Frontiers in Economics and Management Volume 7 Issue 1, 2026
ISSN: 2692-7608 DOI: 10.6981/FEM.202601_7(1).0004

The Institutional Change Logic and Dynamic Evolution of China's Energy Storage Policies: A Long-Term Evaluation based on Social Network Analysis (2011-2024)

Fujian Song[1,2,*]

[1] School of Business Administration, Henan Polytechnic University, Jiaozuo, China

[2] School of Business Administration, Henan Polytechnic University, Jiaozuo 454003, China

[*]Corresponding Author

Abstract

As fundamental infrastructure for modern power systems, energy storage represents a pivotal enabler of worldwide sustainable energy strategies. Comprehending the trajectory of policy system evolution is essential to resolving key challenges in energy governance. Despite China leading in global energy storage deployment, current studies exhibit substantial limitations in deciphering the policy system's evolutionary dynamics, stage-specific features, and developmental trajectories. We construct a textual database of 121 central government policy documents, applying social network analysis through Python's Jieba tokenization and Gephi network visualization to decode keyword co-occurrence patterns, which illuminates the policy hotspot evolution and institutional transition mechanisms during 2011-2024. The research reveals a three-phase policy evolution: from "technology demonstration guidance" to "market ecosystem cultivation" and ultimately "system-level integration promotion", evolving from unitary fiscal support to an integrated framework incorporating market-based incentives, regulatory standards, and multi-stakeholder governance, resulting in synergistic advancement across three dimensions: institutional adaptability strengthening, market mechanism diversification, and technological paradigm shifts. The policy architecture exhibits comprehensive restructuring involving coordinated governance among generation facilities, grid operators, and end-users, along with perfected market mechanisms combining capacity payments, electricity spot trading, and ancillary service provisions, plus innovative policy models integrating mandatory standardization, commercial viability drivers, and core technology breakthroughs. These findings offer valuable institutional innovation references for international energy storage policy formulation.

Keywords

China's Energy Storage Policy; Dynamic Evolution; Social Network Analysis; Co-occurrence Analysis; Policy Metrics.

1. Introduction

As the largest global energy consumer, China's carbon emission governance performance is pivotal to achieving international climate targets [1]. According to International Energy Agency (IEA) statistics, China's total greenhouse gas emissions amounted to 12.6 billion metric tons CO2 equivalent in 2023, representing a 4.13% year-on-year growth [2] - substantially exceeding the global average growth rate. Under these circumstances, China's Carbon Peak and Carbon Neutrality strategy (hereafter "Dual Carbon" targets) has identified low-carbon energy structure transformation as the central pathway for emission mitigation [3]. Renewable energy, serving as the critical vector for energy transition, has emerged as the globally recognized solution for energy revolution owing to its clean nature, low-carbon characteristics and resource endowment advantages [4].

Nevertheless, the intrinsic variability, intermittency, and stochastic nature of renewable energy sources (RES) such as wind and solar photovoltaic (PV) generation impose substantial stability challenges to power systems when integrated at scale [5]. Consequently, system operators must deploy novel flexibility resources to ensure real-time supply-demand equilibrium [6]. This technical imperative highlights the regulatory merits of Energy Storage Systems (ESS): their dual capability of spatiotemporal energy shifting and rapid power response significantly enhances system flexibility for variable renewable integration. Operationally, ESS reduces renewable energy curtailment through price arbitrage between off-peak charging and peak discharging cycles [7]. Moreover, their millisecond-level inertial response capabilities can constrain frequency deviations within ±0.2Hz [8]. Thus, in the context of global low-carbon energy transition, energy storage emerges as a pivotal technological enabler for power system transformation [9].

Ensuring policy precision and efficacy constitutes the cornerstone for fostering sustainable industrial growth [10]. The growing policy consensus on energy storage prioritization has triggered global regulatory responses to accelerate storage deployment [11,12,13]. Nevertheless, energy storage policy research lags significantly behind technological advancements [14,15,16]. Existing research predominantly examines investment decision-making frameworks within discrete policy regimes [17,18,19,20]. Multi-criteria dispatch optimization frameworks for storage systems [21,22,23,24]. Game-theoretic approaches to multi-stakeholder coordination in storage systems [25,26,27,28]. Moreover, scarce empirical assessments of storage policy outcomes predominantly rely on qualitative methodologies, including systematic reviews [29], field investigations [30], and case analyses [31]. [32] conducted a global survey of compressed-air energy storage initiatives, synthesizing pertinent regulatory architectures and policy instruments. [33] analyzed U.S. energy storage legislation, policy interventions, and innovation pathways, while maintaining a qualitative research paradigm. Despite their merits, existing studies tend to focus on discrete policy instruments or qualitative assessments, lacking robust quantitative analysis of policy regime dynamics.

Notably, quantitative analysis of policy evolution is essential for deciphering intricate policy architectures, yet remains markedly underrepresented in the literature. This research gap constrains systematic understanding of policy transition mechanisms, impeding the discernment of evolutionary trajectories and optimization pathways. Several studies have adopted quantitative methodologies to examine technological and media trends in energy storage development. [34] utilized trend analysis and co-occurrence network modeling to scrutinize 4,168 news reports and 9,120 scholarly articles on South Korea's energy storage systems (2010–2023). [35] performed keyword co-occurrence analysis via CiteSpace software, mining lexical patterns from electrochemical energy storage publications. The findings reveal sustained exponential growth in global energy storage research, wherein China emerges as the predominant contributor, followed by the United States. [36] extracted Web of Science-indexed publications (2000–2023) covering five large-scale underground storage technologies, employing VOSviewer and CiteSpace to generate visualized knowledge maps that delineate publication trajectories, collaborative networks, research foci, and emerging frontiers. Nevertheless, these investigations lack quantitative visual decomposition of energy storage policy evolution.

To summarize, extant quantitative textual analysis of energy storage policies exhibits three critical limitations: (1) Inadequate policy document coverage, constrained to singular policy instruments or technology-specific storage policies. Considering the systemic attributes of energy storage development, where cross-sectoral energy policies exhibit synergistic effects, even general policy frameworks incorporate substantial storage-related provisions, particularly new energy industry promotion policies during the nascent phase of storage development. (2) They fail to delineate the dynamic evolution trajectories of thematic keywords, particularly the temporal patterns of keyword hotspots. (3) Absence of systematic investigation into the phase-transition logic underlying storage policy priority shifts.

To systematically elucidate the dynamic transition mechanisms and evolutionary pathways of China's energy storage policies We established a comprehensive database of China's national energy storage policy documents, employing Social Network Analysis (SNA) methodology, analyzing keyword co-occurrence networks in energy storage policies using Python's Jieba for text segmentation and Gephi for network visualization, uncovering the evolutionary trajectories of policy hotspots and their underlying transition mechanisms in China's energy storage sector (2011-2024). Social network analysis enables systematic mapping of policy actors and their interrelationships, while identifying key stakeholders and cohesive subgroups within the network. Network-based co-occurrence analysis facilitates the detection of thematic linkages across policy documents. [37] employed social network analysis combined with co-word analysis to investigate the historical evolution of China's resource recycling policies (1978-2016). These studies offer crucial methodological references for our current research.

This study makes three key contributions: (1) Construction of a systematic Chinese energy storage policy database comprising 121 central government documents (2011-2024) with direct/indirect relevance to energy storage. (2) Implementation of text mining (via Python's Jieba) and social network analysis (via Gephi) to deconstruct keyword co-occurrence networks, revealing the dynamic evolution of policy focuses . (3) Systematic analysis of policy transition mechanisms across three developmental phases - R&D demonstration (2011-2015), initial commercialization (2016-2020), and industrial scaling (2021-2024) - through chronological matrices, thematic network maps, and transition matrices, offering innovative institutional paradigms for global energy storage governance.

The paper proceeds as follows: Section 2 details the methodology, encompassing (1) policy document collection, (2) keyword extraction techniques, and (3) co-occurrence network visualization tools. Section 3 examines the historical progression and underlying transition mechanisms of China's energy storage policies. Section 4 synthesizes the evolutionary trajectories and emerging trends in China's energy storage policy framework.

2. Data Sources and Methodolog

2.1. Data Sources

This study analyzes preprocessed national-level energy storage policy documents (2011-2024) from China. The "12th Five-Year Plan" Outline (March 2011) marked China's first official mention of energy storage in national planning documents, mandating coordinated development of renewable energy, smart grids, and energy storage infrastructure during 2011-2015, thereby catalyzing the rapid growth of China's energy storage sector. This historical milestone justifies our 2011-2024 study period selection. Our analytical framework deliberately excludes subnational policy documents based on two methodological rationales: (1) Significant regional heterogeneity in energy storage deployment [38] creates fragmented policy landscapes, where policy implementation gradients correlate strongly with regional resource endowments, undermining cross-regional comparability;(2)The institutional dependency of local policies, requiring alignment with central government mandates, renders provincial documents administrative interpretations of national policies rather than independent analytical units [39].This hierarchical exclusion approach mitigates endogeneity bias from policy document redundancy [40].

Primary data sources comprise: (1) Official portals of Chinese regulatory bodies (National Energy Administration, NDRC, Ministry of Science and Technology, State Council) promulgating energy storage policies; (2) Specialized policy databases (e.g., Polar Star Energy Storage, Solarbe Energy Storage Network); (3) National legislative databases (e.g., PKULAW). The keyword strategy incorporated both direct terms (energy storage, pumped hydro storage, hydrogen storage) and indirect terms (renewables-plus-storage, virtual power plants, integrated energy systems, ancillary service markets, time-of-use pricing), ensuring comprehensive policy coverage. Our systematic review identified 121 national-level energy storage policies, spanning legislative documents, policy blueprints, and regulatory notices. After filtering generic terms (e.g., "national", "China", "department"), we conducted term frequency analysis.

2.2. Methodology

This study employs social network analysis (SNA) [41] to examine the dynamic evolution of energy storage policy priorities through network visualization. Using network nodes and their associations, we quantify topological metrics to reveal (a) global network characteristics, (b) inter-node relationships, and (c) nodal centrality measures [42]. Our analytical framework comprises two sequential phases: Phase 1: Policy keyword extraction Utilizing Python's jieba text segmentation module, we automatically identify keywords with quantity (3-5 terms per document) calibrated by text length, followed by manual refinement to derive core policy themes. Phase 2: Co-occurrence network analysis [43] where co-occurrence denotes the simultaneous appearance of keyword sets within individual policy documents. Network nodes represent policy keywords, with edge weights reflecting co-occurrence frequencies [44]. The resulting network visualization encodes (a) thematic importance via node size and (b) inter-thematic relationships through spatial proximity. We selected Gephi [45] as our primary visualization platform due to its: (1) Open-source architecture optimized for network visualization (2) Superior graphical rendering capabilities for complex networks [46] Our Gephi implementation generated co-occurrence networks revealing energy storage policy dynamics. Key analytical benefits include: (a) Automated filtering of low-weight edges to minimize lexical redundancy (b) Community detection algorithms that identify thematic clusters for temporal comparative analysis [47] The detailed analytical workflow proceeds as follows:

The policy evolution is periodized into three distinct stages per NDRC (2017) guidelines: (i) demonstration phase, (ii) commercialization period, and (iii) industrial scaling phase, denoted as $T_s(s=1,2,3)$ respectively. For T_s phase , keyword co-occurrence matrices generated via Python's text mining pipeline were input into Gephi, yielding network nodes i_{T_s}、 $j_{T_s}(i \neq j)$ and undirected edges L_{ij}^{Ts} .Node i_{T_s}、 j_{T_s} symbolizes policy keywords during T_s phase in the co-occurrence network. Each node pair i_{T_s}、 $j_{T_s}(i \neq j)$ constitutes a thematic dyad, where edge L_{ij}^{Ts} embodies inter-keyword i_{T_s}、 $j_{T_s}(i \neq j)$ linkages, with weight quantifying co-occurrence frequency across policy documents as a proxy for conceptual relatedness. Edge geometry encodes association strength - thicker and shorter edges denote higher co-occurrence frequencies.

Through Gephi's filtering module, irrelevant nodes and edges were pruned in T_s phase, generating a weighted network with N nodes. For node categorization, each policy-related keyword node was first defined as a distinct community module. A community module is defined as a group of energy storage policy keywords sharing categorical coherence within T_s phase, where a node's modularity benefit upon joining this group surpasses potential benefits from alternative groupings. For each node i_{T_s} with neighbor $j_{T_s}(i \neq j)$,assess the modular impact of transferring i_{T_S} from community I_{T_s} to host community J_{T_s} of j_{T_s} .Let ΔQ_{Ts}^{iJ} represent the modularity gain change. Node i_{T_s} migrates to J_{T_s} if $\Delta Q_{Ts}^{iJ} > 0$, otherwise retaining its original community affiliation. This algorithmic process iterates across all nodes until convergence (i.e., $\Delta Q_{Ts}^{iJ} \leq 0$ universally). Notably, empirical studies demonstrate that keyword nodes' chronological emergence order exerts negligible influence on community assignments (Dunford et al., 2004). The modularity gain ΔQ induced by transferring node i_{T_s} to community J_{T_s} is quantified as:

$$\Delta Q_{Ts}^{iJ} = \left[\frac{\sum in + 2k_{i,in}}{2m} - \left(\frac{\sum tot + k_i}{2m} \right)^2 \right] - \left[\frac{\sum in}{2m} - \left(\frac{\sum tot}{2m} \right)^2 - \left(\frac{k_i}{2m} \right)^2 \right] \tag{1}$$

ΔQ_{Ts}^{iJ} denotes the modularity gain of node i_{T_s} upon integration into community j_{T_s} ; $\sum in$ represents the total edge weight between policy keywords within community J_{T_s}, equivalent to the aggregated co-occurrence frequencies of keywords in the community J_{T_s} ; $\sum tot$ corresponds to the total edge weight between community J_{T_s} and the entire network, reflecting co-occurrences between community-specific and global policy keywords; k_i quantifies the global connectivity of keyword i_{T_s}, calculated as its cumulative co-occurrence frequencies across the network; $k_{i,in}$ captures the internal alignment of keyword i_{T_s} with community J_{T_s}, measured by its co-occurrence frequencies with keywords in J_{T_s} ; m serves as the global network metric, defined as the total co-occurrence frequencies between all keyword pairs.

The algorithm terminates when the community assignments of all nodes stabilize, indicating that keywords in period T_s are optimally clustered to maximize modularity. These community modules are then aggregated as super-nodes, with inter-community edge weights defined as the sum of all pairwise edges between their constituent nodes. The algorithm reapplies the initial clustering logic until convergence. Post-second iteration, the algorithm continues refining classifications through iterations until modularity peaks and no structural improvements are possible. This process yields a modular clustering of policy hotspot terms specific to the energy storage domain during period T_s.

3. The Categorization and Evolution Logic of Energy Storage Policy Development Stages

3.1. The Categorization of the Development Stages of Energy Storage Policies

This paper first conducts an annual quantitative analysis of national-level policy documents pertaining to the energy storage industry for the period 2011-2024. As shown in Figure 1. The results show a relatively low number of policies issued prior to 2020, with a marked increase occurring from 2021 onward. Between 2011 and 2020, the country released an average of about five relevant policies per year. This annual average rose to 15 policies during the three years from 2021 to 2023. The year 2024 saw the policy count reach its peak. As detailed in the top-left chart of Figure 1, the aggregate policy count grew from 19 in the 2011-2015 phase to 73 in the 2021-2024 phase, corresponding to an annual average growth rate of 20.3%.

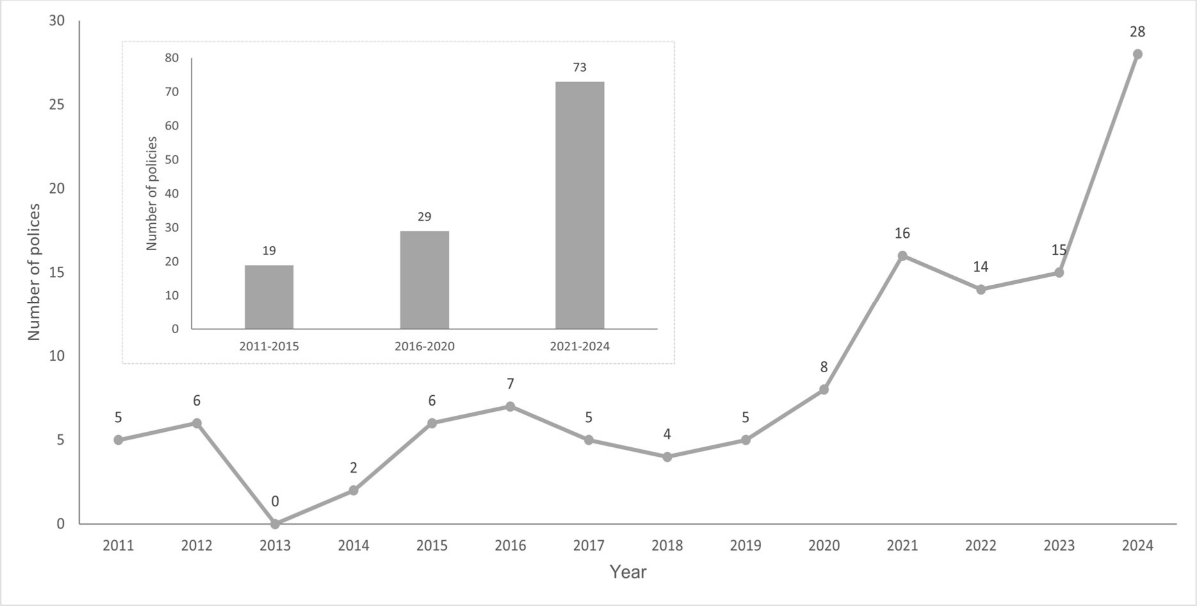

Figure 1. The Quantity and Temporal Distribution of Energy Storage Policy Issuance in China

Through a comparative analysis of keywords across different policy periods and considering major background events in the development of energy storage in China, the policy evolution is categorized into three phases: the Research, Development and Demonstration Phase (2011-2015), the Early Commercialization Phase (2016-2020), and the Industrial-Scale Expansion Phase (2021-2024). The general development features of China's energy storage policy evolution are presented in Table 1.

Table 1. Overview of the Evolution Process of Energy Storage Policies

Stage	Development Characteristics
R&D and Demonstration Phase(2011-2015)	The policy network, with “pilot demonstration,” “technology R&D,” and “financial subsidies” as its core nodes, established a “policy testbed” mechanism. This facilitated the establishment of seven national-level energy storage demonstration zones, including those in Shenzhen and Zhangjiakou, thereby completing the verification of technical feasibility and the initial cultivation of the industrial ecosystem.
Initial Commercialization Period(2016-2020)	The policy focus shifted towards “electricity pricing mechanisms,” “energy storage grid integration,” and “capacity markets.” The network structure transitioned from decentralized pilots to institutionalized construction, with key systems such as the energy storage project filing system and ancillary service market compensation mechanisms being implemented. This has propelled energy storage from the stage of technical validation into the initial phase of commercialization.
Industrial-Scale Development Period(2021-2024)	Dominated by key nodes including the “Dual Carbon Goals,” “Source-Grid-Load-Storage Integration,” and “New Power Systems,” the policy network has formed a hierarchical structure. Concurrently, policy tools have evolved from subsidy-driven measures to a mix of “market-based pricing, technical standards, and cross-industry coordination,” promoting the in-depth coupling of energy storage with applications in renewable energy, smart grids, electric vehicles, and other sectors.

Building upon the established periodization-the R&D and Demonstration Period (2011-2015), the Initial Commercialization Period (2016-2020), and the Industrial-Scale Expansion Phase (2021-2024)-the dynamic evolution of China's energy storage policies is visualized using three types of figures: a representative policy timeline, a modularity-based policy hotspot clustering network graph, and a dynamic keyword migration table. The first is a representative policy timeline that highlights the primary policy concerns at each stage. The second is a policy hotspot classification network graph derived from modularity analysis; the size of the node labels represents the relative importance of each policy hotspot. Specific clustering results are also marked in the graph, e.g., “Cluster 1: Energy Storage Technology R&D,” denoting a community of policy keywords pertaining to technological development in energy storage. The third is a dynamic keyword migration table across years, where each cell contains a (keyword, frequency) pair.

3.1.1. R&D and Demonstration Phase (2011-2015)

In late 2009, the development of the energy storage industry was first written into law. The development of energy storage was first mentioned in the "Renewable Energy Law Amendment," where Article 14 explicitly stipulated that "grid enterprises shall develop and apply smart grid and energy storage technologies" [48]. Guided by this legislation, regions such as Shenzhen, Shanghai, Jiangsu, Hunan, Gansu, and Hebei began formulating policies related to energy storage to promote the development of the industry. In March 2011, the Fourth Session of the 11th National People's Congress promulgated the "National 12th Five-Year Plan Outline," which for the first time included the term "energy storage" and proposed promoting smart grid construction by leveraging energy storage technologies. With the increasing scale of renewable energy grid integration and grid intelligence, the need for energy storage technology to enhance grid stability began to emerge, providing a practical and contextual foundation for the development of the energy storage industry. Consequently, this period is characterized as the R&D and demonstration stage. For this phase, 19 policies were collected; key representative policies are presented in Table 2. The dynamic shifts in policy focus, derived from automated keyword extraction using the Python jieba library, are summarized in Table 3.

Table 2. Timeline of Key Policies during the R&D and Demonstration Stage

Year	Policy
2011	Outline of the National 12th Five-Year Plan
2012	National Plan for Strategic Emerging Industries during the 12th Five-Year Period
2014	Action Plan for Energy Development Strategy
2015	Guidelines for Promoting Smart Grid Development

Table 3. Evolution of Policy Focus in the Research and Demonstration Period

Year	Keyword Frequency in Policy Focus
2011	Technology (121), System (63), Energy Storage (63), Grid (47), Battery (30)
2012	Energy Storage (81), Technology (75), Grid (68), Smart (60), Battery (35)
2014	Power Station (86), Construction (50), Planning (36), Management (25)
2015	Grid (62), Energy Storage (21), Smart (38), Technology (29), New Energy (24)

Utilizing the policy keyword frequencies presented in Table 3, which illustrates the evolving policy focus during the research and demonstration phase, a keyword co-occurrence matrix was constructed and analyzed using Gephi software to visualize the policy hotspot network and conduct modularity analysis (see Figure 2). The modularity analysis revealed three distinct clusters of policy hotspots for the energy storage sector from 2011 to 2015: energy storage technology research and development, power station construction, and grid development.

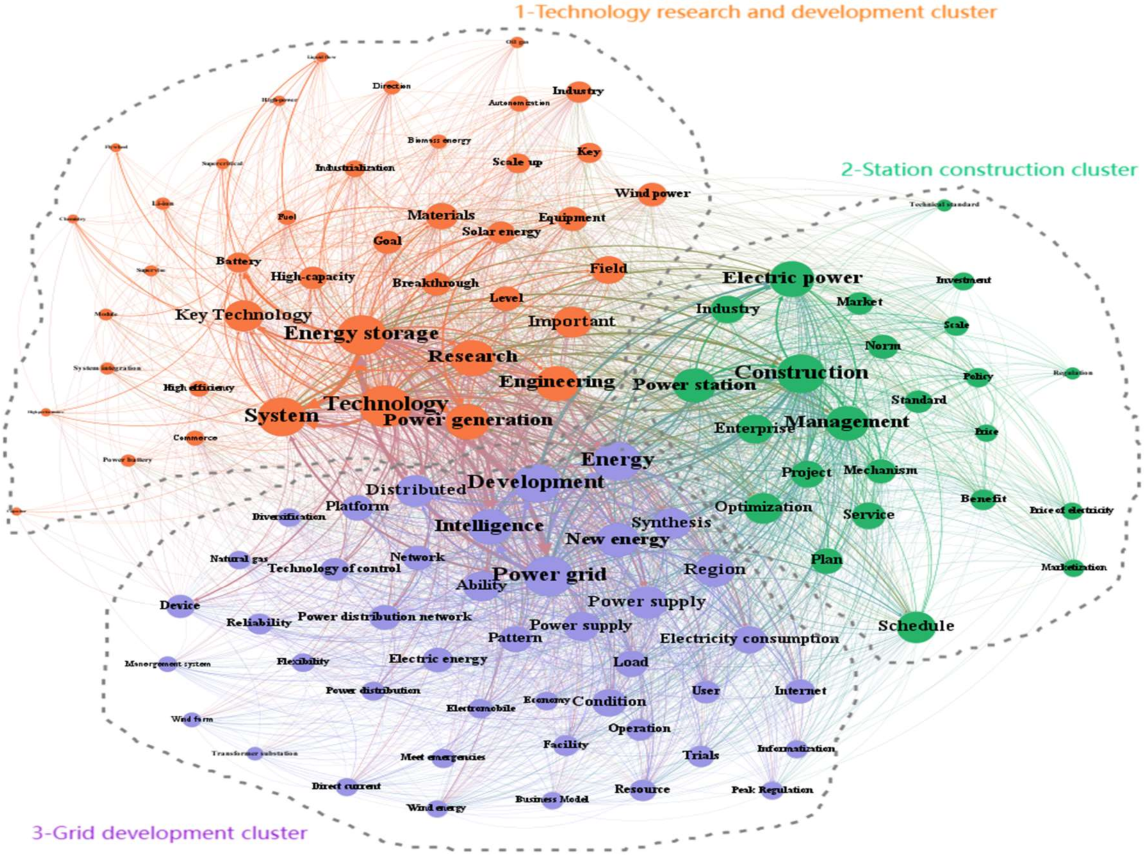

Figure 2. Policy hotspot network diagram during the R&D and demonstration period

Figure 2 and Table 3 reveal that "technology" was the highest-frequency keyword in policies of the research and demonstration phase (2011-2015), underscoring that policy focus during this period was predominantly on energy storage technology R&D. This emphasis is exemplified by policies such as the *Energy Development Strategy Action Plan (2014-2020)*, which explicitly called for enhanced R&D in energy storage technologies. The primary objectives were to develop key chemical energy storage technologies applicable to smart grids and renewable energy integration, and to advance low-cost, high-performance battery technologies and related key technologies for large-scale storage applications. Specifically, R&D efforts under this policy category included key technology research for long-life lithium manganate-based storage batteries, low-cost lithium titanate-based lithium-ion batteries, novel lithium-sulfur batteries, silicon-based next-generation chemical storage batteries, high-specific-energy and low-cost new supercapacitors, and other emerging chemical storage technologies. Within the research on other novel chemical storage technologies, the focus was on exploring new solutions characterized by high safety, long cycle life, and low cost, with prioritized support for key technologies such as lithium-ion flow batteries and all-solid-state lithium-ion batteries. For physical energy storage, key technology development centered on two main research streams: the R&D and demonstration of supercritical compressed air energy storage systems, and critical technologies for flywheel energy storage. The development of large-capacity, rapid-response energy storage systems was a continuous thread throughout this period, encompassing projects such as 10MW-class large-scale supercritical compressed air storage, MW-scale flywheel storage systems and arrays, MW-scale supercapacitor devices, MW-scale superconducting magnetic energy storage (SMES) systems, MW-scale sodium-sulfur (NaS) battery systems, and MW-scale flow battery systems.

Analysis of the power station construction policy cluster, as indicated by the keyword frequencies in Table 3, reveals a strong focus on "power station" and "construction". The energy storage stations deployed in this phase were predominantly government- or corporate-led pilot projects, exemplified by initiatives like the Zhangbei Wind-PV-Storage-Transmission Demonstration Project in Hebei Province, which served to validate the integrated operation of wind, solar, and storage technologies. These storage stations faced poor economic viability, depending heavily on policy subsidies and research grants. Pure merchant storage projects were rare; most were built as complementary assets paired with new energy generation facilities. Given its technological maturity, pumped hydro storage (PHS) continued to be the dominant form of utility-scale energy storage during the R&D and demonstration phase. PHS plants represented the most cost-effective option for large-scale energy storage infrastructure. Characterized by operational flexibility and fast response, PHS serves as a unique asset in power systems, providing multiple services including peak shaving, load valley filling, frequency regulation, phase compensation, operating reserves, and black-start capability. The large-scale integration of variable and intermittent renewable energy sources created heightened demand for the services provided by PHS. In response, the national policy "Guiding Opinions on Promoting the Sound and Orderly Development of Pumped Storage Power Stations" was issued, explicitly calling for "research into policies for the coordinated development of pumped storage and new energy." Co-locating PHS plants of appropriate scale within new energy bases was highlighted as a measure to improve renewable energy utilization rates and transmission economics. This underscored the need for further research into supportive development policies, including investment frameworks and market pricing mechanisms, to ensure the coordinated deployment of generation assets like PHS within renewable energy bases.

In the grid development policy cluster, the establishment of smart grid and microgrid demonstration projects constituted a major objective for the energy sector during this R&D and demonstration phase.Smart grid development, in particular, was a focal point for demonstration efforts. As early as 2011, China Southern Power Grid initiated the key National High-Tech R&D Program (863 Program) project "Smart Grid Key Technology Research and Development (Phase I)". Energy storage was recognized as crucial for smart grids, providing multiple benefits such as demand-side management, peak shaving and load leveling, enhanced efficiency of electrical equipment, reduced supply costs, facilitated renewable integration, improved grid stability, frequency regulation, and compensation for load variations. The *12th Five-Year Special Plan for Major Smart Grid Science & Technology Industrialization Projects* outlined specific targets, including 20-30 dedicated technology demonstrations, 3-5 integrated system demonstrations, 5-10 demonstration cities, and 50 demonstration parks for smart grids. Moreover, these demonstration projects were intended to stimulate innovation and growth in related industries like energy, advanced materials, and energy storage through targeted investment and knowledge diffusion. A key objective of the new energy microgrid demonstrations was to pilot integrated local power systems capable of hosting high shares of variable renewables, combining generation, grid management, storage, and consumption. Guided by the principles of "site-specific adaptation, multi-energy complementarity, flexible configuration, and cost-effectiveness," these microgrid demonstrations were deployed in regions with abundant renewables and diverse application potentials, leveraging smart grid, IoT, and storage technologies to maximize the role of new energy. These microgrids aimed to operate largely autonomously to meet local electricity demand, creating a new supply-consumption model that maximizes local renewable generation while maintaining supportive connections to the main grid. The *Renewable Energy Development 12th Five-Year Plan* set a target of establishing 30 new energy microgrid demonstration projects by 2015.

To conclude, the policy framework during the research and demonstration phase (2011-2015) was structured around key pillars of "pilot projects," "technology research and development," and "fiscal subsidies." This framework functioned as a "policy test-bed," which successfully promoted the implementation of seven national energy storage demonstration zones, such as those in Shenzhen and Zhangjiakou. This approach achieved the dual objectives of validating technological feasibility and fostering the initial development of an industrial ecosystem.

3.1.2. Early Commercial Stage (2016-2020)

The year 2016 saw the National Energy Administration release the *Notice on Promoting Electricity Storage Participation in Power Auxiliary Services in the "Three Norths" Regions*, which officially allowed energy storage systems to participate in the peak shaving and frequency regulation markets. Following this market entry, the volume of energy storage-related policies grew steadily, with their scope and depth also becoming more substantial. For this phase, a collection of 29 policies was compiled. Key representative policies are presented in Table 4. The shifting focus of policy hotspots over time is detailed in Table 5.

Table 4. Timeline of Key Policies in the Early Commercial Stage

Year	Policy
2016	Notice on the Pilot Program for Electricity Storage Participation in the Power Auxiliary Service Compensation (Market) Mechanism in the Three Northern Regions
2017	Guiding Opinions on Promoting Energy Storage Technology and Industrial Development
2018	2018 Guiding Opinions for Energy Work
2019	Action Plan for the Implementation of the Guiding Opinions on Promoting Energy Storage Technology and Industrial Development (2019-2020)
2020	Implementation Plan on Strengthening Energy Storage Standardization

Table 5. Evolution of Policy Focus in the Early Commercial Stage

Year	Keyword Frequency in Policy Focus
2016	Energy Storage (190), R&D/Technology (176), System (60), Battery (52), Material (42)
2017	Energy Storage (141), Technology (42), Service (18), Market (16), Transaction (15)
2018	Energy Storage (31), Technology (14), Electricity Price (13), Power Station (11), Peak Shaving (8)
2019	Energy Storage (75), Technology (21), Construction (15), Market (13), Ancillary Services (8)
2020	Energy Storage (138), Technology (71), Standard (29), Discipline (15), Talent (12)

The social network analysis of policy hotspots for this phase is presented in Figure 3. The keywords are clustered into four categories: grid infrastructure development, pilot project deployment, electricity market mechanism design, and energy storage technology R&D. Figure 3 and Table 5 indicate a rise in the frequency of the keywords "technology" and "grid" compared to the preceding phase. Additionally, "market", "service", and "pilot" became prominent keywords. Policy during this era addressed not only technological advancement and grid expansion but also actively explored commercial models for energy storage and the deployment of pilot projects. This phase marked a pivotal period characterized by rapid energy storage technology development, smart grid upgrades, large-scale pilot project rollout, and the initial formulation of electricity market mechanisms in China. The 2017 *Guiding Opinions on Promoting Energy Storage Technology and Industrial Development* outlined a two-stage roadmap, with the first milestone being the transition from the R&D demonstration phase to initial commercialization, followed by the second milestone of evolving from initial commercialization to large-scale development. Energy storage technologies progressed from pilot demonstrations toward commercial deployment, while grid infrastructure was rapidly enhanced to accommodate growing renewable energy integration. In 2019, State Grid Corporation of China proposed the "Ubiquitous Power Internet of Things" strategy to promote the digital and intelligent upgrade of the power grid. The issuance of the *Guiding Opinions on Promoting the Integration of "Wind-PV-Hydro-Thermal-Storage" and "Source-Grid-Load-Storage"* deeply embedded storage within the power sector, spurring technological progress and accelerating the adoption of the "renewables-plus-storage" model. Notably, the high-frequency keywords "talent" and "discipline" emerged in policy documents. The expanding renewable energy capacity fueled a growing demand for specialized technical professionals within the storage industry. In 2019, a joint *Action Plan for Discipline Development in Energy Storage Technology* was released by the Ministry of Education, NDRC, and NEA to expedite the establishment of dedicated energy storage programs in universities. In the early commercial stage, China's energy storage technology landscape exhibited healthy diversification. Pumped hydro storage (PHS) continued its rapid development and maintained its dominant market position. The development and deployment of various technologies accelerated, including compressed air energy storage (CAES), flywheels, superconducting magnetic energy storage (SMES), supercapacitors, lead-acid batteries, lithium-ion batteries, sodium-sulfur (NaS) batteries, and flow batteries. Lithium-ion batteries emerged as the market leader, while all-vanadium redox flow batteries were successfully validated in grid-scale demonstration projects. An example is the Dalian Flow Battery Energy Storage Peak-Shaving Station, which commenced operation in 2020. Post-2017, domestic research institutes and companies like HiNa Battery started pursuing sodium-ion battery technology as a potential low-cost alternative. Following technological breakthroughs, the national objective was to establish a diverse portfolio of pilot projects across various applications, develop scalable business models, and nurture competitive market players. On the grid side, China Southern Power Grid implemented frequency regulation demonstrations using storage in Shenzhen and elsewhere to improve grid flexibility. On the user side, Shanghai, Guangdong, and other regions utilized peak-valley price differentials to conduct energy storage arbitrage. The industry's entry into the early commercial stage saw the initial manifestation of energy storage's crucial role in the energy transition. The high-frequency keywords "ancillary," "service," "peak shaving," and "frequency regulation" signify that storage was primarily deployed to provide grid ancillary services, namely peak shaving and frequency regulation, during this period. During this phase, storage evolved into a key grid dispatch asset, supported distributed generation, and contributed to the development of electricity markets for storage. The National Energy Administration issued the *Basic Rules for Medium- and Long-term Electricity Trading*. This was significant as it formally recognized energy storage companies as independent entities eligible to participate in medium- and long-term electricity markets, a status they previously lacked. Despite remaining barriers to market participation, the establishment of these rules signaled growing governmental recognition of storage's value and its gradually strengthening position within the electricity market. Additionally, the *Notice on Relevant Work for the Continuous Trial Settlement of Electricity Spot Market Pilots* advocated for evolving medium- and long-term contracts from "energy-only" to "time-stamped power and energy" products, thereby refining the spot market price formation mechanism. During the early commercial stage (2016-2020), China witnessed the gradual maturation of storage technologies, the advancement of smart and ultra-high-voltage grid infrastructure, the large-scale rollout of pilot projects across grid-side, generation-side (with renewables), and consumer-side applications, and the initial establishment of electricity market mechanisms. This phase laid the essential groundwork for the industry's exponential growth post-2020.

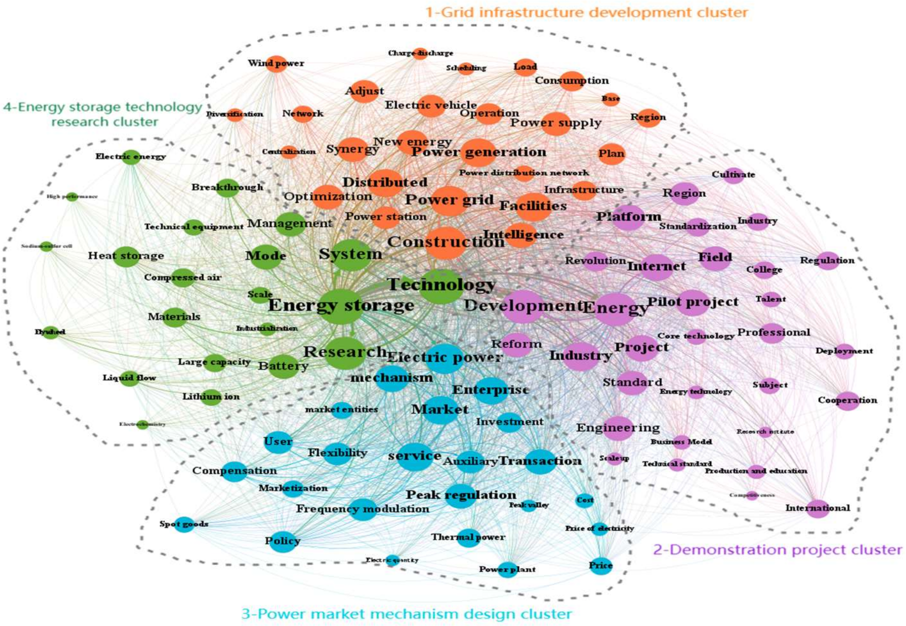

Figure 3. Network Visualization of Policy Focus during the Early Commercialization Stage

3.1.3. Phase of Industrial Scale-up and Expansion (2021-2024)

The year 2021 saw the release of the *Guiding Opinions on Promoting the Integration of Power Source, Grid, Load, and Storage and the Development of Multi-Energy Complementarity* by the NDRC. This policy gave rise to the concept of "Source-Grid-Load-Storage" integration, significantly elevating focus on the energy storage sector. This phase marked the beginning of a boom period for the energy storage market. The number of energy storage policies promulgated by the central government rose markedly in this period, totaling 73. key representative policies are presented in Table 6. The social network analysis for the phase of industrial scale-up and expansion is shown in Figure 4. The policy keywords in this phase are clustered into three primary categories: energy storage deployment, power market mechanisms, and energy security/risk.

Table 6. Representative Policies during the Industrial Scale-up Development Phase

Year	Policy
2021	Guiding Opinions on Accelerating the Advancement of New-Type Energy Storage
2022	Implementation Plan for New-Type Energy Storage Development in the 14th Five-Year Plan Period
2023	Guiding Opinions for Energy Sector Work
2024	Notice on Facilitating the Grid Integration, Dispatch, and Utilization of New-Type Energy Storage

Figure 4 and Table 7 clearly show that "electric power" was the highest-frequency keyword. This underscores the central government's emphasis on advancing electricity market reform and accelerating the commercial deployment of energy storage during this phase. The 2022 *Notice on Accelerating the Construction of the Electricity Spot Market* called for deepening power sector reform, speeding up the development of a unified national electricity market, and optimizing resource allocation through market mechanisms. The rollout of a substantial policy framework attracted increased investment into the storage market, fostering the development of diverse revenue streams. In contrast to the prior phase, the keywords "capacity" and "compensation" gained significant prominence in policy documents. This period saw the government instituting market-oriented capacity compensation mechanisms to incentivize investment in generation resources, thereby guaranteeing adequate system capacity, flexibility, and operational security. The *Basic Rules for Electricity Market Operation* outlined steps to establish a market-based capacity cost recovery mechanism, exploring tools like capacity payments and capacity markets to guide rational investment by market participants. Moreover, capacity leasing fees emerged as a key determinant of the economic feasibility for independent energy storage projects. Per the *Notice on Encouraging Renewable Energy Generators to Build or Purchase Peak-Shaving Capacity for Increased Grid Integration*, independent storage plants can lease capacity to off-takers for a fee. The fee structure, not yet standardized, is largely negotiated based on project revenue needs. Revenue from ancillary service markets and electricity spot markets also became significant income streams during this era. The *Regulations on Grid-Connected Entity Operation* and the *Measures for the Management of Power System Ancillary Services* formally granted new-type energy storage the status of an independent grid entity. This allowed it to participate in ancillary service markets for revenue, subject to relevant safety and operational rules. The Southern Regulatory Bureau of the National Energy Administration promulgated the revised "Two Detailed Rules" for the southern region. These rules elevated the qualification criteria for standalone energy storage stations, reaffirmed their independent market entity status, encouraged diversification of their revenue streams, enhanced compensation benchmarks, and thereby fostered the refinement of their business models. Functioning as an independent market participant, storage facilities could optimize their charge/discharge schedules using grid load forecasts and other data, with settlements based on spot market prices. In the electricity spot market, storage systems act as buyers (load) when charging, purchasing power directly from the market, and as sellers (generation) when discharging, selling power directly into the market. The keyword "technology" remained highly prevalent throughout all three policy phases. The sector's growth is intimately linked to technological advancement, which serves as its core driver. Lithium-ion battery costs fell persistently during this time (to approximately 0.6 RMB/Wh by 2024), cementing its position as the dominant storage technology. Firms like HiNa Battery facilitated the deployment of sodium-ion battery storage projects, advancing the technology toward commercialization. Integrated "wind-solar-hydrogen-storage" projects were initiated in regions like Zhangjiakou, Hebei, exploring hydrogen's role in energy storage. The keyword "scale up" appeared more frequently than in the preceding phase. Electricity market reforms and refined market mechanisms created favorable conditions for the scaled deployment of energy storage. The rising frequency of "electrochemical" and "battery" keywords, compared to earlier stages, reflects how new storage technologies broadened the sector's technological footprint. Consequently, government focus shifted towards new-type energy storage, leading to targeted policy formulation. In 2021, the NDRC released the *Guiding Opinions on Accelerating the Development of New-Type Energy Storage*. This policy introduced multifaceted measures aimed at advancing new-type energy storage. The growing prevalence of "pilot" and "standard" keywords signals the government's push to accelerate demonstration projects and establish a foundation for industrial scale-up through standardization. In 2023, a joint *Implementation Plan for the New Industry Standardization Leadership Project* was issued by MIIT, MOST, NEA, and SAC to enhance the standardization framework for the energy storage industry. The keyword "emergency" appeared with notable frequency. Safety concerns emerged alongside the growing scale of energy storage deployments. The release of the *Notice on Strengthening Safety Management of Electrochemical Energy Storage Power Stations* reflected the government's heightened focus on storage safety. The government enforced accountability, assigned clear responsibilities, and worked to improve the emergency response capacity of storage facilities. The keyword "reform" also saw increased frequency relative to the prior phase. The *Notice on Deepening the Market-Based Reform of New Energy Feed-in*

Tariffs eliminated fixed FITs for renewables, mandating full market participation and requiring storage to demonstrate its economic value through market mechanisms. During this phase, China's energy storage sector shifted from being policy-driven to competing in a market-oriented landscape. Technological diversification and business model innovation emerged as central trends. Government reforms facilitated the full integration of renewables into markets, enhanced electricity market mechanisms, and transformed storage's role from a passively allocated asset to an actively profitable one.

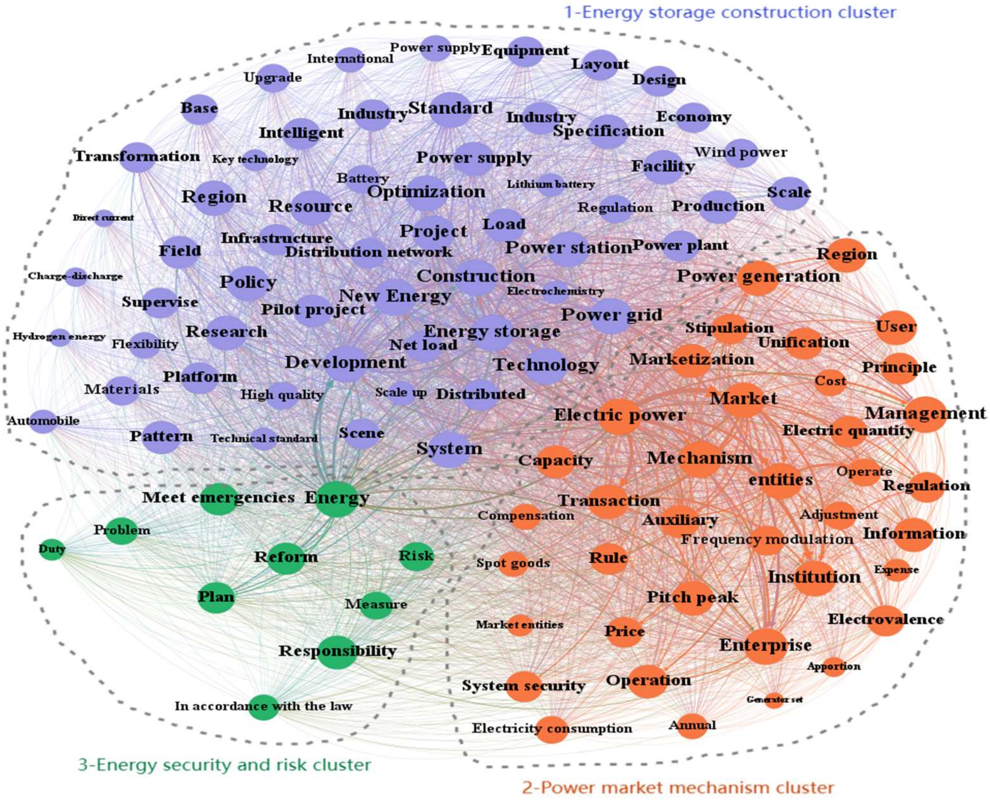

Figure 4. Policy Focus Co-occurrence Network for the Industrial Scale-up Phase

Table 7. Evolution of Policy Focus in the Industrial Scale-up Development Stage

Year	Keyword Frequency in Policy Focus
2021	Energy Storage (222), Technology (99), Institutional Design (59), Market (48), Capacity (42)
2022	Electricity/Power (154), Technology (141), Market (115), Pilot (40), Emergency Management (37)
2023	Electricity/Power (136), Energy Storage (126), Technology (82), Battery (66), Market (33)
2024	Electricity/Power (673), Market (653), Energy Storage (351), Capacity (244), Standardization (196)

3.2. The Logic and Reflections on the Evolution of China's Energy Storage Policies

The policy transition logic for energy storage is depicted in Figure 5.

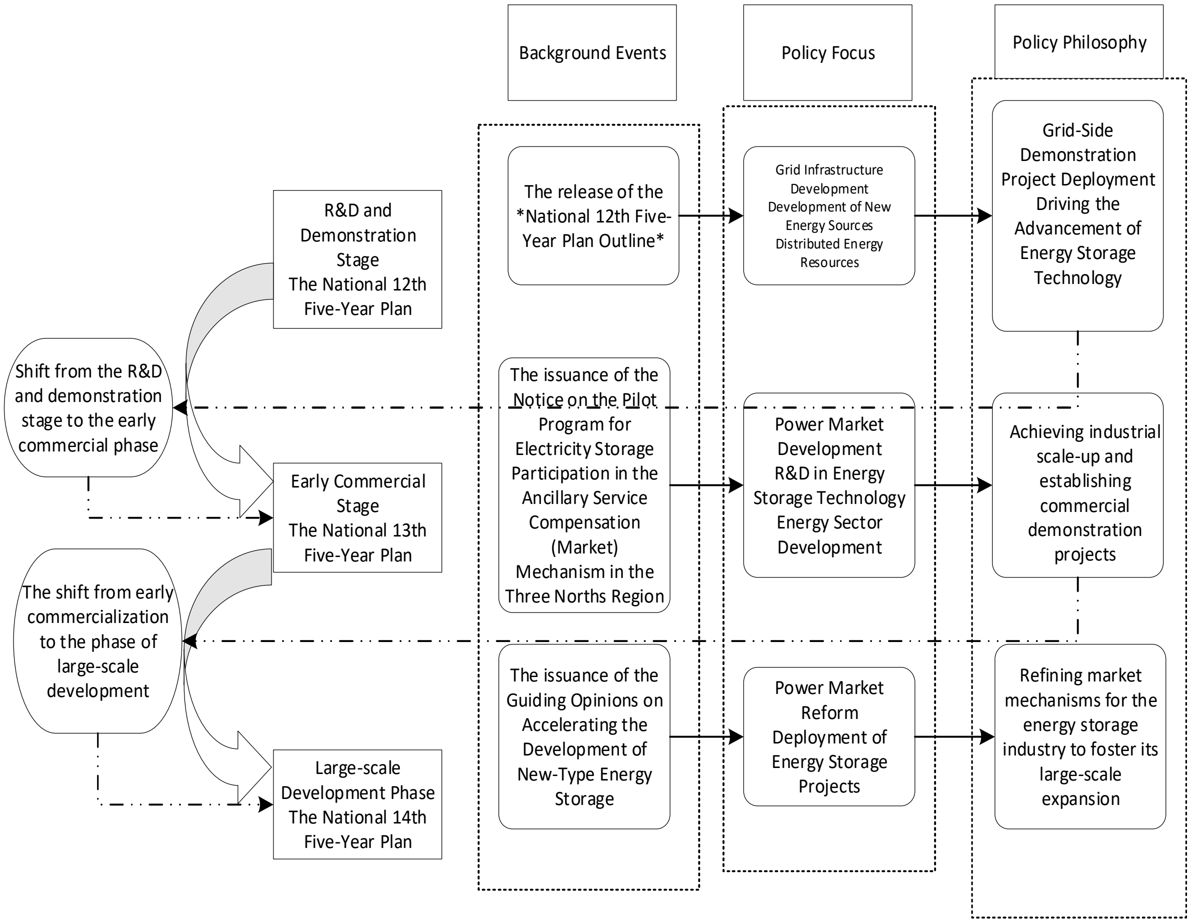

Figure 5. China's Energy Storage Policy Evolution Logic

During the 14th Five-Year Plan period, China's new energy storage target is to transition from the initial commercialization phase to the large-scale development stage. As a crucial tool for promoting energy storage development and deployment, its policy system is fragmented, making it difficult to form synergies, and the issue of inefficient implementation urgently needs to be resolved. Meanwhile, as an emerging industry, the energy storage sector inevitably encounters difficulties and challenges in the market, necessitating government support to safeguard its development. The relatively narrow range of policy instruments available at the national level and the incomplete nature of the policy architecture itself highlight critical areas for future improvement. This context gives rise to concrete demands for enhancing China's energy storage policy framework in three key dimensions: rebuilding the policy system, refining operational mechanisms, and achieving coordinated multi-stakeholder governance.

3.2.1. Enhancement Requirements for Restructuring the Energy Storage Policy Framework

National policies provide a principled macro-framework for the energy storage industry, yet they often lack specific operational guidance. Practical and actionable energy storage policies are primarily developed at the provincial level, tailored to local industrial conditions and needs. While this localized approach offers flexibility and relevance, it is often characterized by limited authority and weak enforceability. Furthermore, significant variations in regional subsidy standards and mechanisms, coupled with their narrow applicability, contribute to a fragmented policy landscape. The absence of effective coordination between these policies hinders the formation of a cohesive strategy, risks creating internal contradictions, and substantially undermines overall implementation efficiency. Consequently, a critical challenge lies in strengthening central guidance and leadership while fostering better alignment and synergy among local policies-a challenge that necessitates rethinking and reconstructing the policy system itself.

3.2.2. Enhancement Imperatives for the Energy Storage Market Mechanism

The sustained, healthy, and high-quality development of the energy storage sector hinges not on its duration or installed capacity, but on establishing effective cost pass-through mechanisms and viable business models. First, the revenue streams for energy storage projects in China are limited and uncertain. Although national policies advocate for storage participation in power markets to earn revenue from capacity leasing, spot market participation, ancillary services, and capacity compensation, China's electricity market remains dominated by planned dispatch and bilateral negotiations, with a relatively low level of marketization. Consequently, most provinces cannot access all these revenue streams concurrently. For instance, feed-in and charging tariffs for independent storage plants lack clear definitions, ancillary service markets offer limited products, and a national capacity payment mechanism for storage is absent. In provinces with high renewable penetration like Inner Mongolia, Ningxia, and Xinjiang, where power market reforms lag, market-based revenues are constrained, leading to generally low profitability. Even in regions with more advanced market reforms like Shandong and Shaanxi, storage revenues are hampered by small ancillary service market size, limits on spot price volatility, short-term leases, and unfavorable leasing cycles. Second, the absence of a cost pass-through mechanism makes it challenging to ensure project profitability. On one hand, the lack of large-scale deployment keeps the technological costs of energy storage high. Added to this are significant non-technological costs related to project development, land use, grid connection, compliance, and financing, keeping overall costs elevated. On the other hand, China's spot market is still largely a single-sided (generation-side) market. Storage costs cannot be passed through to consumers via grid tariffs and are primarily borne by generators. This structure fails to incentivize diverse stakeholders to optimally deploy storage or attract broad social investment into the sector. Therefore, improving the business models and market mechanisms for energy storage to effectively incentivize broader social investment and enhance policy efficacy remains a critical area for further research.

3.2.3. The Need for Enhanced Diversification of Energy Storage Policy Instruments

Current policy support for China's energy storage sector relies heavily on administrative instruments, with corresponding economic incentives being relatively insufficient and often short-lived. The absence of effective channels to recover high upfront investment costs directly hampers the rapid scaling of storage deployment, undermining its potential for optimal resource allocation across the power system. The critical role and future potential of long-duration energy storage (LDES) as a flexible grid resource is widely acknowledged within the sector. Moreover, China's energy storage industry is still nascent, and existing technologies do not yet fully cater to all application needs. Consequently, there is a pressing need for R&D focused on storage technologies characterized by low cost, high safety, and long cycle life. Presently, there is a notable scarcity of policies designed to boost R&D investment, especially those targeting innovation by upstream technology providers in the storage supply chain. Quality and safety are non-negotiable prerequisites for the large-scale deployment and sustainable growth of energy storage. Driven by policy signals and market prospects, a recent influx of firms and capital with limited technical expertise has entered the storage sector. To compete, many resort to low-price strategies, triggering a price war across the value chain. This fosters a "race to the bottom" in project tenders, where price outweighs quality, allowing substandard and unsafe products to enter the market and creating a chaotic landscape of disorderly competition. Therefore, competent authorities must act on multiple fronts-including standardization, enhanced regulation, and proper market cultivation-to restore order.

This involves refining policy mechanisms, strengthening industry standards and certification, and tightening market access, thereby guiding the sector back to market-driven and sustainable development. Hence, diversifying the toolkit of policy instruments emerges as another critical area for improvement that demands research and actionable solutions.

4. Conclusion

Drawing on a systematic analysis of the evolution of China's energy storage policy framework and targeting its core deficiencies-a fragmented structure, implementation inefficiencies, and an imbalanced policy toolkit-this research synthesizes and proposes enhancements. It outlines improvement pathways centered on restructuring the policy system, refining market mechanisms, and diversifying policy instruments. Specifically, system restructuring aims to enha-nce central-local coordination and planning. Mechanism refinement focuses on establishing r-obust business models and market mechanisms. Policy diversification seeks to address the se-ctor's multifaceted challenges with a tailored mix of instruments, preventing over-reliance on a narrow set of policy types. These proposed policy improvement pathways are visualized in Figure 6.

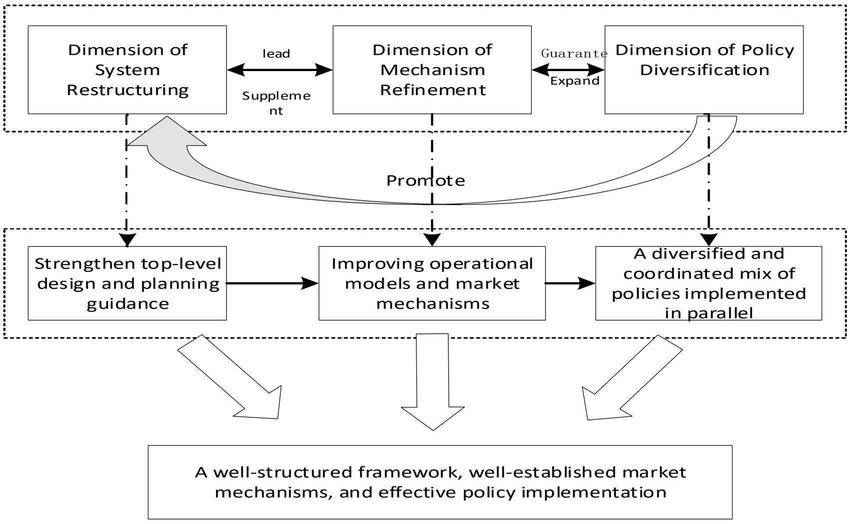

Figure 6. A Tripartite Enhancement Framework for China's Energy Storage Policy

4.1. Dimension of System Restructuring: Strengthen top-level design and planning guidance

Establish a coordinated policy ecosystem engaging diverse stakeholders from generation, grid, and consumer sides; Refine a tripartite price formation mechanism integrating capacity payments, spot markets, and ancillary services; Strengthen the mandatory regulatory framework g-overning renewables-plus-storage quotas and storage system efficiency standards; Explore policy alignment for emerging business models like virtual power plant (VPP) aggregation and shared storage; Develop an innovation policy portfolio that combines application-driven R&D with frontier technology breakthroughs. At the national level, top-level design should define appropriate scales and siting for renewable and storage projects, based on a comprehensive assessment of factors like grid integration capacity and national clean energy targets. Provincial energy authorities should propose region-specific scales and project layouts, ensuring alignment with national plans. This top-down and bottom-up coordination is crucial to prevent haphazard expansion, redundant investment, and inefficient resource allocation in the storage sector. Market identity for storage must be unequivocally established, both in ancillary service and spot energy markets. Achieving this requires consensus across national and local governments to formulate detailed rules for grid connection and access for independent storage facilities, enabling their operation as independent market entities. For example, for consumer-side storage, strategies should be developed to incorporate behind-the-meter storage into grid planning. Furthermore, to enhance operational flexibility and optimize system-wide storage deployment and dispatch, it is advisable to allow independent storage plants of varying capacities to connect at different grid voltage levels, ensuring they receive fair dispatch and market pricing.

4.2. Dimension of Mechanism Improvement: Improve operational models and market mechanisms

The establishment of robust market and pricing mechanisms is crucial for the sustainable and healthy development of the energy storage sector, serving as a primary catalyst for its transition from early commercialization to a phase of large-scale expansion. First, it is imperative to develop a comprehensive value assessment framework for energy storage. Aligned with the progression of China's power market reform, it is essential to nationally define clear market access criteria and entity status for storage applications, foster a level policy playing field, and ensure its multiple value streams are recognized through refined market mechanisms. Second, rational pricing policies specific to energy storage must be formulated. For storage primarily providing grid flexibility services, a two-part tariff system (integrating energy and capacity payments), modeled on the mechanism for pumped hydro storage, should be considered. For storage deployed as a non-wires alternative, it must demonstrate superior cost-effectiveness compared to traditional grid upgrades. Following rigorous evaluation, its costs could be incorporated into the grid tariff for recovery. Concurrently, efforts must accelerate to integrate storage into the electricity spot market and implement dynamic time-of-use pricing for end-users. This would enable storage to provide peak shaving and load shifting services, allow price signals to guide operations, suitably widen spot market spreads, and thereby enhance storage's revenue potential. A capacity market should be established in a timely manner to value storage's contribution to system adequacy and ensure it secures fair compensation. Third, the equitable allocation of storage costs must be addressed. Guided by the "beneficiary pays" principle, cost-sharing mechanisms among multiple stakeholders (generators, grid operators, consumers) should be developed, based on a clear identification of beneficiaries. The gradual pass-through of ancillary service costs to consumers should be piloted. Initially, costs could be shared by users participating in market transactions, with a future transition to broad allocation across all consumers in a fully competitive market.

4.3. Dimension of Policy Diversification: A diversified and coordinated mix of policies implemented in parallel

To achieve genuine commercialization and marketization, the energy storage sector requires more proactive economic incentive policies to attract a broader range of investors. During the industry's nascent phase, deployment should prioritize "quick-win" storage projects. Strong financial incentives, including substantial subsidies and tax breaks, are needed to lower costs and stimulate investment. Priority should be given to system-friendly projects (e.g., renewables with high storage penetration, integrated wind-PV-storage) and grid-side independent storage that enhances security and grid services. This approach builds a healthy foundation and accelerates the achievement of scale effects. Concurrently, a coordinated industrial policy is required to nurture the entire storage value chain. Supporting core enterprises with proprietary IP and competitiveness can drive full-chain development and foster strategic emerging industrial clusters. Continuous innovation and policy support will reduce costs and improve efficiency, leading to more robust and良性 market competition and ultimately, industrial-scale development.

Concerning technology R&D, the first priority is to initiate strategic R&D布局 for key long-duration storage (LDES) technologies, such as hydrogen storage, and to accelerate the development of a national LDES technology roadmap. This requires increased basic research funding, dedicated financial support for original innovation, securing proprietary IP, and enhancing the cost-performance of applied technologies. Second, actively promote the demonstration of advanced LDES technologies. Pilot projects can drive innovation and improve LDES competitiveness across efficiency, lifespan, and cost. Third, establish a technical standard system for LDES, updating it with industry progress and new applications to elevate sector-wide technical capabilities. Fourth, establish and improve the policy guarantee mechanism for long-duration energy storage, and gradually perfect the policy support mechanism for its development from aspects such as project management, technological innovation, market environment, pricing mechanisms, and industrial development.

The large-scale deployment of storage necessitates that authorities intervene on multiple fronts-standardization, regulation, and market cultivation-to bring order, refine policies, strengthen standards and certification, and tighten market access, ultimately guiding the sector toward sustainable, market-driven growth. First, accelerate the development and enforcement of critical technical standards. This involves forming dedicated standardization committees and working groups to prioritize standards for safety, quality, and environmental protection. Second, deepen safety and quality testing and certification regimes. This entails establishing a robust safety testing and certification system for lithium-based storage and fostering the growth of comprehensive testing platforms and accredited certification bodies. Third, enhance full lifecycle management of storage projects. Expedite the implementation of comprehensive and systematic management across all processes and factors, constructing a full lifecycle management framework for energy storage projects to ensure the systems' long-term safe and stable operation along with their environmentally sound recycling. Fourth, strengthen market oversight to regulate stakeholder behavior across the value chain, cleanse the competitive landscape, and prevent market failures.

Acknowledgments

We thank the anonymous reviewers and the editor for their helpful comments on the revision of the paper. This work is partially supported by The National Social Science Fund of China Grants (No. 23BGL230).

References

[1] State Council, 2024. China’s Energy Transition. 2024-08-29. https://www.gov.cn/zhengce/202408/content_6971115.htm.

[2] International Energy Agency, 2024. CO2 Emissions in 2023. 2024-03. https://www.iea.org/reports/co2-emissions-in-2023.

[3] Han J , Tan Q , Ding Y ,et al. Exploring the diffusion of low-carbon power generation and energy storage technologies under electricity market reform in China: An agent-based modeling framework for power sector[J].Energy, 2024, 308: 133060.

[4] International Renewable Energy Agency, 2024, World Energy Transitions Outlook 2024. 2024-11. https://www.irena.org/Publications/2024/Nov/World-Energy-Transitions-Outlook-2024-ZH.

[5] Zhang Z, Chen Y, Chen X, et al. A real options-based framework for multi-generation liquid air energy storage investment decision under multiple uncertainties and policy incentives[J]. Energy, 2024,309:133025.

[6] Franke K, Garcia JF, Kleinschmitt C, Sensfuß F. Assessing worldwide future potentials of renewable electricity generation: installable capacity, full load hours and costs Renew Energy, 2024, 226: 120376.

[7] Burgio A, Cimmino D, Dolatabadi M, et al., Virtual energy storage system for peak shaving and power balancing the generation of a MW photovoltaic plant[J], Journal of Energy Storage, 2023, 71: 108204.

[8] Johnson S C, Papageorgiou D, Harper M R, et al. The economic and reliability impacts of grid-scale storage in a high penetration renewable energy system[J], Advances in Applied Energy, 2021, 3: 100052.

[9] Li J, Hu J, Xin D. Cooperative control of hydrogen-energy storage microgrid system based on disturbance-rejection model predictive control[J]. Journal of Energy Storage, 2025,118:116242.

[10] Sun W , Hu S , Shen L .Quantitative Text Analysis of Circular Economy Policies for Electric Vehicle Batteries in China: Focus on Objectives and Tools[J].Journal of Cleaner Production, 2025, 501: 145021.

[11] Zhang J, Cho H, Luck R, et al. Integrated photovoltaic and battery energy storage (PV-BES) systems: An analysis of existing financial incentive policies in the US[J]. Applied Energy, 2018,212:895-908.

[12] Sani S B, Celvakumaran P, Ramachandaramurthy V K, et al. Energy storage system policies: Way forward and opportunities for emerging economies[J]. Journal of Energy Storage, 2020,32:101902.

[13] Deng L, Huan J, Wang W, et al. Market Operation of Energy Storage System in Smart Grid: A Review[J]. Energy Engineering, 2024,121(6):1403-1437.

[14] Huang Q, Aftab W, Cheng Y, et al. Form-stable metal ion coordination organic sorbent aerogel and its application in low temperature microwave-powered sorption thermochemical energy storage[J]. Journal of Energy Storage, 2025,114:115810.

[15] Chen Y, Li Z, Luo C, et al. Preparation and performance of tubular carbon-based carbonate composites for thermochemical energy storage[J]. Energy, 2025,319:134826.

[16] Wang X, Wang C, Xu Y, et al. Thermodynamic analysis of a novel multi-layer packed bed cold energy storage with low exergy loss for liquid air energy storage system[J]. Renewable Energy, 2025,240:122271.

[17] Liu J, Zhang Q, Teng F, et al. A new investment decision-making model of hydrogen energy storage technology based on real-time operation optimization and learning effects[J]. Journal of Energy Storage, 2024,96:112745.

[18] Sun B, Zhang Y, Fan B, et al. An optimal sequential investment decision model for generation-side energy storage projects in China considering policy uncertainty[J]. Journal of Energy Storage, 2024,83:110748.

[19] Sun B, Fan B, Zhang Y, et al. Investment decisions and strategies of China's energy storage technology under policy uncertainty: A real options approach[J]. Energy, 2023,278:127905.

[20] Zhao M, Zhang X, Hueng C J. The user-side energy storage investment under subsidy policy uncertainty[J]. Applied Energy, 2025,386:125508.

[21] Sun B. A multi-objective optimization model for fast electric vehicle charging stations with wind, PV power and energy storage[J]. Journal of Cleaner Production, 2021,288:125564.

[22] Adeyemo A A, Amusan O T. Modelling and multi-objective optimization of hybrid energy storage solution for photovoltaic powered off-grid net zero energy building[J]. Journal of Energy Storage, 2022,55:105273.

[23] Liu J, Song Y. Multi-objective configuration optimization model of shared energy storage on the power side[J]. Journal of Energy Storage, 2025,114:115706.

[24] Tang H, Li R, Song T, et al. Short-term optimal scheduling and comprehensive assessment of hydro-photovoltaic-wind systems augmented with hybrid pumped storage hydropower plants and diversified energy storage configurations[J]. Applied Energy, 2025,389:125787.

[25] Wang H, Zhang C, Li K, et al. Game theory-based multi-agent capacity optimization for integrated energy systems with compressed air energy storage[J]. Energy, 2021,221:119777.

[26] Shi J, Zhang W, Bao Y, et al. Game theory-based peer-to-peer energy storage sharing for multiple bus charging stations: A real-time distributed cooperative framework[J]. Journal of Energy Storage, 2025,109:115148.

[27] He Y, Wu H, Wu A Y, et al. Optimized shared energy storage in a peer-to-peer energy trading market: Two-stage strategic model regards bargaining and evolutionary game theory[J]. Renewable Energy, 2024,224:120190.

[28] Huang Z F, Wan Y D, Chen W D, et al. Optimizing government strategy for deep decarbonization in towns: A game theory approach incorporating energy storage services[J]. Journal of Cleaner Production, 2024,469:143107.

[29] Ölmez M E, Ari I, Tuzkaya G. A comprehensive review of the impacts of energy storage on power markets[J]. Journal of Energy Storage, 2024,91:111935.

[30] Semmelmann L, Konermann M, Dietze D, et al. Empirical field evaluation of self-consumption promoting regulation of household battery energy storage systems[J]. Energy Policy, 2024,194:114343.

[31] Ganege H C, Chandima D P, Karunadasa J P, et al. Optimization of grid-connected solar PV systems with Hybrid Energy Storage System: A case study of the Sri Lankan power system[J]. Journal of Energy Storage, 2025,114:115634.

[32] Matos C R, Silva P P, Carneiro J F. Overview of compressed air energy storage projects and regulatory framework for energy storage[J]. Journal of Energy Storage, 2022,55:105862.

[33] Gençer E, Agrawal R. A commentary on the US policies for efficient large scale renewable energy storage systems: Focus on carbon storage cycles[J]. Energy Policy, 2016,88:477-484.

[34] Jeoung J, Hong J, Choi J, et al. Analyzing news and research articles about energy storage systems in South Korea based on network analysis and topic modeling[J]. Energy and Buildings, 2025,335:115547.

[35] Dai J, Selvaraj J, Hasanuzzaman M, et al. Scientometric analysis of research hotspots in electrochemical energy storage technology[J]. Journal of Energy Storage, 2024,93:112300.

[36] Huang L, Hou Z, Fang Y, et al. The development, frontier and prospect of Large-Scale Underground Energy Storage: A bibliometric review[J]. Journal of Energy Storage, 2024,103:114293.

[37] Yao H, Zhang C. A bibliometric study of China’s resource recycling industry policies: 1978–2016[J]. Resources, Conservation and Recycling, 2018,134:80-90.

[38] Li J, Hu J, Xin D. Cooperative control of hydrogen-energy storage microgrid system based on disturbance-rejection model predictive control[J]. Journal of Energy Storage, 2025,118:116242.

[39] Sadabadi A A, Rahimirad Z, Nikijoo I. Enhancing cross-sector partnerships in energy saving through social entrepreneurship: A social network analysis approach[J]. Energy Research & Social Science, 2024,109:103412.

[40] Tang S, Fang A. Analysis of viewpoint evolution based on WeiBo data mining[J]. Applied Mathematics and Computation, 2025,491:129212.

[41] Liu W, Song Y, Bi K. Exploring the patent collaboration network of China's wind energy industry: A study based on patent data from CNIPA[J]. Renewable and Sustainable Energy Reviews, 2021,144:110989.

[42] Martin C, Cai W. Social Networks and Organizations [M]. Wang Feng B, Zhu Chao W, et al. Beijing: China Renmin University Press, 2007:5-6.

[43] Vahidzadeh R, Bertanza G, Sbaffoni S, et al. Regional industrial symbiosis: A review based on social network analysis[J]. Journal of Cleaner Production, 2021,280:124054.

[44] Yuan C, Zhu Y. Research on China's photovoltaic industry based on dynamic hot spots [J]. Science and Technology Management Research, 2020,40 (14): 43-53.

[45] Okonta D E. The scientometric analysis and visualization of sustainable procurement[J]. Heliyon, 2023,9(10):e20985.

[46] Yang J, Wang P, Liu X, et al. Analysis on causes of chemical industry accident from2015 to 2020 in China's mainland: A complex network theory approach[J]. Journal of Loss Prevention in the Process Industries, 2023,83:105061.

[47] Liu Y. Network data visualization and analysis tool [M]. Beijing: Electronic Industry Press, 2017.

[48] National People’s Congress, 2009. Renewable Energy Law of the People's Republic of Ch-ina (Amendment). 2009-12-26. http://www.npc.gov.cn/npc//c2/c12435/c12488/201905/t20190522_65300.html.