indicates the high frequency of occurrence of these terms in the dataset used.

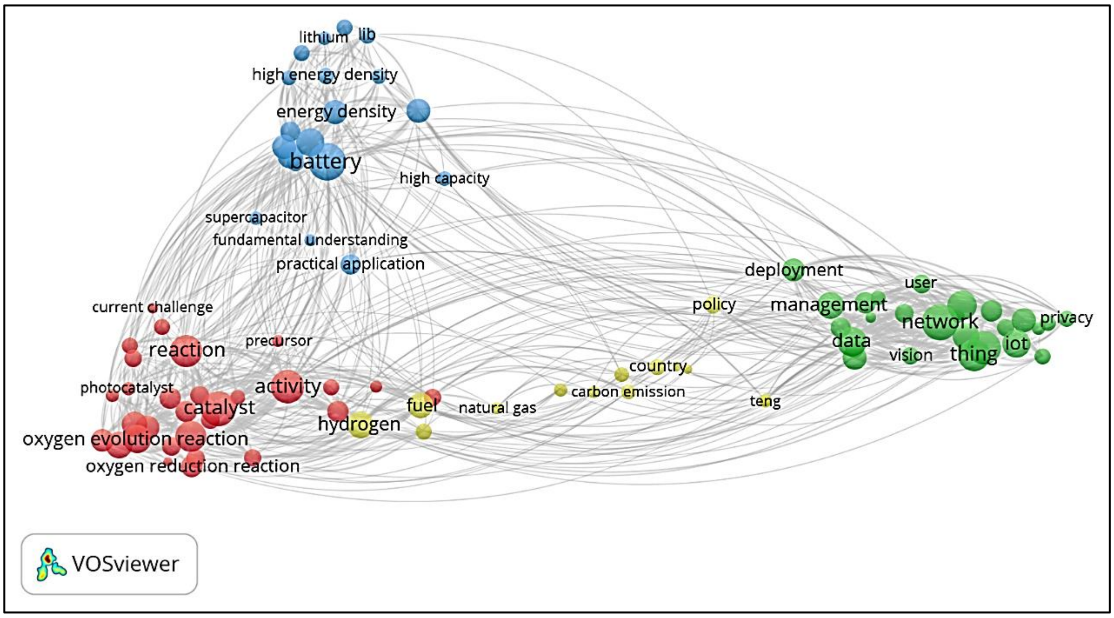

Fig.1. Visualizing Term Relationships Using VOSviewer

On the other hand, the red cluster on the left side of the image includes terms such as reaction, catalyst, and oxygen evolution reaction. This cluster may be related to research or discussions that focus more on catalysis and chemical reactions, especially in the context of hydrogen energy or chemical energy conversion. The terms activity and response appear to have relatively large nodes, indicating that they are essential topics in this discussion. The many connecting lines suggest that these concepts connect to other categories. The green cluster on the right side of the image includes terms more related to information and communication technologies, such as network, data, IoT, and privacy. The strong connections between its nodes indicate a close relationship between networking technologies and the Internet of Things (IoT), which may include data management, security, and privacy in IoT-based systems. The terms management and deployment have large nodes, which may indicate that data management and network system implementation are the main focus in this context. Finally, a smaller yellow cluster includes terms such as carbon emission, country, and policy. This may indicate a focus on energy policy and carbon emissions, reflecting concerns about environmental and regulatory aspects in the context of energy technologies. The relationship between carbon emissions and natural gas may reflect discussions about energy sources and their impacts on the environment, including how policy can play a role in mitigating climate change.

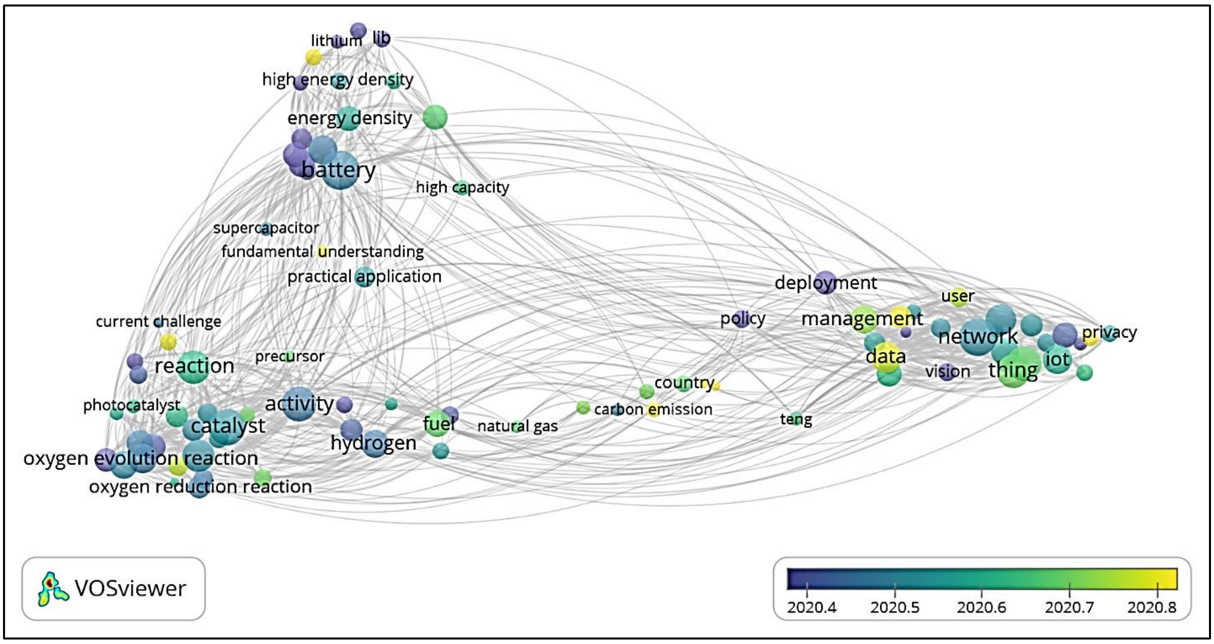

Fig. 2. depicts the relationship between the terms over time

The color scale at the bottom of **Fig. 2** depicts the relationship between the terms over time in VOSviewer. The color of each node (dot) reflected when the term became a significant topic, with a color spectrum from blue (2020.4) to yellow (2020.8), indicating when the term appeared in research or publications. This visualization illustrates the evolution of attention or focus on a research topic over time. In the blue cluster at the top, we see terms such as the battery, energy density, and high energy density, which are blue to light green. These terms emerged and became relevant in discussions or research in early 2020. This category is closely related to energy storage technology, especially related to high energy density batteries. This evolution of terms may indicate an increased focus on battery technology development in the first half of 2020. On the lower left side, the red cluster in the previous figure, which includes terms such as catalyst, reaction, and oxygen evolution reaction, also shows colors that tend to be bluer and greener. This indicates that discussions related to catalysis and chemical reactions began to develop around the same time as discussions about battery technology. Terms such as hydrogen and oxygen reduction reactions are also closely related to this cluster, indicating that the topic of hydrogen and oxidation reactions began to attract research attention relatively early in 2020.

In the green cluster on the right side of the figure, we see terms such as network, IoT, and privacy, which are green to yellow. This indicates that these terms became more relevant or top of mind in the second half of 2020. This cluster is most likely related to developing Internet of Things (IoT) technologies and the networking, data security, and privacy challenges. The development of these topics shows that information and communication technologies, especially those related to data management and networking, have experienced increased attention in the more recent period. Finally, the time scale shown in **Fig. 2** provides a deeper insight into how different research topics emerged and evolved throughout 2020. This visualization is beneficial for understanding how different fields of science or technology, such as energy, catalysis, and information technology, developed simultaneously but with slightly different time focuses.

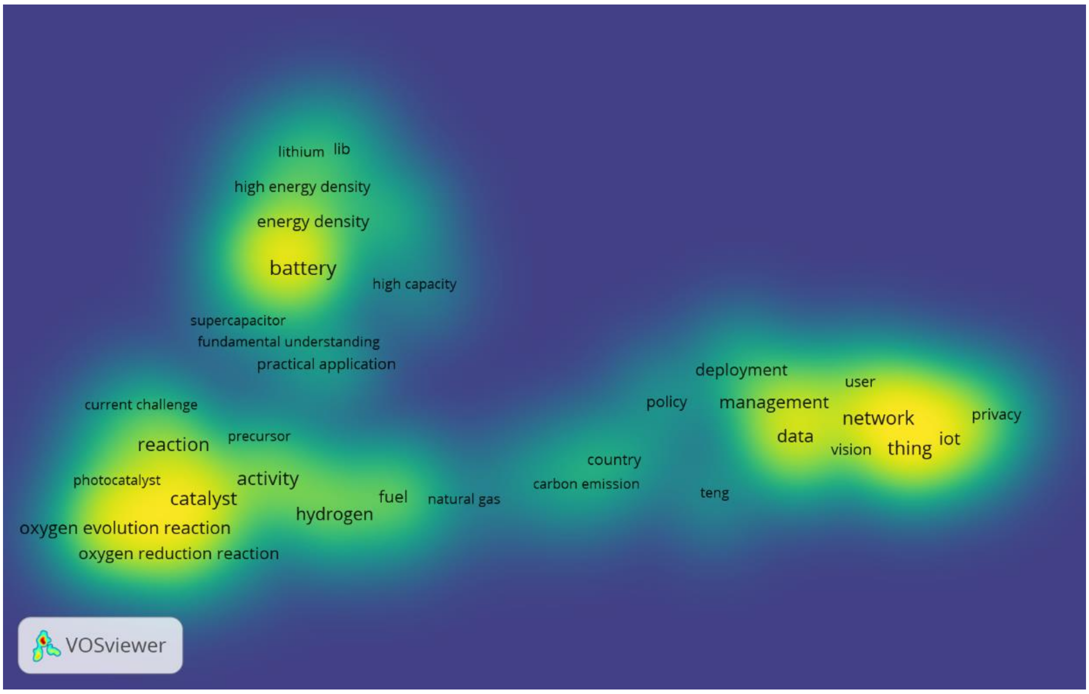

Fig. 3. VOSviewer visualization in heatmap format

Fig. 3 above is a VOSviewer visualization in heatmap format, showing the intensity of the relationship between various terms. Brighter colors (yellow) indicate areas with higher density or frequency of relationships or interactions between concepts, while darker colors (blue) indicate areas with lower intensity. This visualization provides a clear picture of the most frequently occurring and interconnected terms in a particular research field. In the upper left part of the figure, the brightest area is seen, focusing on the terms on battery, energy density, and high energy density. This shows that terms related to battery technology, especially those related to energy storage, have a powerful relationship and are often the focus of research. This information is consistent with the importance of battery technology development in the context of more efficient and high-capacity energy storage. The close relationship between these terms also indicates intensive discussion regarding innovation in the battery field.

At the bottom left, another bright cluster is the reaction, catalyst, and oxygen evolution reaction. This shows that topics related to chemical reactions and catalysis, especially in the context of oxygen evolution and reduction reactions, often appear together in discussions or research. The bright colors around these terms indicate that these concepts are closely related and may be a significant focus in research on hydrogen, energy conversion, or other catalytic processes. On the right side of the figure, another cluster includes terms such as network, data, IoT, and management. This area is also marked with a relatively bright yellow, indicating that information and communication technologies, especially those related to networks and the Internet of Things (IoT), are active research areas. This suggests that IoT implementation and data management are significant in various technology research, perhaps related to developing intelligent grid systems or applications involving extensive data management and security.

In conclusion, **Fig. 3** shows three main clusters with high interaction intensity: battery technology and energy storage, catalysis and chemical reactions, and networks and IoT. Bright colors in these areas highlight topics of central interest in research discussions. In contrast, darker areas indicate that other terms, although related, have lower frequency or intensity in this relationship network.

4. Conclusion

The results and discussion above conclude that three main clusters dominate research and technology development based on bibliometric analysis using VOSviewer. The first and most prominent cluster is battery and energy storage technology, primarily related to battery, energy density, and high energy density. The emphasis on these terms indicates that developing high-capacity and efficient batteries is a significant focus, reflecting the global need for better energy storage solutions to face future energy challenges. The second cluster relates to chemical reactions and catalysis, which includes terms such as reaction, catalyst, and oxygen evolution reaction. This shows that innovation in the field of catalysis and electrochemical reactions, especially in the context of hydrogen-based energy conversion, is also a very active area of research. The emphasis on these terms underlines the importance of hydrogen as a renewable energy source and its role in a cleaner and more efficient energy future. The third cluster relates to information and communication technologies, especially networks, IoT, and data, which shows great attention to the development of smart grids and the Internet of Things (IoT). The increasing use of IoT and the importance of extensive data management and privacy are highlighted in the context of modern technological developments, especially in the industrial and digital infrastructure sectors. Overall, this analysis shows that research on batteries, catalysis, and information technology is closely interrelated, demonstrating synergies between the development of energy storage technology, energy conversion innovation, and digital technology integration. These three clusters indicate the future research focusing on energy sustainability, technological efficiency, and digital transformation.

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