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Optimizing Energy Storage Systems Supply Chains: A Bibliometric Analysis (2014-2024)

Dalal Bamufleh and Yong Wang
School of Systems Science and Industrial Engineering
Binghamton University
Binghamton, NY, United States
dbamufl1@binghamton.edu, yongwang@binghamton.edu

Abstract

Energy storage systems (ESSs) are essential in stabilizing energy systems, improving reliability, enabling the effective integration of renewable energy sources, addressing sustainability challenges, providing power backup, and strengthen energy security. This study uses bibliometric analysis methodology to explore research trends in ESSs supply chain modeling and optimization, analyzing 6,793 documents published between 2014-2024 using tools such as VOSviewer and OpenRefine. Findings reveal rapid growth in ESS supply chain publications , driven by the global transition to renewable energy, increased adoption of electric vehicles (EVs), and emphasis on supply chain sustainability. The current ESSs research progression analysis identified the future research direction focusing on machine learning (ML) and deep reinforcement learning (DRL) technologies integration and optimization of multiple renewable energy systems, ESSs supply chain sustainability, distributed and decentralized ESSs supply chain, and large-scale ESSs technologies. To the best of our knowledge, this study is the first that systematically outline the entire research landscape of ESS supply chain modeling and optimization utilizing a detailed bibliometric methodology. This study contributes to the literature by outlining the progression of ESSs research, underlining significant trends, and suggesting future research directions.

Keywords
Energy storage systems (ESSs), Battery Energy Storage Systems (BESS), Supply Chain, Renewable Energy Integration, and Bibliometric Analysis.

1. Introduction
Energy storage systems (ESSs) encompass technologies that store energy, which will be released when demanded to balance and stabilize supply and demand within energy systems. ESSs encompass diverse storage technologies categorized into mechanical, thermal, chemical, and electrochemical systems, allowing energy flexibility and reliability (Koohi-Fayegh and Rosen, 2020). Battery energy storage systems (BESS) are one type of ESSs under the electrochemical category, which stores and discharges energy effectively for short-term needs such as stabilizing power grids, managing energy peak demand, improving grid suitability, and facilitating renewable energy sources integration like solar and wind (Balaman & Selim, 2016; Zamar et al., 2017; Saghaei & Soleimani, 2020). Additionally, BESS is essential in decentralizing energy systems, electric vehicles (EVs), and individual-use energy storage, thereby enhancing sustainability and energy efficiency (Li et al., 2018).

ESSs include diverse types of storage technologies, such as compressed air energy storage (CAES) (Zhao et al., 2021), pumped hydro storage (Al-Nory, 2019), thermal storage (Balaman and Selim, 2016), dense energy carriers (Demirhan et al., 2020), and biomass-based energy storage (Balaman and Selim, 2016; Zamar et al., 2017; Saghaei and Soleimani, 2020). Each of these ESSs have a unique supply chain structure; however, it can be generalized into the following stages. The supply chain starts with raw materials mining and production, followed by energy conversion and storage, which is then released when demanded. Finally, the generated energy is transported to end users.

For battery-based ESSs, which is BESS, the supply chain structure is relatively standardized among the studies addressing battery supply chain optimization (Li et al., 2018; Mayyas et al., 2019; Júnior et al., 2022; Yang et al., 2022). The supply chain begins with collecting raw materials for batteries, such as lithium, cobalt, nickel, and graphite, which are required for lithium-ion batteries (LIBs). These materials are refined to improve their purity before moving to the battery manufacturing stage, where battery cells are produced and then distributed to end users. Once batteries have consumed approximately 80% of their capacity, they must be replaced. Battery end-of-life (EOL) management extends the battery life cycle through recycling, remanufacturing, or repurposing strategies (Li et al., 2018; Mayyas et al., 2019; Zhao et al., 2021; Júnior et al., 2022). The retired batteries are collected at collection centers (Li et al., 2018; Mayyas et al., 2019) and then forwarded to the material separation stage, where the valuable raw materials are extracted, processed, and used to produce new batteries. This is the recycling method (Mayyas et al., 2019; Wang et al., 2020). Another battery EOL management strategy is remanufacturing, where the retired batteries are evaluated to identify the degraded components that need to be replaced with new ones and reused effectively (Li et al., 2018).

The objectives of optimizing ESSs supply chains are to minimize supply chain total costs, maximize profits, reduce environmental impacts, support renewables integration, and improve social effects, grid stability, and sustainability (Sarker et al., 2019; Wu and Ma, 2021; Popien et al., 2023). The demand for ESSs/ BESS supply chain optimization models has recently increased because of some factors. First, the global switch to renewable energy sources implies integrating sources with high uncertainty in nature. Optimization models can help mitigate this uncertainty and balance energy demand with supply (Jiang et al., 2021; Potrč et al., 2021). Second, the increasing adoption and use of EVs leads to some changes to the ESSs supply chain structure to encompass more components, starting from mining battery's raw materials to the recycling or remanufacturing phase (Li et al., 2018; Wang et al., 2020; Popien et al., 2023). Optimization models for these supply chains allow for achieving efficiency and sustainability, which include economic, environmental, and social objectives.

Despite the growing research on ESSs supply chains modeling and optimization, various research gaps and unresolved difficulties still not sufficiently explored. First, the majority of current research emphasizes improving a particular element of the ESSs supply chain while lacks comprehensive integrated models that encompass the whole stages of ESSs supply chain, including EOL (Li et al., 2018; Popien et al., 2023). Secondly, the dynamic and stochastic characteristic of ESSs, which is due to the uncertainties associated with the renewable energy, necessitate sophisticated predictive models and intelligent optimization techniques that remain inadequately examined (Wu and Ma, 2021). Third, the sustainability assessment for ESSs supply chains, encompassing economic, environmental, and social aspects within an integrated framework, is inadequately addressed (Júnior et al., 2022). Finally, research on large-scale and distributed ESSs remains insufficient in the current literature, which presents opportunities for future investigations to address the technological, economic, and policy-related challenges. Recognizing and addressing these research gaps is essential for promoting the sustainable design and optimization of ESSs supply chains. To address these gaps, this study conducts a bibliometric analysis to outline the global research trends and direction on ESS supply chain modeling and optimization from 2014 to 2024. The key objectives are to: analyze publication trends, identify main research clusters and technologies, and to uncover gaps and emerging directions. Therefore, the study’s research questions are: what are the dominant themes in ESS modeling’s literature, what is its progression, and what are the potential areas for future research.

This paper is organized into four sections; after this introduction, the methodology section illustrates the applied bibliometric approach and tools utilized for the analysis. After that, the results and discussion section describe the main findings, which include ESSs publication trends, keyword co-occurrence networks, and topics’ clusters within the scope of ESSs supply chain research. Last, the conclusion section summarizes the main insights and highlights the study contributions, limitations, and directions for future research in the context of ESSs supply chain modeling and optimization.

2. Methodology

The bibliometric analysis is performed to assess the research landscape, recognize key trends in ESSs supply chain modeling and optimization and familiar authors' keywords, and uncover a co-occurrence network for authors' keywords. This analysis (Figure 1) also aims to guide future research by identifying literature gaps and ensuring new works build on existing knowledge. The used search query was designed to comprehensively cover three critical dimensions: (i) ESSs and their wide-ranging technologies, (ii) supply chain and logistics, and (iii) modeling and optimization terms. The specified keywords were selected after reviewing previous studies in the field of ESSs supply chain (Byrne et al., 2017; Koohi-Fayegh and Rosen, 2020). To eliminate potential bias during the creation of the datasets, a wide array of term variations and synonyms was included (e.g., 'supply chain', 'supply chain management', 'logistics'). Likewise, additional documents and publications were thoroughly and manually examined from several databases to guarantee the inclusion of works utilizing non-standard or emergent terminologies. Non-English publications, duplicates, documents unrelated to the study scope, and non-academic sources were excluded.

The acceptable documents include more types (Figure 2) besides journal articles and conference proceedings to gain a comprehensive understanding and general exploration of the research topic, related terms, and most commonly connected areas to ESSs/ BESS supply chain modeling and optimization. The examined timeframe of 2014–2024 was specified based on the observation that publications in the context of the ESSs supply chain modeling and optimization started to grow significantly after 2014. The period 2014-2024 captures the rapid expansion and wide adoption of renewable energy adoption, EVs, and increasing research attention to ESSs supply chains. While 2024 data is incomplete as the dataset was collected in July 2024, it was included to provide insights about the most recent emerging trends incorporated in the field of ESSs supply chain modeling and optimization. The lower publication counts for 2024 due to the partial year publications' data availability.

Several tools were used to complete this analysis. 'Publish or Perish' is a software used to import search results from Scopus and Google Scholar databases and to gather citation metrics and other relevant data. Because some documents were gathered manually from databases such as IEEE and MDPI, 'Mendeley,' a reference management software, was used to organize and manage all references and produce their bibliographies. To resolve inconsistencies, merge similar authors' keywords, standardize formats, and correct errors in the collected dataset, OpenRefine software was used. Lastly, VOSviewer software was used to visualize bibliometric analysis.

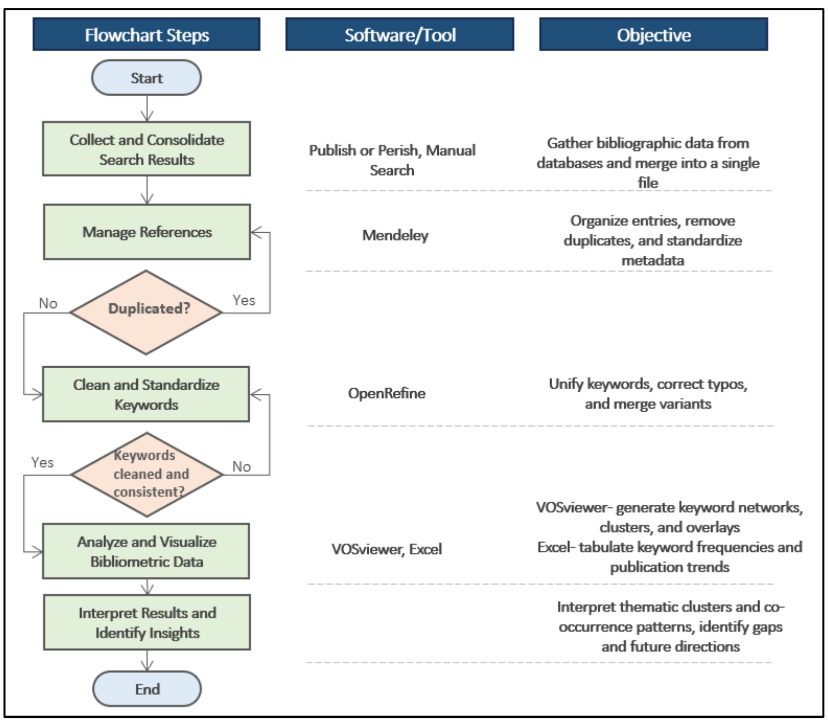

Figure 1. Study Methodology

3. Results and Discussion

The applied search query resulted in a large dataset with 98% journal articles (Figure 2). The growing interest in the field can be seen in the substantial rise in published research from 2014 to 2024. In 2014, 153 papers were published, and the count increased gradually to reach its peak of 1368 documents in 2023. In addition, the growth rate was considered to measure and identify significant changes (if any) in the publication activity. It was calculated using the formula:

$$\text{Growth Rate} = \frac{\text{Documents in Current Year} - \text{Documents in Previous Year}}{\text{Documents in Previous Year}} \times 100\%$$

Based on the data shown in Figure 3, substantial growth rates were observed in 2017 (60.73%), 2021 (31.78%), and 2022 (48.49%). These increases in growth rates highlight greater global interest and technological advancements in the field. The growth rate in 2024 is notably lower (-19.15%) because the dataset was collected in the middle of the year (July 2024), and not all the publications are fully available in the academic databases yet. Analysis of authors' keywords is a vital aspect of bibliometric analysis as it helps identify the study scope more precisely, the objectives of the research conducted so far, prospects, and research gaps. A total of 13,513 keywords were found in the previously mentioned databases; however, a minimum of 10 occurrences was applied as recommended for large datasets by Huang et al., (2022), and Martins et al., (2022). Only 137 keywords met the threshold. The keyword clusters were determined by the modularity-based clustering algorithm of VOSviewer software according to the keywords' common focus areas and topics:

- Cluster 1: Renewable Energy and System Flexibility.
  - The cluster focuses on renewable energy systems, energy storage's flexibility and conversion technologies. Also, it focuses on multiple energy sources integration, and emissions and decarbonization issues.
- Cluster 2: Optimization and Energy Systems Management.
  - This cluster focuses on the management of energy systems including EVs, microgrids, and demand management and optimization. It covers also advanced control and predictive techniques integration.
- Cluster 3: Thermal and Chemical Energy Storage Systems.
  - This cluster discusses the thermal and chemical ESSs such as phase change materials, solar energy storage, liquid air energy storage and salt-based energy storage.
- Cluster 4: Battery Energy Storage and Distributed Energy Systems.
  - The cluster is centered around the BESS, solar PV, distributed energy systems, and associated economic and policy topics.
- Cluster 5: Energy System Resilience and Demand Response.
  - This cluster concerns with energy systems' resilience, energy storage supply chain, reliability, and diverse energy sources and energy systems integration.
- Cluster 6: Advanced Techniques in Energy Systems
  - This cluster includes the advanced and emerging techniques and methodologies in energy systems like machine learning, artificial neural network and optimization algorithms.
- Cluster 7: Wind and Mechanical Energy Storage
  - This cluster highlights wind and mechanical ESSs including flywheels, compressed air, or pumped hydro storage. It also discusses associated cost analysis and computational techniques.
- Cluster 8: Energy System Efficiency
  - This cluster addresses energy systems' efficiency besides several energy storage methods.
- Cluster 9: Sustainability and Climate Impact
  - This cluster spotlights on energy storage supply chain sustainability, simulation, and the impacts of climate change. Also, it covers the role of geothermal energy in energy systems.
- Cluster 10: Electrochemical Energy Storage
  - This cluster discusses the electrochemical energy storage technologies, mainly supercapacitors and fuel cells.

Table 1. Most Frequently Occurring Keywords in The Reviewed Publications

Keyword	Occurrences	Cluster
Energy Storage Systems (ESSs)	2039	3
Optimization	1097	2
Thermal Energy Storage System	905	3
Phase Change Materials (PCMS)	632	3
Battery Energy Storage System (BESS)	593	4
Renewable Energy	416	1
Solar Energy Storage	316	3
Electric Vehicles	262	2
Modeling	236	1
Hybrid Renewable Energy System	214	2

The top ten most frequently occurring keywords, their cluster and occurrence counts, are summarized in Table 1. The bibliometric analysis presented in this paper investigates the network of keyword co-occurrences (Figures 4 through 8) and keyword overlay visualization (Figures 9 through 10). The analysis of the authors' keywords from publications included in the dataset is visualized using VOSviewer software, where the labels and circle size represent the frequency of keyword occurrences, and the lines connecting them show their co-occurrences and research relationships. The keyword clusters are recognized using different colors; each represents an area of knowledge within the study scope.

Figure 4 demonstrates that the most frequently occurring keyword is "energy storage systems (ESSs)" with (2039) occurrences, followed by "optimization" (1097), "thermal energy storage systems" (905), and "phase change materials (PCMs)" (632). The ESSs, being the most used keyword, aligns with the bibliometric analysis done by Borri et al., (2020). Figure 4 highlights the global concerns toward adopting green energy sources, which are reflected in the emphasis on integrating renewable energy sources, such as wind and solar, into ESSs. Optimizing these systems is gaining more attention to reduce overall costs, satisfy demands, and improve efficiency. Similarly, there is a growing interest in EVs because of the government's efforts to reduce the use and adverse effects of ICEVs. This co-occurrence network underlines the interconnected nature of several essential research topics within the scope of ESSs supply chain modeling and optimization, with priorities centered on developing efficient and cost-effective solutions to maintain sustainable ESSs.

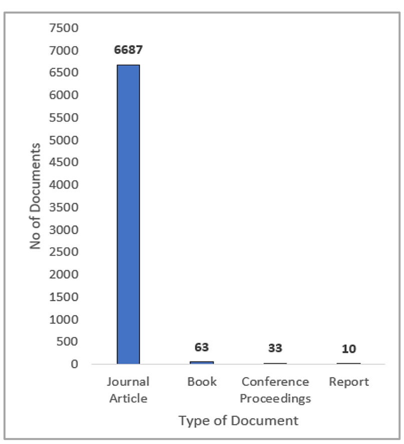

Figure 2. Types and Counts of

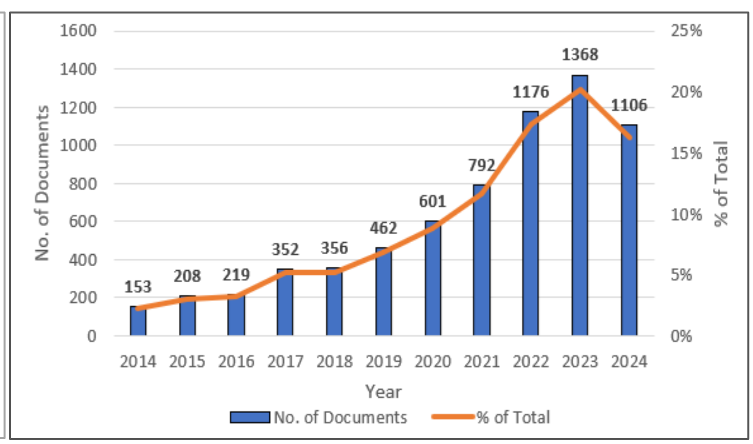

Figure 3. Annual Publication Counts from 2014 to 2024

Focusing on the 'energy storage systems (ESSs)' keyword, the co-occurrence network presented in Figure 5 reveals ESSs strong interconnections with several keywords within the research field, including "Thermal Energy Storage," "Battery Energy Storage System (BESS)," and "Phase Change Materials (PCMs)." This indicates a significant emphasis on numerous energy storage technologies in the literature, such as studies by Helbig et al. (2018) and

Bahlawan et al. (2022) investigating the risks associated with optimizing the ESSs supply chain. In addition, as investigated by Li et al. (2018) and Jing et al. (2021), the network shows the connections between BESSs and "Electric Vehicles," emphasizing the significance of batteries in enabling electric mobility. Because of the prominence of optimizing ESSs, the 'Optimization' keyword is found close to the ESSs term (the medium-sized right green circle) and has connections (Figure 6) with the majority of the terms in the research (Wang et al., 2021; Wu and Ma, 2021). Additionally, the networks depicted in Figures 5 and 6 emphasize the research focus on distributed ESSs, emerging technologies such as supercapacitors, machine learning, and deep learning, and the importance of sustainability and ESSs supply chain considerations as explored by (Worighi et al., 2019; Berr et al., 2022; Mah et al., 2022).

The relationships connected with the keywords "energy storage supply chain" (Figure 7) highlight the crucial role of supply chain management in supporting a wide range of energy storage technologies. For example, the connection with 'Battery Energy Storage System (BESS)' stresses the significance of supply chain efficiency in expanding battery technologies markets, as mentioned by Olivetti et al., (2017), who examine and assess the bottlenecks in LIBs supply chains caused by shortages of critical materials for batteries. The network shows an emerging focus on 'liquid air energy storage,' an alternative energy storage technology. Alternative technologies are receiving attention in ESSs supply chain research because of their capability in large-scale energy storage capabilities. Moreover, the growing interest of energy producers and consumers in integrating multiple energy sources within storage systems is reflected in recent research that connects the ‘energy storage systems’ keyword with the 'hybrid renewable energy storage' keyword.’ That is because some challenges are faced while optimizing the renewable energy storage supply chain, as discussed by (Tso et al., 2019; Bahlawan et al., 2022). Last, the 'reliability' keyword connection emphasizes the importance of ensuring the robustness and dependability of the energy storage supply chain. That is consistent with several studies (Jin et al., 2017; Li et al., 2018; Mikolajková-Alifov et al., 2019; Potrč et al., 2021).

The 'renewable energy storage' keyword (Figure 8) is strongly connected with the primary keywords in the research area, such as 'battery energy storage,' 'energy storage systems (ESSs),' 'electric vehicles,' 'optimization,' and 'sustainability.' These relationships indicate the influential role of renewables in maintaining sustainable ESSs. That was discussed by Popien et al. (2023), in which a sustainability assessment was performed for LIBs supply chains, highlighting their significant role in supporting renewable energy integration using energy storage solutions. Also, the map includes links to 'techno-economics' and 'distributed energy storage systems' terms that reflect the economic and technical aspects of renewable energy storage implementation and optimization. Asha et al. (2022) proved this relationship in their study, which focuses on optimizing a sustainable green storage supply chain. That study emphasizes the effect of economic and techno-economic assessments on the development and deployment of distributed ESSs that are regularly powered by renewable energy sources. In addition, because EVs increasingly depend on renewable energy sources for charging, controlling energy supply and demand, and lowering carbon emissions, there is a strong connection between 'renewable energy storage' and 'electric vehicles' terms. This connection was supported in the literature and motivated by several studies such as Sadeghi and Haapala (2019), Sarker et al. (2019), and Worighi et al. (2019). These interconnected networks prove the multidisciplinary nature of energy storage research, integrating numerous technologies, multi-objective optimization, and sustainability to address the growing complexity and emergent challenges in the ESSs supply chain modeling and optimization domain.

The author keywords' overlay visualization map (Figures 9) integrates the keyword co-occurrence map provided in Figure 4 with a timeline (2019-2023) to illustrate the evolution of research topics in the context of energy system supply chain modeling and optimization over the specified period. The average publishing year is represented by the color of the nodes and edges, while the gradient reflects the progression of the research over time. The specified timeframe here (i.e., 2019-2023) is because of the following reasons:

(1) The number of publications has increased significantly since 2019, as shown in Figure 3, indicating a considerable increase in the field of energy storage supply chain modeling and optimization. This is aligned with the findings of Koohi-Fayegh and Rosen (2020) review.
(2) There have been notable changes in policy and markets since 2019, mainly due to the COVID-19 pandemic, which has extensively affected worldwide logistics systems, including energy storage supply chains (Shih, 2020).
(3) Advanced techniques have emerged recently in energy storage supply chain modeling and optimization (Qie, 2021). Additionally, most publications from 2019 to 2023 focus on integrating green hydrogen and sustainability, reflecting a global shift towards green energy adoption (Lund et al., 2017; IRENA, 2020).

To explore the research progression concerning the main two keywords, 'energy storage systems (ESSs)' and 'optimization' terms were selected, as shown in Figure 10. The 'ESSs' term is being integrated with machine learning (ML) and deep reinforcement learning (DRL) (Figures 9 through 11) to address the escalating complexity and dynamic features of energy systems, improve forecast accuracy, optimize ESSs performance, and improve the corresponding decision-making processes in real-time. Specifically, ML is employed to estimate energy demand and optimize ESSs operations, which is critical when ESSs are integrated with battery storage systems or renewable energy sources on the grid (Figure 9 to Figure 11), like solar and wind (Rojek et al., 2023). However, DRL is employed to learn optimal strategies through continuous communications and interactions with the ESSs to adapt and adjust to the dynamic nature (Wang et al., 2023). According to Geng et al., (2024), the growing adoption of ML and DRL in ESSs research arises from the need for more intelligent, adaptive storage systems that are efficient enough to manage the variability, inconsistency, and complexity of current ESSs while ensuring resilience, reliability, and efficiency.

4. Conclusion

The objectives of this study were to explore and evaluate the research trends and emerging themes within the scope of ESSs supply chain modeling and optimization from 2014 to 2024. A bibliometric analysis methodology was employed using tools like Publish or Perish, VOSviewer, and OpenRefine to analyze 6,793 publications of diverse types, including journal and conference articles, books, and reports. The analysis revealed significant developments and growth in ESSs research, which was motivated by three primary factors: (1) the global shift towards higher integration of renewable energy, (2) the rising adoption of EVs, and (3) the pressing need for supply chain sustainability. Also, the analysis provides valuable insights for future research directions based on research progression analysis, which identified ML, DRL, hybrid renewable energy systems, and green energy source optimizations as recently explored areas in the context of the ESSs and BESS supply chain. The analysis findings of publication trends, keyword co-occurrence networks, and keyword clusters contribute to ESSs supply chain research literature to recognize the topics that dominate the ESSs supply chain research domain and highlight the research gaps to be explored in future studies. On the other hand, the study has a limitation as the result of reliance on the bibliometric analysis method, which mainly focuses on the quantitative analysis of the documents included in the dataset, overlooking the qualitative insights that could enrich the study results and provide a deeper understanding of ESSs supply chain research. For future works, according to the conducted analysis, scholars could explore ESSs supply chain optimization integrated with any of the following topics: (1) ML and DRL technologies to optimize the ESSs supply chain and address the dynamics and complexity of energy systems, (2) Design and optimization of multiple renewable energy storage systems, (3) Comprehensive sustainability evaluation for ESSs and BESS supply chains, (3) Distributed energy systems and ESSs supply chain decentralization, and (4) Large-scale energy storage challenges and the utilization of emergent technologies for this purpose, such as liquid air and green hydrogen.

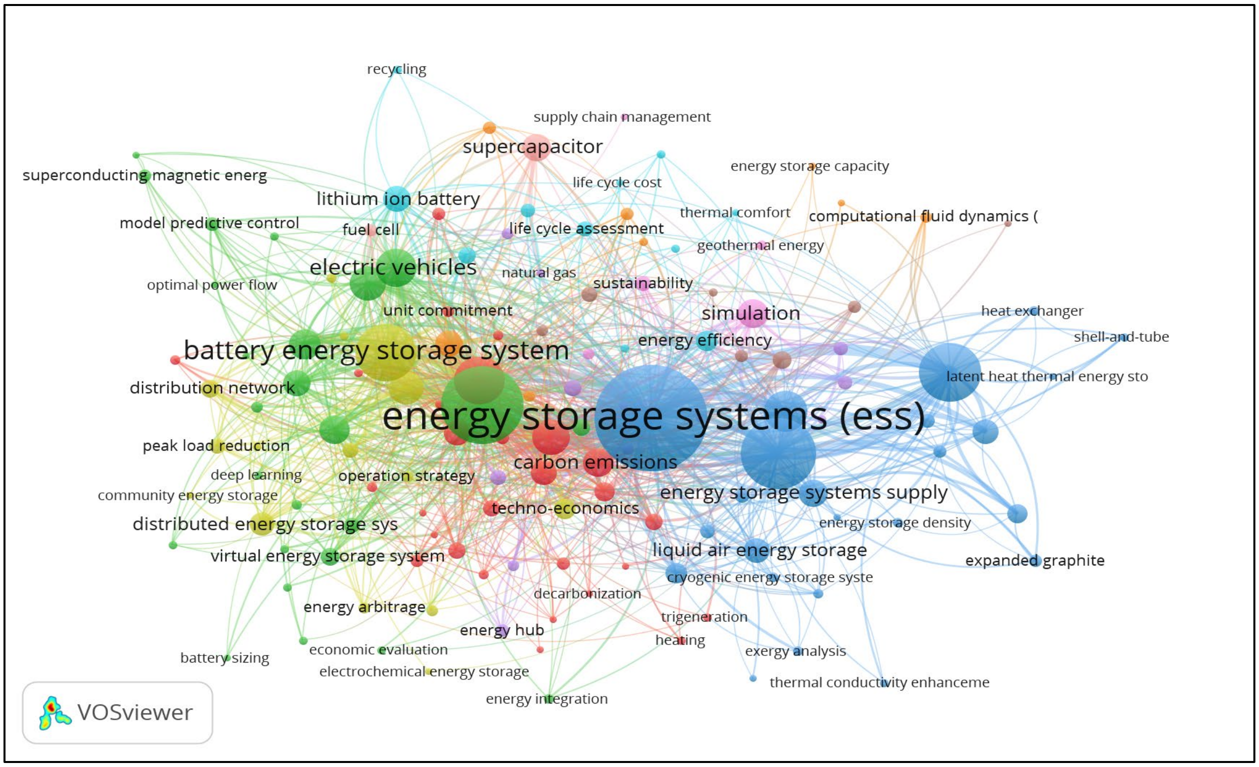

Figure 4. Author Keyword Co-occurrence Network Map

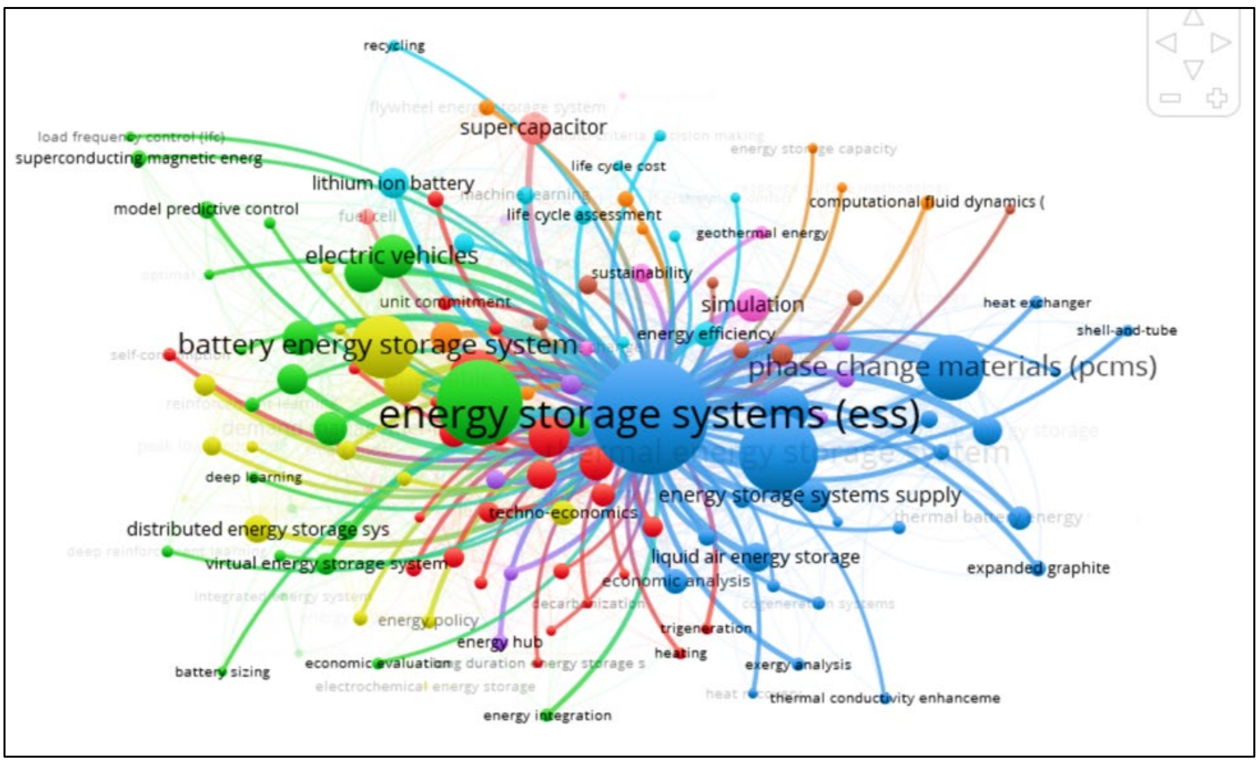

Figure 5. Co-occurrence Map of “Energy Storage Systems (ESSs)” Keyword

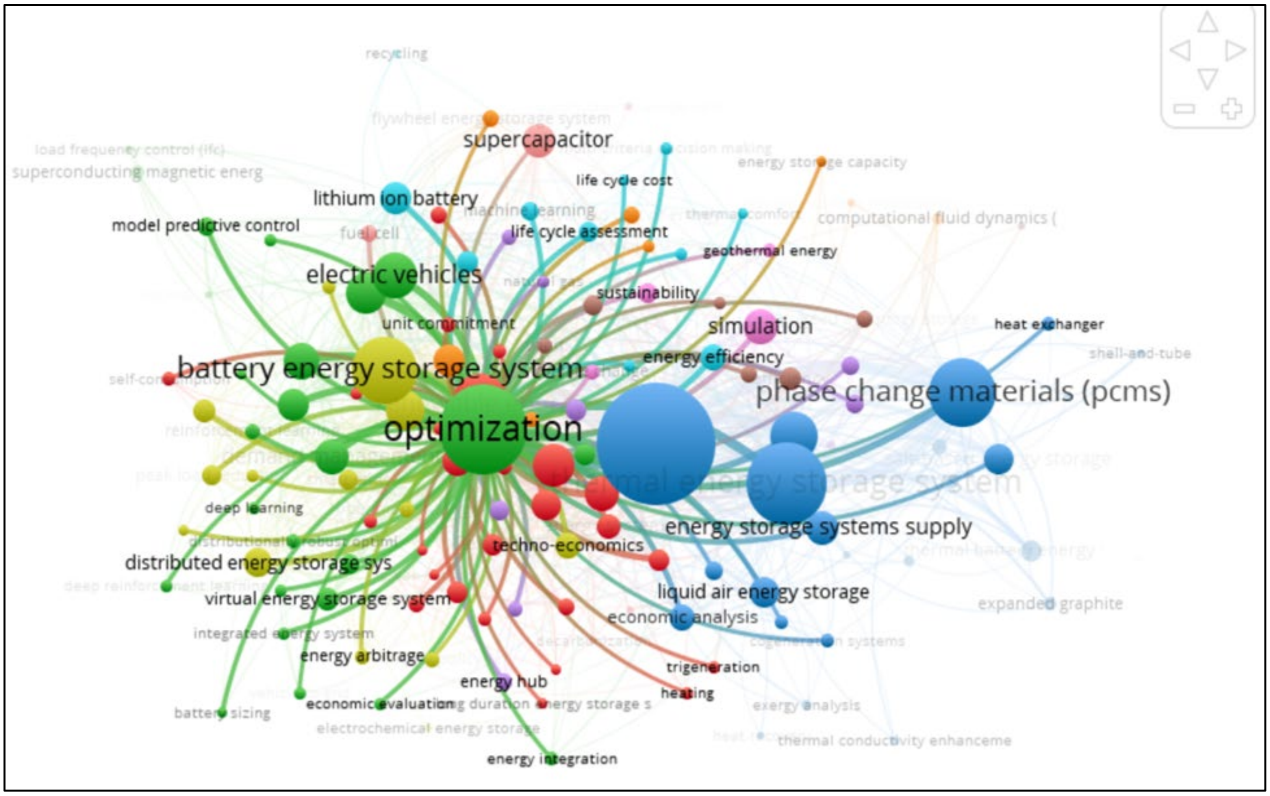

Figure 6. Co-occurrence Map of "Optimization" Keyword

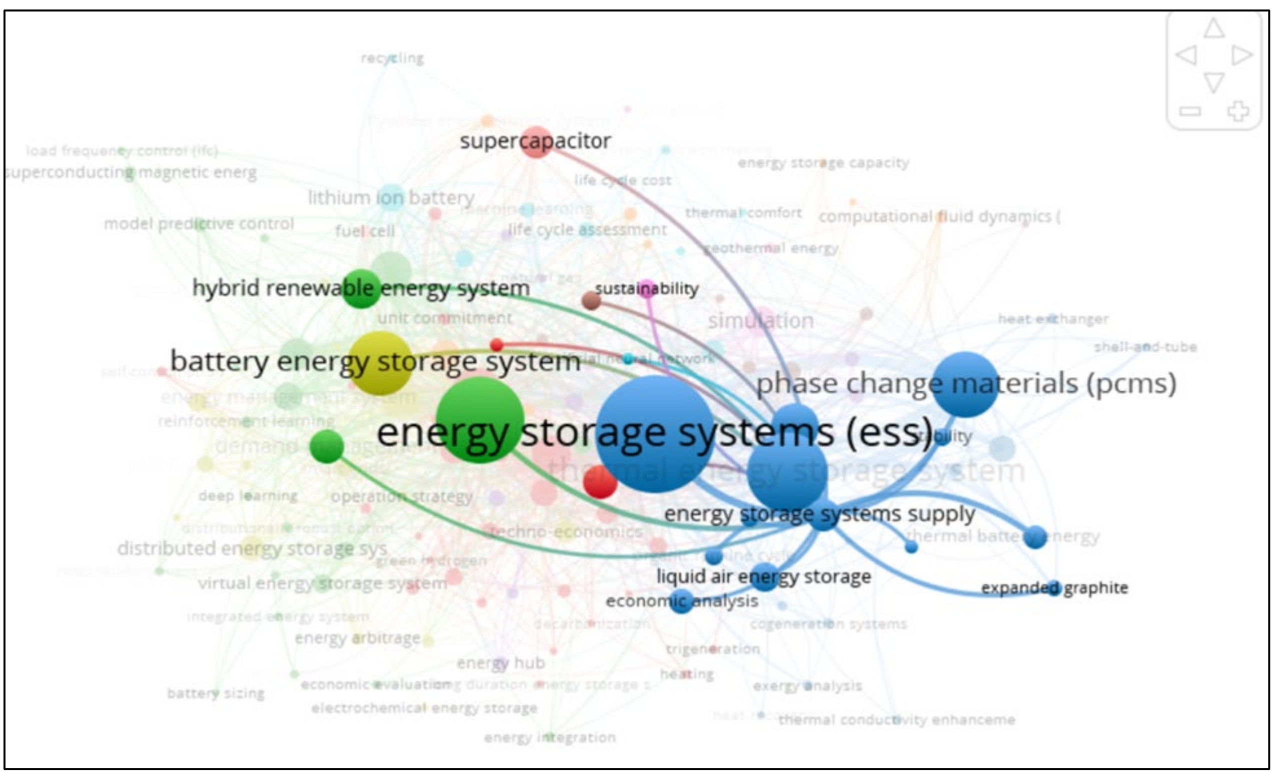

Figure 7. Co-occurrence Map of "Energy Storage Systems Supply Chain" Keyword

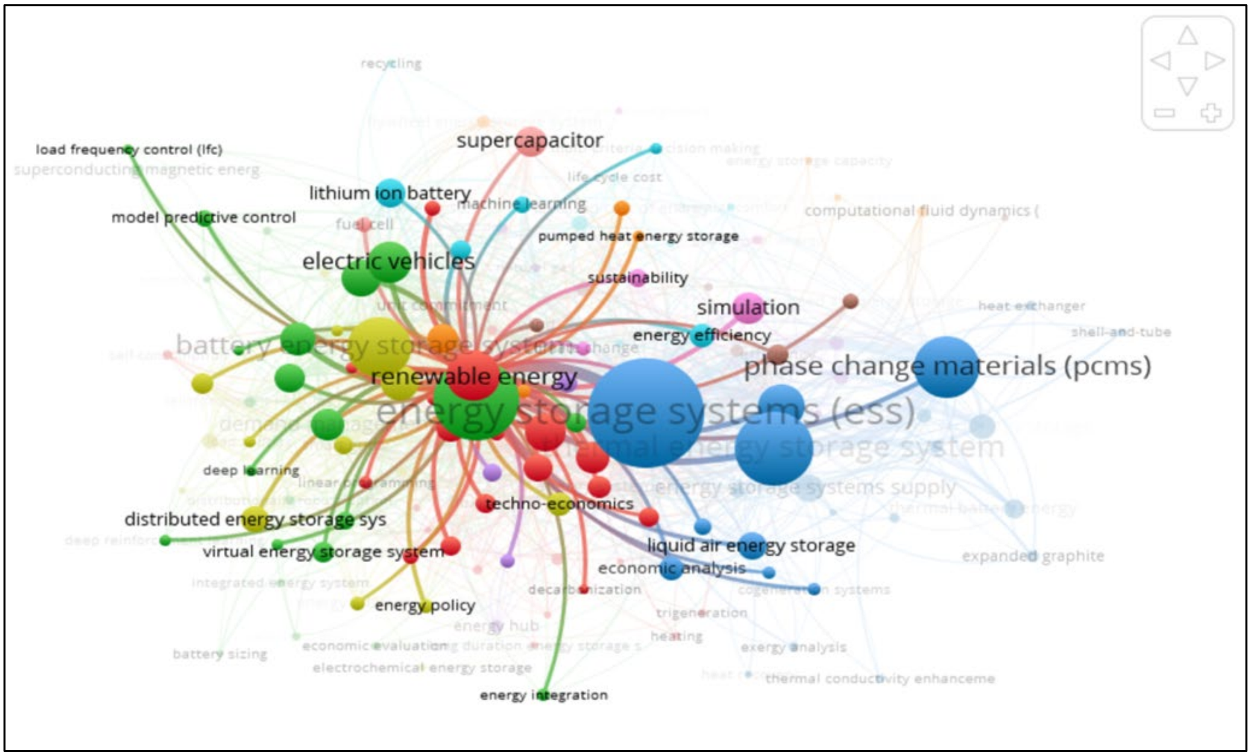

Figure 8. Co-occurrence Map of “Renewable Energy Storage” Keyword

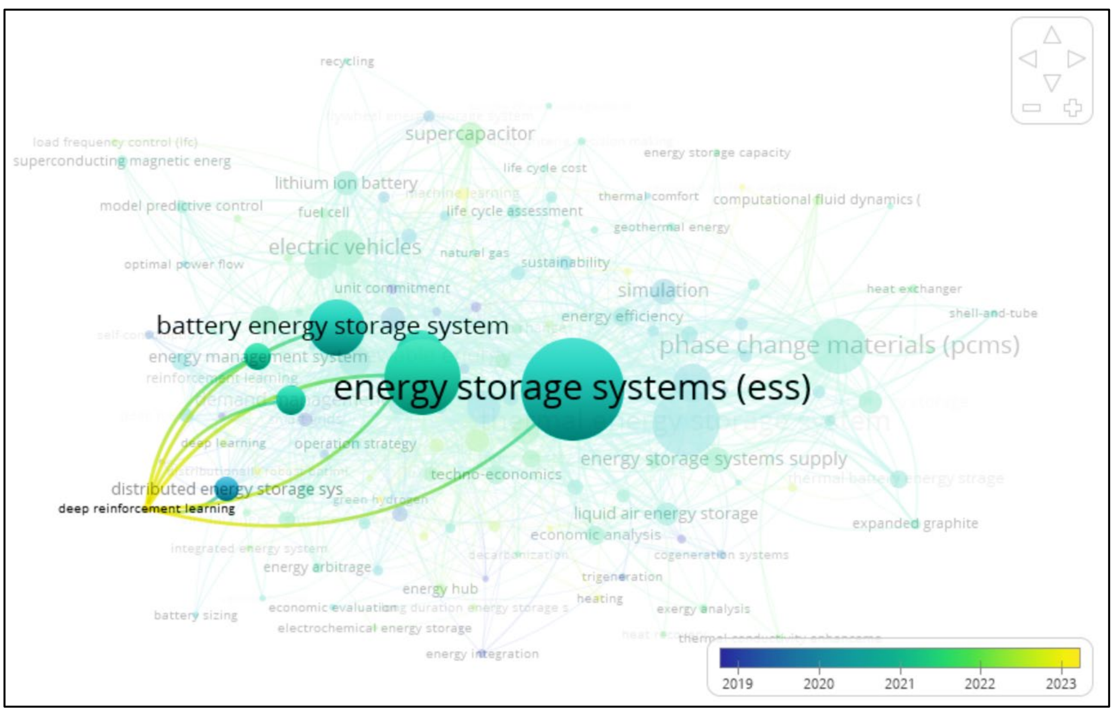

Figure 9. Author Keyword Overlay Visualization Map for The Main Keywords (a)

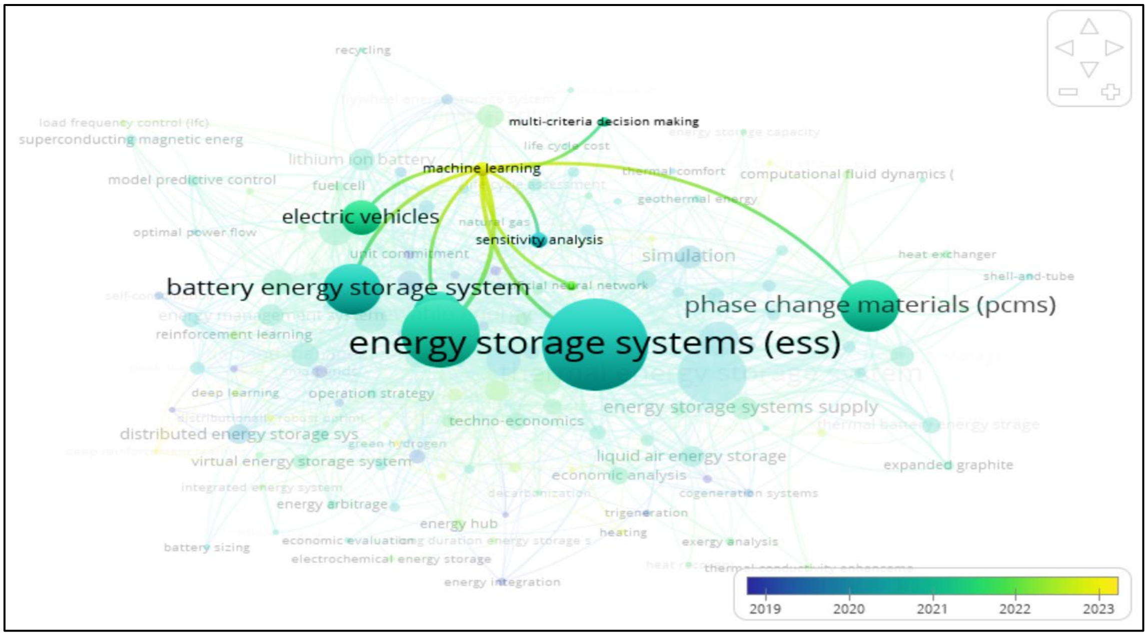

Figure 10. Author Keyword Overlay Visualization Map for The Main Keywords (b)

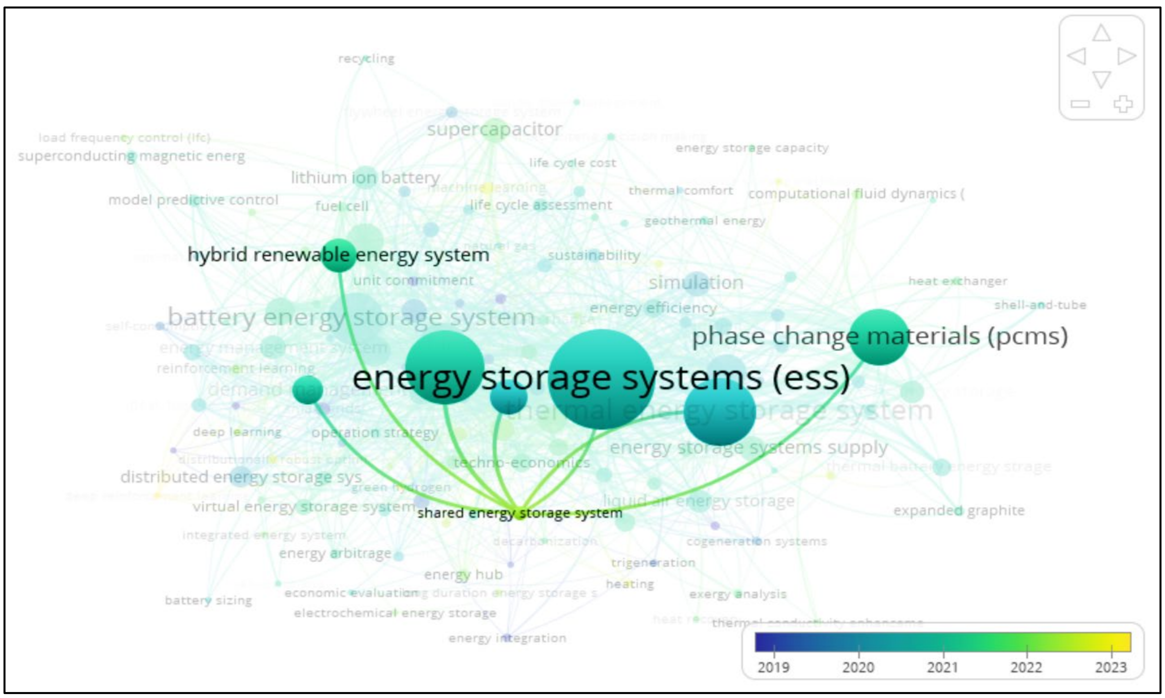

Figure 11. Author Keyword Overlay Visualization Map for The Main Keywords (c)

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Biographies

Dalal Bamufleh is currently a PhD candidate in the Department of Systems Science and Industrial Engineering at Binghamton University, State University of New York (USA). She holds a Master of Science degree in Management Information Systems from the University of Illinois at Springfield (USA) and a Bachelor's degree in Management Information Systems from Yanbu Industrial College (Saudi Arabia). She has more than nine years of academic teaching experience at Yanbu Industrial College. Her research focuses on supply chain modeling and optimization, with particular emphasis on energy storage systems (ESSs), battery supply chains, and the integration of renewable energy technologies such as solar photovoltaic (PV) modules.

Dr. Yong Wang is an accomplished researcher with a dual PhD background in Industrial Engineering & Operations Research from the University of Illinois at Chicago (USA) and Energy & Power Engineering from Huazhong University of Science and Technology (China). His academic journey includes a significant stage as a Visiting Scholar at the Department of Mechanical Engineering, University of Michigan, Ann Arbor. Presently, Dr. Wang serves as Associate Professor and Associate Director of the School of Systems Science and Industrial Engineering, Binghamton

University, USA. Dr. Yong Wang's research endeavors at Binghamton University are dedicated to the design, modeling, and management of various industrial systems, spanning energy, healthcare, manufacturing, and transportation sectors.