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

# Exploration of predictive models in optimising renewable energy integration in grid systems

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## Abstract
This study analyzes key trends in energy research by mapping keyword associations using network visualization and bibliometric data. The results show a strong relationship between technical aspects such as control systems and energy optimization with policy and sustainability. New technologies like blockchain and prosumers are increasingly integrated into energy systems to improve transparency and efficiency. In addition, grid stability and optimization of power system parameters are becoming significant in ensuring reliable and efficient system performance. Keywords such as sustainability, carbon neutrality, and renewable energy also show increasing attention to the transition to renewable sources. This study uses algorithms and artificial intelligence to emphasise the importance of technological innovation in energy system optimization and management. The conclusions of this analysis emphasize the need for a holistic approach that combines technical innovation, supportive energy policies, and a focus on sustainability to achieve a clean and efficient energy transition.

**Article Info**
Received: 13 November 2024
Revised: 25 December 2024
Accepted: 25 January 2025
Available online: 05 February 2025

**Keywords**
Artificial intelligence
Sustainability
Blockchain
Energy System Optimization
Energy policy

## 1. Introduction
In recent decades, the energy sector has undergone significant changes driven by the development of new technologies and increasing awareness of the importance of sustainability. Transitioning to renewable and low-carbon energy sources is now a top priority worldwide (Dahlan, Ahmad, Ilham, & Yusoff, 2022; Erdiwansyah, Gani, MH, Mamat, & Sarjono, 2022; Erdiwansyah, Mamat, Sani, & Sudhakar, 2019; Kabeyi & Olanrewaju, 2022; L. Wang, Wei, & Brown, 2017). Global pressure to reduce greenhouse gas emissions and increase energy efficiency has driven more intensive research, including power system optimization, renewable energy integration, and technological innovations that support sustainability (Javid & Khan, 2020; Nadel & Ungar, 2019; Q.-J. Wang, Feng, Wang, & Chang, 2022). Therefore, research that examines trends and linkages in the energy sector is essential to provide a comprehensive picture of current developments and future research directions. Energy-related studies focus on technical aspects such as grid stability and system control, including policy and sustainability dimensions (Annaswamy & Amin, 2013; Massoud Amin, 2011; Sanchez-Hidalgo & Cano, 2018). The importance of integrating advanced technologies and supportive energy policies is becoming increasingly evident in pursuing a cleaner and more efficient energy transition (R.

M. Elavarasan, Nadarajah, & Shafiullah, 2024; Ghoniem, 2011; Obada et al., 2024). This study aims to map the interrelationships between crucial keywords in the energy and technology literature and to analyze trends and patterns in developing these topics.

One of the essential aspects of this study is the role of new technologies, such as blockchain and prosumers, in changing the dynamics of the energy sector (Andoni et al., 2019; Lavrijssen & Carrillo Parra, 2017; Mika & Goudz, 2021). These technologies allow consumers to use energy and act as energy producers, introducing new models in energy distribution and trading (Di Silvestre, Ippolito, Sanseverino, Sciumè, & Vasile, 2021; Erdiwansyah et al., 2021; Giulietti, Le Coq, Willems, & Anaya, 2019). Blockchain, for example, has become essential in increasing transparency and security in energy transactions, especially in the context of renewable and distributed energy (Gawusu et al., 2024; Teufel, Sentic, & Barmet, 2019; Zhao et al., 2024). On the other hand, power system stability and optimization remain a primary focus in energy research. Algorithms and artificial intelligence have played a significant role in automation and more efficient decision-making in power system management (Ahmad et al., 2021; Heymann, Quest, Lopez Garcia, Ballif, & Galus, 2024; Wollenberg & Sakaguchi, 1987). Topics such as system control, grid stability, and technical parameter optimization frequently appear in energy-related literature. This shows that technical aspects remain the backbone of energy innovation, aiming to ensure system reliability and improve operational efficiency.

Sustainability and energy policy aspects have also shown increasing attention in recent years (Engström, Nilsson, & Finnveden, 2008; Lior, 2010; Özbek & Özbek, 2024). Concepts such as sustainability, carbon neutrality, and renewable energy development increasingly dominate research (Al-Shetwi, 2022; Joseph Sekhar, Samuel, Glivin, Le, & Mathimani, 2024; Yuan, Su, Umar, Shao, & LobonŢ, 2022; Zhang, Hu, Mu, & Kong, 2022). Sustainability is a significant focus as countries race worldwide to reduce their dependence on fossil fuels and shift to renewable energy. In addition, supportive energy policies also play a crucial role in ensuring the success of this transition. Given the interconnectedness of technological innovation, system optimization, and supportive policies, a holistic approach to energy research becomes highly relevant. This research contributes by mapping and analyzing trends in energy research and showing how various technical and non-technical factors interact to pursue a more sustainable, efficient, and environmentally friendly energy system.

Although previous studies have discussed the integration of renewable energy and technology optimization in microgrid systems, most of them still focus on technical aspects without comprehensively considering economic and sustainability factors in on-grid network scenarios. In addition, there are still limitations in studies related to the use of HOMER Pro software for microgrid optimization under specific conditions that consider energy price variability and local incentive policies. Therefore, this study fills the gap by evaluating HOMER Pro-based optimization strategies that consider not only technical aspects but also economic and environmental factors in the context of an integrated power grid.

The novelty of this research lies in the holistic approach used to map the interrelationships between technical, policy, and sustainability aspects in energy research, using bibliometric analysis and network visualization. Rather than focusing on one dimension, this research explores the complex relationship between technological innovations such as artificial intelligence and blockchain, the stability of the electric power system, and energy policies that support the transition to renewable energy sources. In addition, this research identifies new trends in integrating prosumer and blockchain technologies that were rarely discussed in depth in previous research, showing how these technologies are changing the dynamics of energy production and consumption. Another novelty is bibliometric analysis that displays the evolutionary patterns of critical topics in energy research, providing more comprehensive insights into future research directions.

## 2. Methodology

This study uses a bibliometric approach to analyze trends and keyword relationships in energy-related scientific literature. This approach aims to identify critical patterns in energy research, including technological innovation, policy, and sustainability issues. The analysis is conducted in several main stages, including data collection, processing, and network visualization. Data were taken from indexed scientific literature databases, such as Scopus or Web of Science, which include the latest research articles published in recent years, especially in 2022. Keywords related to energy, technology, policy, and sustainability were used to filter relevant documents. Articles covering blockchain, artificial intelligence, control, grid, sustainability, and renewable energy were selected for further analysis. Once the data was collected, VOSviewer software was used to identify relationships between keywords through co-occurrence analysis. VOSviewer can construct bibliometric network maps that show how different terms are related in literature. Keywords that co-occur in research articles are counted and then grouped into clusters that describe a particular research focus.

The data processing results are then visualized as a network showing the relationship between the keywords analyzed. Keywords that appear more often together will have a stronger relationship, visualized through connecting lines with different thicknesses. Different colours in the clusters indicate the research's focus areas, such as those focusing on technology, control systems, energy policies, and sustainability. In addition to network visualization, bibliometric analysis was performed to measure each keyword's total link strength, occurrences, and averages per year. This data was processed to see how often specific topics are discussed in research and how these trends develop over time. Grouping keywords by clusters provides a clear picture of the interactions between crucial issues, such as the relationship between new technologies, energy policy, and technical and sustainability aspects. The visualization and bibliometric analysis results are interpreted to identify critical trends and patterns in energy research. Focus on emerging technologies such as blockchain and artificial intelligence, as well as other essential topics such as grid stability and policy, are analyzed to provide insights into future research directions.

In this study, bibliometric data were collected from the Scopus and Web of Science databases, which are two indexed databases with extensive coverage in the field of energy and technology. The search was conducted using a combination of keywords "renewable energy," "grid stability," "energy optimization," "blockchain," "prosumer," and "sustainability," with a filter of the 2015–2024-year range to ensure data recency. Inclusion criteria included journal articles and conference proceedings that directly discussed renewable energy technologies, energy policies, and innovations in the electricity grid system. Articles that were not in English, did not have full access, or were not relevant to the research focus were excluded. Prior to analysis, the obtained data were processed through duplication removal, reference format normalization, and technical term adjustment to ensure consistency. The analysis was conducted using VOSviewer software to identify relationships between keywords through co-occurrence analysis, which was then visualized in the form of a research network to reveal trend patterns and interrelationships of key themes in the field of renewable energy and its supporting technologies.

## 3. Result & Discussion

**Fig. 1** is a bibliometric network visualization, probably generated using VOSviewer software, showing the relationships between different terms or concepts from the scientific literature. This image is generated from the co-occurrence analysis of keywords in research documents related to a particular subject. The image is divided into three main clusters, each representing a close relationship between concepts in that domain. The green cluster seems to be related to concepts related to power systems, control, and grids, as seen from words such as power system, control, grid, and uncertainty. In this context, the green cluster reflects research on the technical aspects of power system management and optimization, including parameter calculations, optimization algorithms, and grid stability. These topics are often part of electrical engineering and energy research.

The red cluster seems to group terms related to energy policy, energy sector development, and policy implementation processes. Review, development, sector, and policy dominate this cluster, focusing on the policy side, energy resource management, and studies on energy sustainability. This shows that this cluster is more related to the social, economic, and political dimensions of energy development, including issues of sustainability and $CO_2$ emission reduction. The blue cluster at the top of the figure depicts aspects of new technologies and energy users, with keywords such as prosumer, blockchain, and communication. This suggests that topics in this cluster may focus on the role of digital technologies and user engagement in modern energy systems. Aspects such as the use of blockchain technology and prosumers (users who also become energy producers) are essential issues in research related to the digital transformation of energy systems. Overall, this visualization illustrates how the main topics in modern energy research are related. The interconnections between clusters indicated by the connecting lines show that, despite differences in research focus among the clusters, there are still significant connections between energy research's technical, policy, and technological innovation dimensions.

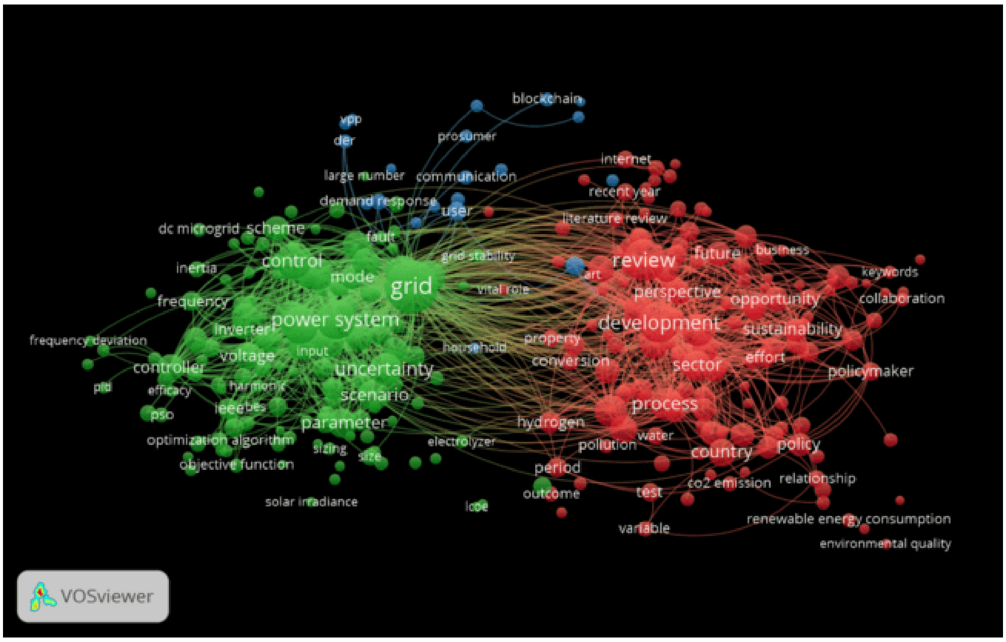


**Fig. 1**. Visualization of conceptual relationships from scientific literature

**Fig. 2** is a visualization generated from VOSviewer, with colours indicating the publication time trend of the analyzed topics. This image illustrates the relationship between keywords that frequently appear in scientific literature, and a colour scale from blue to yellow represents the period from the beginning of 2022 to the end of 2022. Thus, this visualization shows how specific topics evolved or became more prevalent in energy research during that period. The blue-green cluster on the left side of the figure indicates technical issues related to power systems, control, and parameters. The blue colour of this cluster suggests that research on these topics emerged in early 2022 or even earlier. Topics such as power systems, control, grid, and uncertainty are more established research areas. This indicates that the technical aspects of

power grid optimization, control, and stability have long been a primary focus of energy research.
The yellow cluster on the right side of the figure represents more recent research conducted in mid-to-late 2022. The dominant topics here include review, development, sustainability, and policy, indicating an increase in interest in energy policy, sustainability, and energy sector development topics in the last few months of 2022. This suggests that research related to policy implementation, sustainability, and efforts to transition energy towards greener sources has increased during this period. Numerous lines that connect these two clusters demonstrate how closely related the technical and policy aspects of energy research are. This linkage shows that although these two fields may be studied separately, there is a strong interaction between energy grid technologies and the policies that govern them. The lines connecting topics from the technical cluster to the policy cluster, such as grid stability with policy, reflect that grid stability is strongly influenced by the energy policies adopted in different countries. Overall, this visualization provides insight into the evolution of energy research trends in 2022. Technical topics dominated at the beginning of the year, while interest in energy and sustainability policies increased towards the end of the year. This reflects a shift in focus in energy research from technical optimization to policy implementation that supports a greener energy transition.

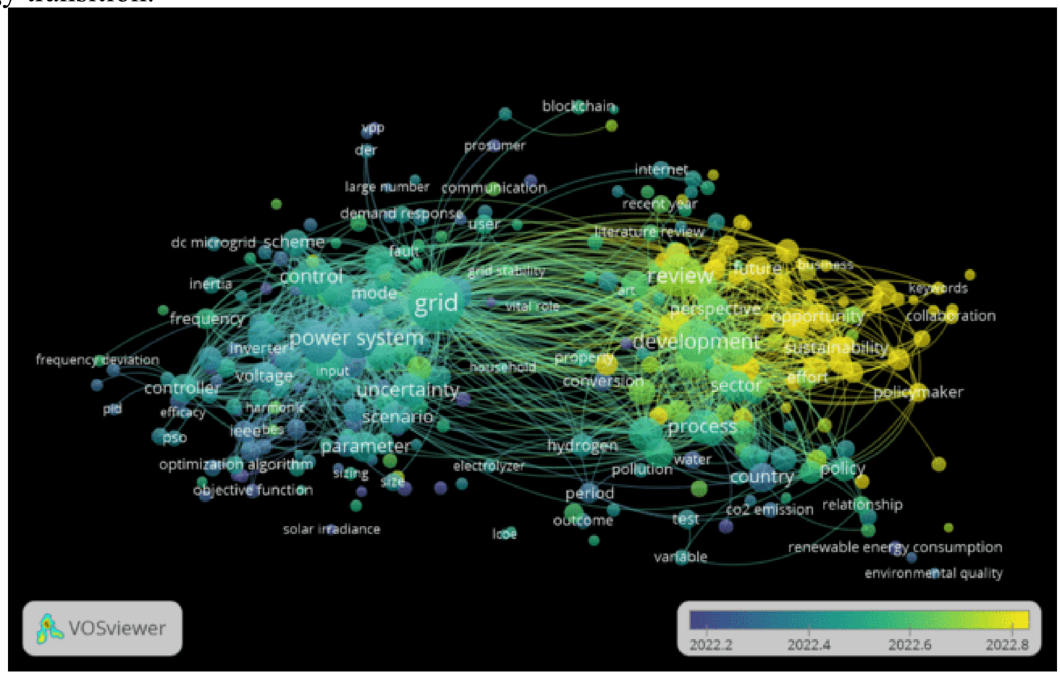


**Fig. 2**. Relationships between keywords that frequently appear together in scientific literature

**Fig. 3** is a visualization of the keyword network generated from VOSviewer, showing clusters of topics that frequently appear together in scientific literature. In this visualization, three main clusters are represented by green, red, and blue, representing groups of related research topics in the energy field. The dominant green cluster on the left side of the figure seems to focus on technical aspects related to the power system and grid. The keywords in this cluster include power system, control, uncertainty, parameter, and inverter. This cluster shows that energy research is often related to the development and optimization of the technical infrastructure of the power system, including control algorithms, grid parameters, and uncertainties in the system. This is a significant focus in energy technical research that aims to improve the efficiency and stability of the power system.

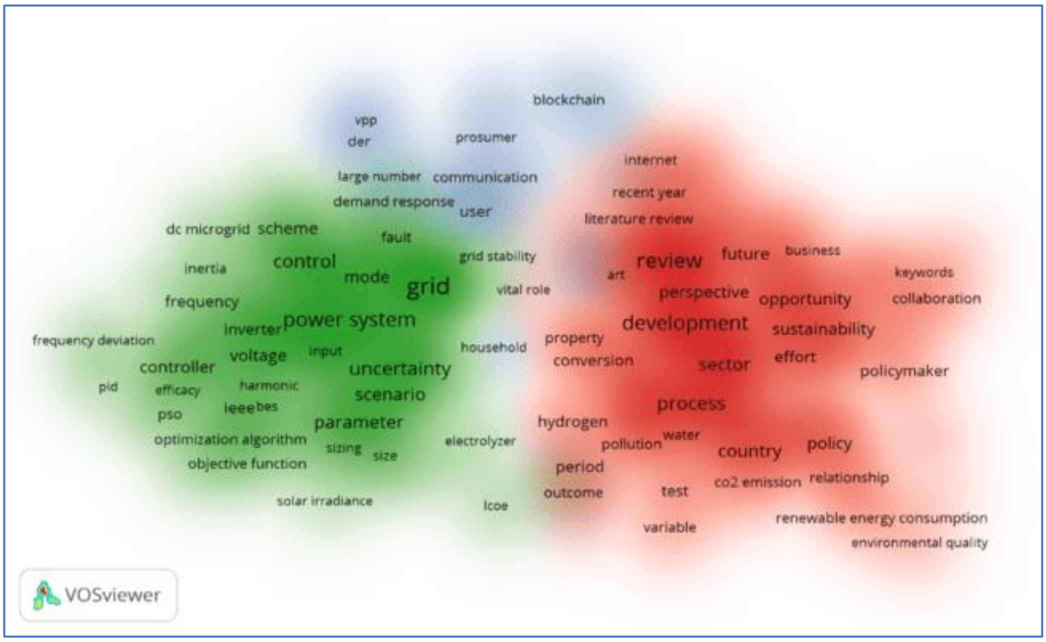


**Fig. 3**. Energy Research Keyword Co-occurrence Visualization

The red cluster on the right side of the figure is more oriented towards topics related to energy sector development and policy. Review, development, policy, and sustainability dominate here, focusing on policy aspects, sustainability, and energy development. These topics relate to non-technical aspects of the energy sector, such as how policies affect renewable energy development, carbon dioxide emissions, and relations between countries regarding energy policy. This indicates a growing interest in sustainability issues and the transition to cleaner and more environmentally friendly energy sources. The blue cluster, although smaller, focuses on concepts such as blockchain, prosumer, and communication, reflecting new technological trends in energy systems. Keywords such as blockchain and prosumer indicate that research in this area includes technological innovations enabling users to become energy producers and using digital technologies to support energy management. This shows that digital innovation and the active role of consumers in energy production and distribution are becoming increasingly important in energy research. Overall, this visualization provides an overview of the interconnectedness of technical research and energy policy. The green and red clusters indicate that energy research involves the interaction between energy system technologies and the policies that govern them. The blue cluster, although smaller, reflects the increasing role of new technologies in energy management. The connecting lines between the clusters show that this research are not separate but interconnected, creating a comprehensive whole in energy research encompassing technical, policy, and technological innovation aspects.

**Table 1** in your document displays the various keyword categories classified into several clusters. The data includes the number of links, total link strength, keyword occurrences in research, and averages per year. The categories in this table represent essential terms and concepts widely used in energy and technology research. For example, the keyword Algorithm in Cluster 2 has 280 links with a total link strength of 1814, indicating a high relevance to other keywords in the study. It occurs 140 times, with an average occurrence in 2022 of 2022.52. This demonstrates that algorithms play a significant role in energy research, especially in developing and optimising complex systems.

The keyword Artificial Intelligence from Cluster 1 shows a reasonably high trend, with 194 links and total link strength of 565. It appears 39 times in the study. With an average appearance year of 2022.87, artificial intelligence is becoming widely adopted in energy research, especially in automation and more efficient decision-making. Other terms, such as Control in

Cluster 2, exhibit very high occurrence, with 137 occurrences in the study, 277 links, and a total link strength of 1763. This shows the importance of system control in the energy context, especially in regulating power grid stability and operational optimization.
To strengthen the bibliometric analysis, this study also identified quantitative trends in the occurrence of key keywords and relationships between concepts in renewable energy research. The analysis results show that the keyword "grid" has 294 occurrences with a total link strength of 3709, confirming the dominance of the topic of power grid system optimization in energy research. In addition, the keywords "blockchain" and "prosumer", although relatively new, showed a significant increase with a total link strength of 285 and 233, respectively, indicating a strong relationship with the trend of energy decentralization and peer-to-peer (P2P) energy trading models. This pattern is also seen in the keyword "policy" which has a total link strength of 762, reflecting the increasing role of policy in facilitating the adoption of renewable energy technologies. With this quantitative approach, this study not only describes the conceptual relationships between keywords but also shows the evolution of the dominance of research topics that increasingly emphasize the synergy between technological innovation and energy regulation.

**Table 1**. Keyword and Cluster Analysis in Energy Research

| Categories | Cluster | Links | Total link strength | Occurrences | Avg/Year |
|---|---|---|---|---|---|
| Accuracy | 2 | 196 | 450 | 43 | 2022.4651 |
| Adoption | 1 | 201 | 688 | 44 | 2022.9318 |
| Advance | 1 | 152 | 288 | 20 | 2022.85 |
| Advancement | 1 | 217 | 836 | 53 | 2022.8491 |
| Algorithm | 2 | 280 | 1814 | 140 | 2022.5214 |
| Alternative | 1 | 192 | 430 | 29 | 2022.6897 |
| Applicability | 2 | 98 | 142 | 12 | 2022.4167 |
| Art | 1 | 126 | 196 | 14 | 2022.5 |
| Artificial intelligence | 1 | 194 | 565 | 39 | 2022.8718 |
| Artificial neural network | 2 | 84 | 132 | 10 | 2022.4 |
| Assessment | 1 | 207 | 616 | 63 | 2022.4921 |
| Barrier | 1 | 162 | 316 | 22 | 2022.5455 |
| Basis | 3 | 123 | 195 | 14 | 2022.5714 |
| Biomass | 1 | 114 | 183 | 16 | 2022.4375 |
| Business | 1 | 131 | 237 | 14 | 2022.8571 |
| Carbon footprint | 1 | 149 | 306 | 23 | 2022.8261 |
| Carbon neutrality | 1 | 99 | 157 | 15 | 2022.4667 |
| Challenges | 1 | 156 | 372 | 28 | 2022.75 |
| China | 1 | 102 | 176 | 20 | 2022.5 |
| Climate change | 1 | 217 | 757 | 55 | 2022.7818 |
| $Co_2$ | 1 | 114 | 210 | 20 | 2022.2 |
| $Co_2$ emission | 1 | 142 | 291 | 25 | 2022.32 |
| Collaboration | 1 | 127 | 369 | 20 | 2023.6 |
| Comprehensive analysis | 1 | 107 | 143 | 10 | 2023.1 |
| Comprehensive overview | 1 | 105 | 159 | 11 | 2022.9091 |
| Comprehensive review | 1 | 218 | 812 | 56 | 2022.9286 |
| Construction | 1 | 102 | 139 | 13 | 2022.1538 |
| Conversion | 1 | 158 | 371 | 35 | 2022.2857 |

| Categories | Cluster | Links | Total link strength | Occurrences | Avg/Year |
|---|---|---|---|---|---|
| Country | 1 | 236 | 897 | 79 | 2022.3165 |
| Criterium | 1 | 169 | 341 | 25 | 2022.68 |
| Critical role | 1 | 106 | 197 | 10 | 2023.5 |
| Crucial role | 1 | 112 | 178 | 11 | 2023.0909 |
| Current state | 1 | 134 | 276 | 18 | 2022.8333 |
| Current status | 1 | 87 | 119 | 11 | 2022.4545 |
| Decade | 1 | 165 | 351 | 30 | 2022.5 |
| Decision maker | 1 | 103 | 150 | 11 | 2022.5455 |
| Detection | 1 | 154 | 322 | 25 | 2022.56 |
| Development | 1 | 296 | 2268 | 176 | 2022.5966 |
| Direction | 1 | 207 | 509 | 38 | 2022.5263 |
| Ecological footprint | 1 | 61 | 114 | 10 | 2022.7 |
| Economic growth | 1 | 114 | 278 | 22 | 2022.5909 |
| Economy | 1 | 212 | 795 | 63 | 2022.4444 |
| Effort | 1 | 216 | 705 | 47 | 2022.6596 |
| Emphasis | 1 | 135 | 286 | 17 | 2023.0588 |
| Energy consumption | 1 | 219 | 648 | 55 | 2022.5818 |
| Energy efficiency | 1 | 233 | 738 | 54 | 2022.6296 |
| Energy integration | 1 | 211 | 560 | 67 | 2022.6567 |
| Energy security | 1 | 125 | 244 | 13 | 2022.4615 |
| Energy storage technology | 1 | 143 | 264 | 18 | 2022.5556 |
| Energy transition | 1 | 156 | 292 | 29 | 2022.6207 |
| Environmental concern | 1 | 115 | 185 | 12 | 2022.75 |
| Environmental impact | 1 | 195 | 602 | 41 | 2022.9512 |
| Environmental Quality | 1 | 56 | 135 | 12 | 2022.3333 |
| Environmental sustainability | 1 | 101 | 220 | 20 | 2022.75 |
| Field | 1 | 253 | 973 | 68 | 2022.6618 |
| Focus | 1 | 213 | 626 | 40 | 2022.8 |
| Framework | 1 | 268 | 1288 | 97 | 2022.7629 |
| Fuel | 1 | 256 | 1058 | 78 | 2022.5385 |
| Further research | 1 | 109 | 193 | 12 | 2022.75 |
| Future | 1 | 238 | 949 | 60 | 2022.9 |
| Future development | 1 | 87 | 123 | 10 | 2022.6 |
| Future direction | 1 | 147 | 307 | 21 | 2022.8095 |
| Future research | 1 | 120 | 193 | 11 | 2022.6364 |
| Gap | 1 | 177 | 372 | 30 | 2022.4667 |
| Global warming | 1 | 99 | 148 | 13 | 2022.4615 |
| Government | 1 | 128 | 281 | 19 | 2022.7895 |
| Greenhouse gas emission | 1 | 189 | 526 | 36 | 2022.75 |
| Hydrogen | 1 | 190 | 553 | 49 | 2022.449 |
| Hydrogen production | 1 | 117 | 253 | 24 | 2022.75 |
| Identification | 1 | 145 | 236 | 15 | 2022.7333 |
| Implication | 1 | 186 | 520 | 34 | 2022.7059 |
| Importance | 1 | 225 | 819 | 49 | 2023.0612 |
| Industry | 1 | 236 | 959 | 69 | 2022.913 |
| Influence | 1 | 170 | 361 | 28 | 2022.6429 |

| Categories | Cluster | Links | Total link strength | Occurrences | Avg/Year |
|---|---|---|---|---|---|
| Innovation | 1 | 189 | 705 | 44 | 2022.8864 |
| Insight | 1 | 195 | 798 | 54 | 2023.0185 |
| Internet | 1 | 173 | 439 | 32 | 2022.4062 |
| Investment | 1 | 201 | 716 | 52 | 2022.5577 |
| IoT | 1 | 134 | 286 | 21 | 2022.5238 |
| Keywords | 1 | 131 | 410 | 18 | 2023.8333 |
| Literature review | 1 | 184 | 421 | 29 | 2022.5862 |
| Light | 1 | 175 | 382 | 21 | 2022.8095 |
| Long run | 1 | 71 | 136 | 11 | 2022.2727 |
| Mean | 1 | 116 | 173 | 14 | 2022.4286 |
| Measure | 1 | 194 | 468 | 37 | 2022.6486 |
| Monitoring | 1 | 166 | 412 | 31 | 2022.9355 |
| Natural gas | 1 | 100 | 160 | 14 | 2022.3571 |
| Negative impact | 1 | 103 | 146 | 11 | 2022.5455 |
| Opportunity | 1 | 213 | 807 | 59 | 2022.8136 |
| Outcome | 1 | 151 | 269 | 23 | 2022.3478 |
| Period | 1 | 222 | 567 | 42 | 2022.3333 |
| Person | 1 | 132 | 214 | 14 | 2022.2143 |
| Perspective | 1 | 217 | 646 | 54 | 2022.5926 |
| Pivotal role | 1 | 112 | 277 | 14 | 2023.7857 |
| Policy | 1 | 209 | 762 | 58 | 2022.5172 |
| Policymaker | 1 | 163 | 628 | 35 | 2022.9143 |
| Pollution | 1 | 137 | 220 | 20 | 2022.45 |
| Potential | 1 | 251 | 1013 | 80 | 2022.6375 |
| Principle | 1 | 162 | 319 | 24 | 2022.6667 |
| Priority | 1 | 129 | 224 | 16 | 2022.4375 |
| Process | 1 | 262 | 1221 | 108 | 2022.5185 |
| Production | 1 | 275 | 1288 | 108 | 2022.5093 |
| Progress | 1 | 168 | 364 | 30 | 2022.5 |
| Property | 1 | 170 | 369 | 32 | 2022.5312 |
| Prospect | 1 | 176 | 426 | 29 | 2022.4483 |
| Recent advance | 1 | 88 | 136 | 13 | 2022.3846 |
| Recent development | 1 | 105 | 166 | 15 | 2022.4 |
| Recent year | 1 | 179 | 415 | 32 | 2022.625 |
| Recommendation | 1 | 167 | 450 | 30 | 2022.6667 |
| Region | 1 | 160 | 385 | 33 | 2022.4242 |
| Relationship | 1 | 149 | 418 | 32 | 2022.5625 |
| Renewable energy consumption | 1 | 76 | 165 | 19 | 2022.2105 |
| Renewable energy sector | 1 | 92 | 220 | 11 | 2023.6364 |
| Renewable energy system | 1 | 213 | 568 | 45 | 2022.8444 |
| Renewable energy technology | 1 | 139 | 265 | 21 | 2022.7143 |
| Research gap | 1 | 122 | 195 | 14 | 2022.5 |
| Researcher | 1 | 265 | 1173 | 75 | 2022.6 |
| Resilience | 1 | 172 | 358 | 25 | 2023.08 |
| Review | 1 | 281 | 2331 | 186 | 2022.6882 |

| Categories | Cluster | Links | Total link strength | Occurrences | Avg/Year |
|---|---|---|---|---|---|
| Review paper | 1 | 106 | 177 | 12 | 2022.75 |
| Risk | 1 | 187 | 390 | 31 | 2022.9032 |
| Role | 1 | 279 | 1463 | 108 | 2022.6389 |
| Safety | 1 | 129 | 267 | 23 | 2022.913 |
| Scalability | 1 | 119 | 197 | 18 | 2022.5556 |
| Sector | 1 | 263 | 1247 | 94 | 2022.5426 |
| Sensor | 1 | 107 | 189 | 15 | 2022.7333 |
| Significance | 1 | 176 | 369 | 21 | 2023.0476 |
| Smart grid technology | 1 | 101 | 167 | 11 | 2022.8182 |
| Solar energy | 1 | 181 | 482 | 44 | 2022.4773 |
| Stakeholder | 1 | 152 | 507 | 28 | 2023.1786 |
| Supercapacitor | 1 | 102 | 153 | 11 | 2022.5455 |
| Sustainability | 1 | 225 | 868 | 58 | 2022.931 |
| Sustainable development | 1 | 174 | 363 | 29 | 2022.6552 |
| Sustainable development goal | 1 | 92 | 122 | 11 | 2022.4545 |
| Sustainable energy future | 1 | 94 | 178 | 11 | 2023.5455 |
| Synthesis | 1 | 113 | 216 | 16 | 2022.6875 |
| Test | 1 | 167 | 405 | 36 | 2022.4167 |
| Thing | 1 | 158 | 379 | 26 | 2022.4615 |
| Topic | 1 | 142 | 268 | 18 | 2022.4444 |
| Transition | 1 | 249 | 925 | 67 | 2022.9104 |
| Trend | 1 | 226 | 813 | 56 | 2022.6429 |
| Understanding | 1 | 183 | 457 | 30 | 2022.7667 |
| Utilization | 1 | 223 | 616 | 48 | 2022.6667 |
| Valuable insight | 1 | 127 | 265 | 13 | 2023.2308 |
| Variable | 1 | 144 | 326 | 25 | 2022.44 |
| Vital role | 1 | 128 | 192 | 12 | 2022.5833 |
| Water | 1 | 159 | 346 | 30 | 2022.2667 |
| Bes | 2 | 119 | 188 | 13 | 2022.6154 |
| Bess | 2 | 149 | 351 | 23 | 2022.4783 |
| Bus | 2 | 148 | 373 | 28 | 2022.3214 |
| Bus system | 2 | 113 | 245 | 17 | 2022.1765 |
| Capacitor | 2 | 90 | 166 | 18 | 2022.2778 |
| Charge | 2 | 123 | 244 | 21 | 2022.2857 |
| Comparative analysis | 2 | 105 | 165 | 15 | 2022.5333 |
| Comparison | 2 | 180 | 422 | 36 | 2022.3056 |
| Control | 2 | 277 | 1763 | 137 | 2022.4745 |
| Control method | 2 | 140 | 301 | 22 | 2022.3636 |
| Control strategy | 2 | 187 | 499 | 34 | 2022.4118 |
| Controller | 2 | 227 | 1084 | 76 | 2022.4605 |
| Converter | 2 | 234 | 1066 | 82 | 2022.4146 |
| Coordination | 2 | 174 | 412 | 28 | 2022.5714 |
| Day | 2 | 198 | 500 | 41 | 2022.439 |
| Dc microgrid | 2 | 118 | 265 | 21 | 2022.381 |
| Diesel generator | 2 | 101 | 169 | 13 | 2022.1538 |
| Distribution network | 2 | 223 | 677 | 51 | 2022.3922 |

| Categories | Cluster | Links | Total link strength | Occurrences | Avg/Year |
|---|---|---|---|---|---|
| Distribution system | 2 | 189 | 550 | 38 | 2022.2368 |
| Efficacy | 2 | 106 | 205 | 14 | 2022.3571 |
| Electrical grid | 2 | 150 | 254 | 19 | 2022.4211 |
| Electricity demand | 2 | 131 | 197 | 16 | 2022.375 |
| Electrolyzer | 2 | 113 | 184 | 16 | 2022.4375 |
| Ems | 2 | 143 | 256 | 17 | 2022.7647 |
| Energy cost | 2 | 135 | 222 | 15 | 2022.4 |
| Energy resource | 2 | 285 | 1583 | 118 | 2022.3898 |
| Energy storage system | 2 | 249 | 1044 | 81 | 2022.4815 |
| Ess | 2 | 156 | 398 | 29 | 2022.5517 |
| Esss | 2 | 137 | 262 | 16 | 2022.75 |
| Evs | 2 | 105 | 176 | 12 | 2022.5 |
| Experimental result | 2 | 82 | 127 | 14 | 2022.5 |
| Fault | 2 | 138 | 243 | 19 | 2022.5263 |
| Frequency | 2 | 189 | 585 | 41 | 2022.5366 |
| Frequency control | 2 | 100 | 191 | 12 | 2022.5833 |
| Frequency deviation | 2 | 93 | 211 | 14 | 2022.5714 |
| Frequency regulation | 2 | 124 | 212 | 15 | 2022.4 |
| Fuel cell | 2 | 176 | 431 | 32 | 2022.5 |
| Generator | 2 | 229 | 767 | 58 | 2022.4138 |
| Genetic algorithm | 2 | 113 | 219 | 15 | 2022.2667 |
| Grid | 2 | 302 | 3709 | 294 | 2022.5 |
| Grid integration | 2 | 170 | 409 | 30 | 2022.4333 |
| Grid stability | 2 | 160 | 279 | 17 | 2022.5882 |
| Harmonic | 2 | 114 | 210 | 16 | 2022.625 |
| High penetration | 2 | 130 | 225 | 15 | 2022.2 |
| High voltage | 2 | 81 | 128 | 11 | 2022.5455 |
| Hour | 2 | 141 | 231 | 19 | 2022.2105 |
| Hybrid system | 2 | 147 | 275 | 21 | 2022.619 |
| IEEE | 2 | 178 | 625 | 44 | 2022.2955 |
| Inertia | 2 | 156 | 391 | 28 | 2022.4643 |
| Input | 2 | 110 | 178 | 17 | 2022.3529 |
| Inverter | 2 | 170 | 497 | 38 | 2022.3947 |
| Kind | 2 | 100 | 153 | 13 | 2022.5385 |
| Large number | 2 | 76 | 108 | 10 | 2022.3 |
| Large scale integration | 2 | 92 | 155 | 11 | 2022.6364 |
| Last decade | 2 | 87 | 133 | 10 | 2022.1 |
| Lcoe | 2 | 103 | 159 | 11 | 2022.4545 |
| Levelized cost | 2 | 99 | 157 | 12 | 2022.5 |
| Limit | 2 | 156 | 318 | 26 | 2022.2692 |
| Load | 2 | 280 | 1899 | 142 | 2022.3521 |
| Load demand | 2 | 182 | 448 | 33 | 2022.4848 |
| Load frequency control | 2 | 74 | 162 | 13 | 2022.3077 |
| Loop | 2 | 140 | 285 | 20 | 2022.3 |
| Loss | 2 | 213 | 563 | 43 | 2022.3488 |
| Matlab simulink | 2 | 161 | 355 | 24 | 2022.4167 |

| Categories | Cluster | Links | Total link strength | Occurrences | Avg/Year |
|---|---|---|---|---|---|
| Microgrid | 2 | 109 | 172 | 13 | 2022.1538 |
| Microgrid | 2 | 270 | 1459 | 112 | 2022.4643 |
| Mode | 2 | 229 | 742 | 54 | 2022.463 |
| Modern power system | 2 | 119 | 195 | 14 | 2022.4286 |
| Mppt | 2 | 92 | 156 | 10 | 2022.5 |
| Optimal design | 2 | 85 | 117 | 10 | 2022.5 |
| Optimal operation | 2 | 107 | 155 | 16 | 2022.3125 |
| Optimization algorithm | 2 | 152 | 374 | 30 | 2022.4667 |
| Optimization technique | 2 | 160 | 343 | 23 | 2022.4783 |
| New challenge | 2 | 117 | 188 | 12 | 2022.5 |
| Novel | 2 | 119 | 176 | 16 | 2022.25 |
| Objective function | 2 | 135 | 280 | 20 | 2022.25 |
| Panel | 2 | 199 | 495 | 36 | 2022.5833 |
| Parameter | 2 | 257 | 1108 | 89 | 2022.4494 |
| Participation | 2 | 139 | 252 | 18 | 2022.3333 |
| Particle swarm optimization | 2 | 138 | 375 | 26 | 2022.3846 |
| Phase | 2 | 156 | 287 | 19 | 2022.5263 |
| Photovoltaic | 2 | 146 | 261 | 24 | 2022.4167 |
| Photovoltaic system | 2 | 149 | 256 | 21 | 2022.7143 |
| PID | 2 | 102 | 238 | 14 | 2022.2857 |
| Point | 2 | 194 | 487 | 37 | 2022.3784 |
| Power electronic | 2 | 139 | 246 | 16 | 2022.5625 |
| Power factor | 2 | 102 | 206 | 11 | 2022.5455 |
| Power flow | 2 | 186 | 504 | 37 | 2022.4865 |
| Power generation | 2 | 214 | 565 | 46 | 2022.5435 |
| Power loss | 2 | 142 | 313 | 24 | 2022.2917 |
| Power quality | 2 | 208 | 615 | 39 | 2022.4359 |
| Power quality issue | 2 | 105 | 193 | 12 | 2022.25 |
| Power system | 2 | 278 | 1953 | 161 | 2022.3851 |
| Presence | 2 | 171 | 370 | 27 | 2022.5185 |
| Promising solution | 2 | 94 | 134 | 11 | 2022.4545 |
| Proposed controller | 2 | 109 | 260 | 16 | 2022.3125 |
| Pso | 2 | 136 | 348 | 23 | 2022.3913 |
| Pv system | 2 | 158 | 283 | 21 | 2022.1905 |
| Reactive power | 2 | 129 | 204 | 12 | 2022.25 |
| Renewable generation | 2 | 145 | 276 | 21 | 2022.2857 |
| Renewable integration | 2 | 106 | 166 | 17 | 2022.5294 |
| Rer | 2 | 107 | 190 | 12 | 2022.4167 |
| Res | 2 | 264 | 1100 | 78 | 2022.5 |
| Respect | 2 | 119 | 166 | 11 | 2022.2727 |
| Response | 2 | 204 | 531 | 41 | 2022.5854 |
| Ress | 2 | 109 | 168 | 12 | 2022.3333 |
| Robustness | 2 | 145 | 377 | 26 | 2022.2692 |
| Scenario | 2 | 265 | 1326 | 102 | 2022.4216 |
| Scheme | 2 | 225 | 871 | 69 | 2022.4493 |
| Sensitivity analysis | 2 | 144 | 239 | 16 | 2022.1875 |

| Categories | Cluster | Links | Total link strength | Occurrences | Avg/Year |
|---|---|---|---|---|---|
| Simulation | 2 | 246 | 1005 | 91 | 2022.4176 |
| Simulation result | 2 | 203 | 697 | 55 | 2022.3818 |
| Size | 2 | 192 | 440 | 31 | 2022.3871 |
| Sizing | 2 | 138 | 259 | 18 | 2022.5 |
| Solar irradiance | 2 | 99 | 158 | 11 | 2022.1818 |
| Solar photovoltaic | 2 | 150 | 314 | 21 | 2022.381 |
| Solar pv | 2 | 122 | 191 | 12 | 2022.0833 |
| Stability | 2 | 256 | 1070 | 79 | 2022.5063 |
| Station | 2 | 233 | 755 | 58 | 2022.6379 |
| Stochastic nature | 2 | 101 | 145 | 10 | 2022.4 |
| Storage system | 2 | 184 | 433 | 33 | 2022.5152 |
| Superiority | 2 | 121 | 248 | 19 | 2022.4211 |
| System performance | 2 | 120 | 179 | 11 | 2022.2727 |
| System stability | 2 | 134 | 243 | 16 | 2022.5 |
| Topology | 2 | 178 | 434 | 36 | 2022.3611 |
| Transmission | 2 | 168 | 332 | 26 | 2022.3846 |
| Uncertainty | 2 | 270 | 1362 | 110 | 2022.4636 |
| Unit | 2 | 259 | 1151 | 84 | 2022.3214 |
| Utility grid | 2 | 121 | 202 | 12 | 2022.3333 |
| V2g | 2 | 118 | 234 | 15 | 2022.5333 |
| Variation | 2 | 188 | 557 | 40 | 2022.3 |
| Vehicle | 2 | 275 | 1541 | 120 | 2022.5833 |
| Voltage | 2 | 233 | 945 | 72 | 2022.375 |
| Wind farm | 2 | 137 | 244 | 18 | 2022.5 |
| Wind power | 2 | 103 | 181 | 16 | 2022.3125 |
| Wind turbine | 2 | 215 | 614 | 44 | 2022.4773 |
| Blockchain | 3 | 124 | 285 | 19 | 2022.5263 |
| Blockchain technology | 3 | 88 | 133 | 10 | 2022.5 |
| Communication | 3 | 156 | 316 | 22 | 2022.6364 |
| Community | 3 | 203 | 546 | 38 | 2022.4211 |
| Demand response | 3 | 154 | 330 | 28 | 2022.4643 |
| Der | 3 | 145 | 334 | 22 | 2022.3636 |
| Electricity market | 3 | 111 | 206 | 16 | 2022.25 |
| Energy market | 3 | 136 | 248 | 17 | 2022.5882 |
| Energy trading | 3 | 110 | 228 | 16 | 2022.4375 |
| Experiment | 3 | 139 | 237 | 21 | 2022.381 |
| Home | 3 | 105 | 190 | 15 | 2022.2667 |
| Household | 3 | 113 | 179 | 12 | 2022.5 |
| Peer | 3 | 107 | 192 | 13 | 2022.6923 |
| Profit | 3 | 129 | 243 | 17 | 2022.3529 |
| Prosumer | 3 | 119 | 233 | 18 | 2022.2222 |
| Real-time | 3 | 114 | 169 | 12 | 2022.4167 |
| User | 3 | 178 | 491 | 38 | 2022.5 |
| Virtual power plant | 3 | 110 | 236 | 15 | 2022.2667 |
| Vpp | 3 | 99 | 203 | 13 | 2022.1538 |

This study makes a new contribution by identifying the trend of the relationship between blockchain and prosumers in the energy system that has not been widely discussed in previous studies. Unlike previous studies that tend to discuss blockchain as a separate energy transaction tool (Andoni et al., 2019; Elgamal, Kocher-Oberlehner, Robu, & Andoni, 2019; Erdiwansyah et al., 2024), the results of the bibliometric analysis in this study show that the integration of blockchain with the prosumer model not only increases the transparency of energy transactions, but also opens up new opportunities in peer-to-peer (P2P) trading mechanisms and optimization of decentralized electricity networks. In addition, compared to previous studies that focused more on the technical aspects of network stability and system control (Mahidin et al., 2020; Pavon, Jaramillo, & Vasquez, 2023), this study highlights the close relationship between technological and policy aspects, which are crucial factors in the sustainability of blockchain implementation in the energy system. With a bibliometric approach that reveals the evolutionary patterns of research in this field, our findings provide new insights into how blockchain technology and prosumers are evolving as part of sustainable energy transition strategies and more democratic energy management.

In addition to the technical aspects of energy system optimization, this study also reveals the important role of energy policies in supporting renewable energy integration. The analysis results show that policies such as feed-in tariff incentives, net metering regulations, and green financing schemes have a significant impact on the adoption of innovative technologies such as blockchain and prosumers in the electricity grid. The study finds that in the context of an increasingly decentralized energy system, flexible and market-based regulations play a key role in ensuring the sustainability of renewable energy integration (R. Elavarasan & Rajaram, 2024; Madurai Elavarasan, Nadarajah, Pugazhendhi, & Gangatharan, 2024). Thus, in addition to relying on technological advances in electricity grid optimization, the success of the energy transition also depends heavily on the synchronization between regulatory policies and technological developments. A more holistic approach that combines technical innovation and an adaptive policy framework is key to creating a more sustainable and inclusive energy system.

## 4. Conclusion

Several key findings, based on the analysis of the network visualization images, provide in-depth insights into energy and technology research trends. These conclusions are based on the patterns of association between keywords, topic clusters, and occurrence data contained in the tables and visualizations. One important finding is the increasing role of new technologies in modern energy systems, as seen from the figure keywords such as blockchain, prosumer, and communication. These technologies play a significant role in changing the dynamics of energy production and consumption, where consumers also become energy producers (prosumers). Blockchain, for example, is starting to be integrated into energy systems to ensure transparency and efficiency in energy transactions. The data in the table, which shows the high frequency of keywords related to technological innovation, also supports this trend. In the visualization and the table, topics such as grid, control, and optimization emerge as the centre of attention. This shows that much research focuses on managing the stability of the power system, regulating the control of the grid, and optimizing the parameters of the energy system to ensure efficient and reliable performance. The table's terms algorithm and artificial intelligence also support this conclusion, indicating that these technologies are widely used for optimising and automating the energy system. Based on the network visualization and tables' findings, sustainability, carbon neutrality, and renewable energy are increasingly gaining attention in energy research. This reflects the increasing global focus on sustainability and the transition to cleaner and renewable energy sources. With the high occurrence of keywords such as policy and development, this study highlights the importance of a policy framework that supports the development of renewable energy sources to reduce environmental impacts and achieve net-zero emission targets.

**Acknowledgement**
We want to express our sincere gratitude to all the authors for their invaluable contributions and collaboration throughout the research process. This work represents each author's collective efforts and dedication, whose expertise and insights were essential in completing this study.

**Declaration of Competing Interest**
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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