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Review

Bibliometric Analysis of Game Theory on Energy and Natural Resource

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Abstract: This paper uses CiteSpace software to conduct a bibliometric analysis of research literature under the topic of game theory which specifically focuses on energy and natural resources in the Web of Science Core Collection. The results show that: since 1990, the number of documents covering the topics of "energy" and "game theory", and "natural resources" and "game theory" has continued to grow steadily, and entered an explosive growth stage after 2017. In terms of disciplinary classification of published papers, Energy & Fuels has the highest frequency, 311 with a significant centrality, 0.22. In terms of journal publications, Applied Energy is the most cited journal whose frequency is 311 and centrality is 0.01. In terms of country, China has the highest number of published papers, and the United States with the highest overall centrality of papers. North China Electric Power University published 31 papers, the largest number of documents from one institution. In terms of author productivity, Puyan Nie has been the most productive author since 2016. The co-citation cluster analysis on the literature topics shows that the game theory of energy and natural resources have roughly gone through four stages: (1) From 1990 to 2009, this is the embryonic stage with no more than 15 new papers per year; (2) From 2010 to 2014, this stage had microgrid as its mainstream research topic, and other topic clusters officially emerged; (3) From 2015 to 2017, the main research topics became the integrated energy system, subsidy mechanism and household energy management, with a hot topic on the evolutionary game process between government and enterprises; (4) From 2018 to 2021, this stage continued to focus on the previous topics, and the research goes much deeper, resulting in more models and new green technologies. Finally, the keyword analysis concludes with nine themes of concern in this research field, and has come to a comprehensive summary of the mainstream research methods in the field of game theory of energy and natural resources.

Keywords: energy; natural resources; game theory; optimal allocation mechanism; bibliometrics; research frontier

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1. Introduction

In this paper, we use CiteSpace software to conduct a bibliometric analysis of research literature under the topic of game theory on energy and natural resources. We focus on articles in the Web of Science Core Collection and screen out 700 literature data. Our analysis shows that the number of documents in this research field had been growing slowly but steadily since 1990, before entering into an explosive growth state in 2017. In terms of disciplinary classification of published papers, environmental science and green innovation technology are the most closely related to this research field. In terms of country origin of papers, China has produced the largest number of research papers while the United States has published the most influential papers in this field. Co-citation cluster analysis on literature topics shows that this field has experienced about four stages: 1990~2009, 2010~2014, 2015~2017 and 2018~2021. Major research themes generally appeared in the second and third stages. Many of these studies went much deeper in the fourth stage, resulting in new models and new green technologies. Last but not least, keyword analysis helps us to identify nine major topics in the field of game theory on energy and natural resources.

The 26th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP26) was held in Glasgow, Scotland, UK on 31 October 2022. This has been the largest and perhaps most landmark climate change event since the Paris climate conference in 2015. At the same time, the world is facing an unprecedented energy crisis: the use of coal is taking the opportunity to return, and the global carbon neutralization process has started a "reversal", and all human beings are confronting with a game dilemma of how to achieve a balance in the predicament of the imminent financial crisis, the increasing frequency of extreme climates and the soaring energy prices [1]. The second half of 2021 saw a soaring energy price driven by a combination of supply shortages and increased demand. Against this backdrop, coal has reemerged as the best option on the market as it is cheaper than other energy sources such as oil and gas, which obviously has a detrimental effect on the metric of achieving carbon neutrality. In the post-pandemic era, the global economy is on track to recover, industrial production activities have resumed, and the frequent occurrence of extreme weather in the northern hemisphere has led to an increase in household energy demand, and the global demand for coal has grown rapidly. Under the triple impact of financial crisis, energy crisis and climate crisis, the study of "game theory in the field of energy and natural resource" should be of great significance to the development of all mankind in the 21st century. Based on CiteSpace software, this paper summarizes the evolution process of the research direction and the current research focus of this cross field through in-depth research on the literature under related subject headings. Under the impact of triple crises in the post-epidemic era, we expect that the future game model will have more constraints. The government's carbon neutrality policy and macroeconomic policy will have a more profound impact on the energy economy. The evolution of the game model will be more complex and more layered. Our paper is informative and innovative in that we fill an important gap. Many researchers have done bibliometric studies on various subdisciplines of sustainability, but few have reviewed an interdisciplinary field that combines economics and sustainability. We believe that our interested research topic, game theory on energy and natural resources, is a remarkable example of a cross-disciplinary field. Additionally, this cross-disciplinary field is not an arbitrarily created research field, but it is of great importance to economists and decision-makers. Applying game theory methods and perspectives to sustainability and innovation helps policy makers to maximize benefit for all, as well as to understand individual behaviors on a micro-level. Thus, a review study on this field, namely game theory on energy and natural resources, can potentially provide researchers with many new perspectives and insights.

2. Methodology and Data

To perform bibliometric analysis with a large number of literature data, first of all, we should choose the most suitable software from a few options: CiteSpace, RefViz, HistCite and SATI. We examined plenty of bibliometric studies on many research topics and eventually narrowed down our focus on bibliometric studies on topics under the sub-disciplines of sustainable technology. For example, researchers have done bibliometric studies on green marketing in sustainable consumption, carbon neutrality, aquaculture, manufacturing product innovation, etc. [2–6]. After studying these papers, as well as experimenting with our options, we have reached conclusions in regard to the advantages and disadvantages of the software. Software such as RefViz and HistCite are well known for keyword frequency counting and topic clustering, but they are not able to generate analysis on co-citation. SATI cannot generate timeline maps of research topics. In comparison, CiteSpace is the superior option due to its timeline map function and co-citation function. Using CiteSpace, we are able to obtain various types of visualizations which helps us to understand knowledge structure and dynamics between documents in our literature dataset [2–6]. We can also gain insights into the knowledge bases, networks, hotspots, tendencies of research fields and dynamic relations between papers, authors and even subgroups of the research field [2]. In addition, we are able to gain quantitative analysis on our collection of documents, and this is a significant advantage because generally researchers can only perform qualitative analyses in literature reviews. Conceptual model of this paper is presented in Figure 1.

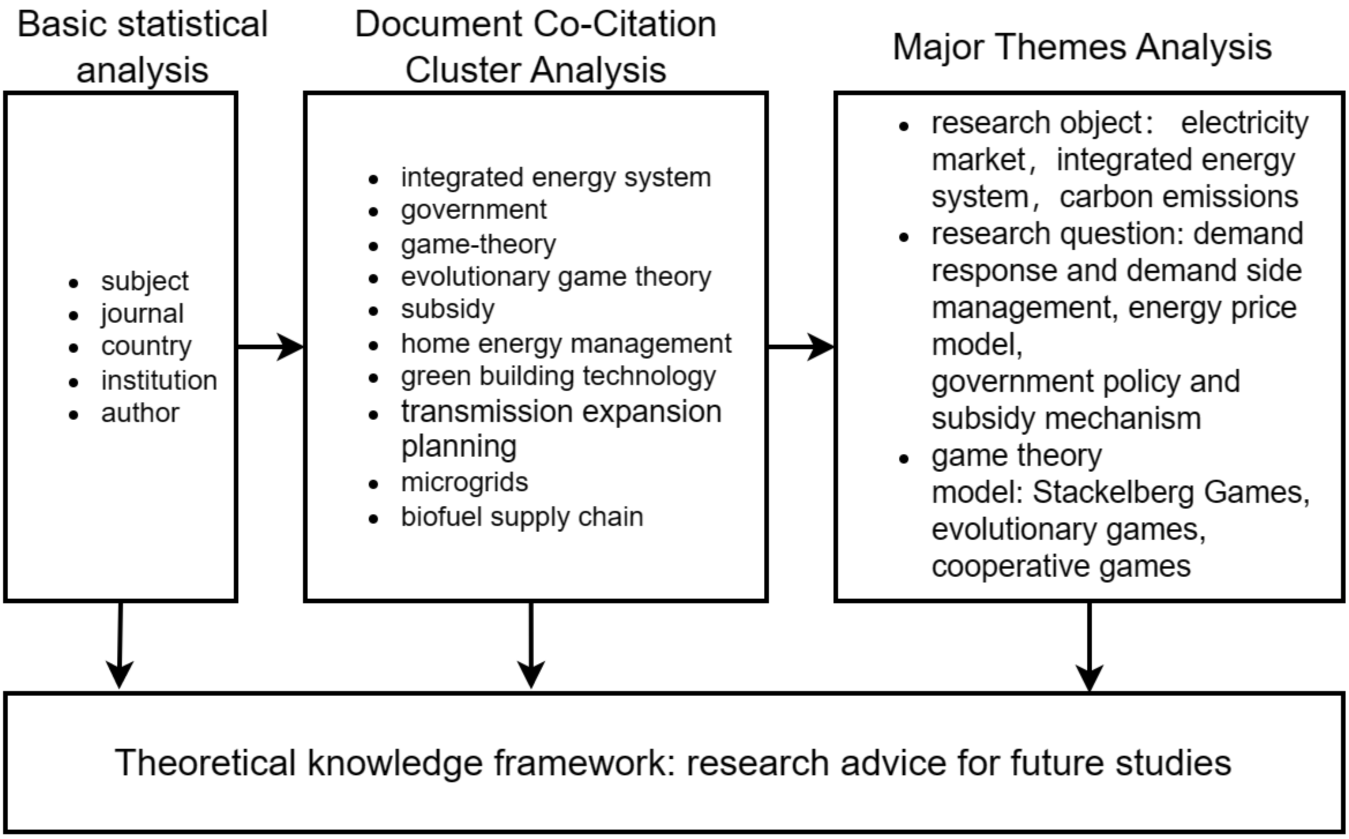

Figure 1. Conceptual model of the paper.

At present, CiteSpace software is widely popular in the field of bibliometric analysis due to its powerful co-citation analysis function, and is widely used in computer science, economics, medicine and other fields. Based on CiteSpace software, this paper conducts a quantitative analysis of all international literatures on the topics of "energy" and "game theory", as well as "natural resources" and "game theory". The data in this article all come from the Web of Science Core Collection, which includes three important paper databases, namely SCI, SSCI, and A&HCI. Each literature data includes the title, authors, publication time, publication journal, paper abstract, references and publishers' address links, so that researchers can download the full text of the literature through the publishers' addresses. First of all, we enter "Energy" and "Game Theory" as the two subject headings under the Web of Science Core Collection with no limit on publication time but with the document type limited to "thesis". We then remove articles under the category of computer and information science and keep classifications of related disciplines such as energy, environmental science, economics and operations research. Next, we enter "natural resources" and "game theory" under the Web of Science Core Collection and then repeat the above operations. After removing duplicates, we obtained a total of 700 valid literature data, the first of which was published in 1990. Since 1990, the number of documents covering the topics of "energy" and "game theory", "natural resources" and "game theory" have grown slowly at a rate of 1 to 6 per year and entered an early development period in 2005 with 7 new articles. In 2010, the number of new documents reached 15, and such research finally entered a period of development. In 2019, more than 100 new papers were published in the field of game theory of energy and natural resources, and such research entered a stage of rapid growth. The annual increase in literature from 1990 to 2021 is shown in Figure 2.

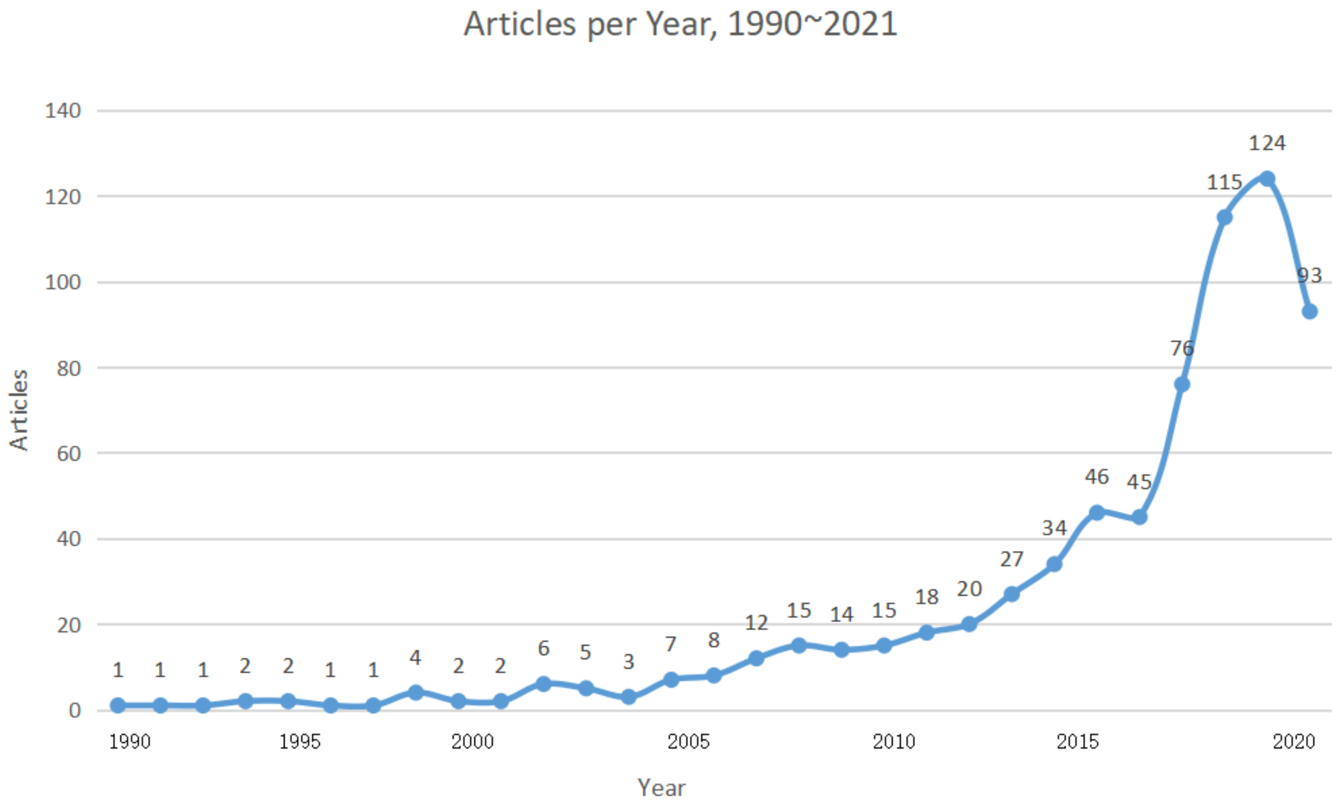

Figure 2. The growth of the number of documents from 1990 to 2021.

3. Results Analysis

3.1. Five Basic Information Analysis of Literature: Subjects, Journals, Countries, Institutions and Authors Background Analysis

First of all, we conduct a subject classification analysis. We use CiteSpace to process titles, abstracts, authors and keywords of the literature data from January 1990 to December 2021 and to select the node types of "Categories", "Cited Journal", "Country", "Institution" and "Author" in turn. The time slice is 1 year, and selection criteria are set as follows: k = 25, LRF = 3.0, L/N = 10, LBY = 5 and e = 1.0. The last selection criteria, g-index, is obtained through $g^2 \leq k \sum_{i \leq g} c,\ k \in z^+$. From the classification results, Energy & Fuels has the highest frequency, 311, and its centrality is 0.22. The occurrence frequencies of Environmental Sciences & Ecology and Engineering are 225 and 204, respectively, and their centralities are as high as 0.47 and 0.36. The categories ranked 4–6 are Environment Sciences, Science & Technology—Other Topics and Green & Sustainable Science & Technology, whose centralities are 0.09, 0.05 and 0.02, respectively. Among the categories ranked 7~10, it is worth mentioning that Business & Economics, whose frequency is 79, has the third highest centrality (0.23). In terms of appearance time, Environmental Sciences & Ecology appeared in 1994 and is the oldest subject, while the youngest category is Green & Sustainable Science & Technology, whose first article was published in 2012.

In terms of cited journals, Applied Energy is the most cited journal and has a frequency of 311 and a low centrality of only 0.01. Applied Energy published the first article in this field in 2013. The second and third most frequently cited journals are Energy and Energy Policy. These two journals have centralities of 0.03 and 0.08, respectively, and they published the first articles in this field in 2003. *Journal of Cleaner Production* and *Renewable & Sustainable Energy Reviews* are the 4th and 5th most cited journals whose citations are 180 and 178 and centralities are 0.04 and 0.01. They published their first articles in this research field in 2012 and 2015, respectively.

In terms of national sources of papers, China is currently the country with the largest number of published papers. It has published 246 papers, accounting for 35% of the total number, and has a centrality value of 0.28. The United States ranks second and has 162 publications. The United States is also the country with the highest centrality, with a value of 0.5. This shows that, although the United States has fallen behind in terms of number of studies in this field, it is still the “center” of this research field. Iran, which ranks third in terms of quantity, started late and only published its first paper in 2006. Iran has published 61 papers so far, with a centrality of 0.21. The 4th country is the United Kingdom, the country with the longest contribution in this field, with its first document published in 1990 and a high centrality of 0.23. It has published 40 papers. Countries ranked 5th to 8th are Canada, Germany, Australia, Italy and Sweden, among which Australia has the highest centrality, which is equal to 0.09. Italy started the latest and published its first literature in 2008. It is worth mentioning that centrality may be affected by the language of the literature, and the global influence of English may also enhance the influence of English-speaking countries in this research field.

The distribution of institutional sources of papers is less dense than the above node types. North China Electric Power University contributed the largest amount of literature, with a number of 31 papers and a centrality of 0.02. Iran’s Islamic Azad University and Tabitha Modales University ranked two to three in terms of the number of papers. They have published 14 and 12 papers, respectively, starting from 2015 and 2011, respectively. Tsinghua University is the last among the top 10 institutions in terms of the number of publications. Its first article was published in 2017, but it is also the institution with the highest centrality, which is equal to 0.05. In terms of centrality, together with North China Electric Power University, MIT ranks second with seven papers, with its first published in 2008.

Finally, in terms of productivity of famous authors in this research field, the most productive author in this field is Puyan Nie, who has published 10 papers since 2016. He is followed by Chan Wang, who has published eight papers since 2017. The 3rd and 4th most productive authors are Morteza Rastibarzoki and Soroush Safarzadeh, who have published six and four articles, respectively, since 2019. Subject, citing journal, country, institution and author information for literature are presented in Table 1.

Table 1. Subject, citing journal, country, institution and author information for literature in the field of game theory regarding energy and natural resources.

Rank	Count	Centrality	Year	Category
1	311	0.22	2003	Energy & Fuels
2	225	0.47	1994	Environmental Sciences & Ecology
3	204	0.36	1996	Engineering
4	173	0.09	2000	Environmental Sciences
5	155	0.05	1995	Science & Technology—Other Topics
6	140	0.02	2012	Green & Sustainable Science & Technology
7	86	0.03	2001	Environmental Studies
8	79	0.23	2000	Business & Economics
9	67	0	2009	Engineering, Chemical
10	61	0	2010	Engineering, Environmental
Rank	**Count**	**Centrality**	**Year**	**Cited Journal**
1	262	0.01	2013	*Appl Energ*
2	222	0.03	2003	*Energy*
3	198	0.08	2003	*Energ Policy*
4	180	0.04	2012	*J Clean Prod*

Table 1. *Cont.*

5	178	0.01	2015	*Renew Sust Energ Rev*
6	174	0.08	2006	*Ieee T Power Syst*
7	162	0.03	2012	*Ieee T Smart Grid*
8	145	0.06	2009	*Eur J Oper Res*
9	121	0.01	2013	*Renew Energ*
10	118	0.01	2013	*Int J Elec Power*
Rank	**Count**	**Centrality**	**Year**	**Country**
1	246	0.28	1999	Peoples R China
2	162	0.5	1992	Usa
3	61	0.21	2006	Iran
4	40	0.23	1990	England
5	33	0.05	2000	Canada
6	24	0.01	2003	Germany
7	23	0.09	2006	Australia
8	20	0.03	2008	Italy
9	19	0.08	2007	Sweden
10	16	0.04	2003	India
Rank	**Count**	**Centrality**	**Year**	**Institution**
1	31	0.02	2015	North China Elect Power Univ
2	14	0	2015	Islamic Azad Univ
3	12	0	2011	Tarbiat Modares Univ
4	10	0	2016	Guangdong Univ Finance & Econ GDUFE
5	10	0.05	2017	Tsinghua Univ
6	8	0	2012	Xi'an Jiao Tong Univ
7	8	0	2016	Shanghai Jiao Tong Univ
8	7	0.01	2016	Hong Kong Polytech Univ
9	7	0.01	2014	Beijing Inst Technol
10	7	0.02	2008	MIT
Rank	**Count**	**Centrality**	**Year**	**Author**
1	10	0	2016	Puyan Nie
2	8	0	2017	Chan Wang
3	6	0	2019	Morteza Rastibarzoki
4	4	0	2019	Soroush Safarzadeh
5	4	0	2017	Qiong Wu
6	4	0	2017	Hongbo Ren
7	3	0	2008	Ariel Dinar
8	3	0	2014	Guanghui Zhou
9	3	0	2019	Nadeem Javaid
10	3	0	2018	Andreas Ehrenmann

3.2. Analysis of Document Topic Evolution: Document Co-Citation Cluster Analysis

Next, we analyze the evolution process of game theory in regard to energy and natural resources based on the literature co-citation clustering function in CiteSpace software. We will show the development context and current hotspots in the field of game theory on energy and natural resources in terms of relevant researchers. Co-citation refers to the fact that two papers are cited simultaneously by one or more papers. The literature co-citation clustering feature of CiteSpace software can capture similarities in literature data, group literature data based on the extraction results and extract the core theme of each cluster. We only perform evolution analysis on research topics from January 2010 to December 2021, because we focus more on recent developments under the topics of game theory on energy and natural resources than past research topics. Just as before, we set the time slice to 1 year, and the selection criteria are set as follows: k = 25, LRF = 3.0, L/N = 10, LBY = 5 and e = 1.0. As a result, we have 625 valid documents, 467 nodes and 1209 connections, with a density of 0.0111. In addition, the value of modularity Q is equal to 0.8477, which means that the boundaries of each research topic are relatively clear, and the fields are highly differentiated. The weighted mean silhouette is equal to 0.9513, indicating that the intra-cluster homogeneity is very strong, and each cluster has a very significant overall theme. Harmonic mean (Q,S), which is equal to 0.8965, refers to the reciprocal of the arithmetic mean of the reciprocal of the Q value and the S value. This value represents the overall result of the degree of cluster differentiation and the degree of homogeneity within the cluster, indicating that we obtained a common theme.

The results of cluster analysis are shown in Table 2. We can roughly divide the 10 clusters into three categories: the first category has only 1 cluster, #8 Microgrids. The timespan of cited papers is 2010–2014 and the average publication year of cited papers is 2012. Cluster #8 Microgrids did not last long and entered a silent period in 2015. No new articles have been published since 2015, indicating that the research has reached mature and clear conclusions, or there has been a breakthrough in the research process, pushing the research into a new direction while putting an end to the previous direction. The second category consists of clusters #2 Game Theory, #7 Transmission Expansion Planning (TEP) and #9 Biofuel Supply Chain (BSC). Among them, #2 Game Theory is a more classic study with a longer timespan. The timespan of the cited literature is 2011~2018, and the average year is 2013. The #7 TEP cited literature spanned from 2013 to 2017, the average publication year was 2015 and it entered a quiet period after 2018. Finally, the timespan of #9 BSC is relatively short. The timespan of the cited literature is 2014~2017, and the average year is 2015. Although the start time and duration of these three clusters in the second largest category are inconsistent, they all entered silent period at around 2017~2018, and no new articles were published after that. Almost all clusters in the first and second categories are short-lived, while all the topics in the third category are still active, and even the year 2021 witnessed a lot of new literatures published. It is the frontier direction of this research field. The third category includes clusters #0 Integrated Energy Systems (IES), #1 Government, #3 Evolutionary Game Theory (EGT), #4 Subsidy, #5 Home Energy Management (HEM) and #6 Green Building Technology (GBT). Among them, clusters #1 Government and #5 HEM have the longest timespan. The starting year of the co-cited documents under this cluster is 2013, and the average publication year is 2016. Clusters #3 and #4 started in 2014, and the average publication year was 2017 and 2016, respectively. Cluster #0 IES started in 2015, and the average publication year was 2017. The latest cluster #6 GBT started in 2016 and has an average publication year of 2017 for co-cited articles. From the enduring cluster #1 Government to the novel and cutting-edge cluster #6 GBT, these six clusters are hot topics in the field of game theory on energy and natural resources. Researchers are still actively exploring mature solutions in these areas.

Table 2. List of subject terms in each cluster.

#	Name	Size	Mean Year	Top Terms (LSI)
0	Integrated Energy Systems	72	2017	game theory; flexibility transaction; p2p transaction mechanism; dynamic flexibility index; nash equilibrium | energy trading; seeking methods; risk assessment; non-linear dynamic system; non-dispatchable energy generation
1	Government	42	2016	game theory; supply-chain management; hazardous waste; closed-loop supply chain; energy-efficiency program | direct tariff; green supply chain; governmental regulation; supply chains competition; intervention schemas
2	Game Theory	40	2013	game theory; renewable energy; energy storage; electricity markets; distribution system | nash equilibrium; palm biomass; supply chain; procurement strategy; networked cournot competition
3	Evolutionary Game Theory	25	2017	evolutionary game theory; electric vehicle; public-private partnership cooperation; solar power; ccs technology adoption | evolutionary game; green transformation; green buildings; governance mechanism; green building material industry
4	Subsidy	24	2016	energy efficiency; green finance; order financing; clean innovation; green insurance | environmental planning; clean innovation; green insurance; countryside development; order financing
5	Home Energy Management	23	2016	photovoltaic installations; game-based pricing strategy; heuristic algorithm; power markets; real-time market | home energy management system; home microgrid; electricity market; profit allocation; coalition formation
6	Green Building Technology	16	2017	evolutionary game; construction industry; green building technology; diffusion model; complex network | diffusion model; complex network; pest analysis; energy substitution; construction industry
7	Transmission Expansion Planning	14	2015	transmission expansion planning; cooperative game theory; cost-benefit allocation; coalitional operation; renewable integration | renewable integration; power system; energy policy; shapley value; offshore grid
8	Microgrids	13	2012	service regulation; electric utility; cooperative game theory; economic efficiency; renewable energy | game theory; demand response; renewable energy; service regulation; electric utility
9	Biofuel Supply Chain	8	2015	biofuel supply chain; government regulations; evolutionary game; strategy selection | evolutionary game; strategy selection; government regulations; biofuel supply chain
ID	**Name**	**Size**	**Mean Year**	**Top Terms (Log Likelihood Ratio, p-Level)**
0	Integrated Energy Systems	72	2017	integrated energy systems (5.09, 0.05); prosumer (5.09, 0.05); prosumer participation (5.09, 0.05); evolutionary game theory (4.65, 0.05); evolutionary game (3.98, 0.05)
1	Government	42	2016	government (12.4, 0.001); supply-chain management (8.23, 0.005); social welfare (8.23, 0.005); consumer behavior (8.23, 0.005); closed-loop supply chain (4.1, 0.05)
2	Game Theory	40	2013	game-theory (7.29, 0.01); optimal bidding strategy (7.29, 0.01); benefit allocation (7.29, 0.01); demand response aggregator (dra) (7.29, 0.01); distributed energy network (7.29, 0.01)
3	Evolutionary Game Theory	25	2017	evolutionary game theory (20.75, 0.0001); game theory (9.74, 0.005); simulation (8.71, 0.005); evolutionary game (5.37, 0.05); electric vehicle (5.03, 0.05)
4	Subsidy	24	2016	subsidy (20.19, 0.0001); energy efficiency (12.35, 0.001); green finance (6.13, 0.05); gongcheng (6.13, 0.05); countryside development (6.13, 0.05)

Table 2. *Cont.*

6	Green Building Technology	16	2017	green building technology (14.4, 0.001); construction industry (14.4, 0.001); evolutionary game (13.68, 0.001); government policy (10.63, 0.005); cleaner energy substitution (4.4, 0.05)
5	Home Energy Management	23	2016	home energy management system (7.64, 0.01); home microgrid (7.64, 0.01); electricity market (4.14, 0.05); stackelberg game (4.14, 0.05); smart grid (4.14, 0.05)
7	Transmission Expansion Planning	14	2015	transmission expansion planning (14.08, 0.001); benders decomposition (6.96, 0.01); cost-benefit allocation (6.96, 0.01); north sea offshore grid (6.96, 0.01); coalitional operation (6.96, 0.01)
8	Microgrids	13	2012	microgrids (7.29, 0.01); micro-grid (7.29, 0.01); cost-benefit (7.29, 0.01); elasticity (7.29, 0.01); incentives (7.29, 0.01)
9	Biofuel Supply Chain	8	2015	biofuel supply chain (16.03, 0.0001); strategy selection (7.89, 0.005); rin (7.89, 0.005); government regulations (7.89, 0.005); decentralized decision-making (7.89, 0.005)

ID	Name	Size	Mean Year	Top Terms (Mutual Information)
0	Integrated Energy Systems	72	2017	risk assessment (1.13); non-linear dynamic system (1.13); technical conversion coefficient (1.13); electricity retailers (1.13); peer-to-peer (p2p) energy trading (1.13)
1	Government	42	2016	closed-loop supply chain (0.41); government subsidy (0.41); energy productivity (0.41); industrial energy efficiency program (0.41); intervention schemas (0.41)
2	Game Theory	40	2013	networked cournot competition (ncc) (0.56); milp (0.56); demand response scheduling (0.56); coordination strategy (0.56); regulation revenue function (0.56)
3	Evolutionary Game Theory	25	2017	new energy vehicles (0.36); fiscal decentralization (0.36); periodical fluctuation (0.36); low-carbon supply chain (0.36); green building material industry (gbmi) (0.36)
4	Subsidy	24	2016	green finance (0.11); gongcheng (0.11); countryside development (0.11); forest (0.11); order financing (0.11)
5	Home Energy Management	23	2016	photovoltaic installations (0.5); distributed game-based pricing strategy (0.5); mgo (0.5); pricing and power-generation strategy (0.5); distributed optimal control (0.5)
6	Green Building Technology	16	2017	photovoltaic installations (0.05); risk assessment (0.05); non-linear dynamic system (0.05); green finance (0.05); closed-loop supply chain (0.05)
7	Transmission Expansion Planning	14	2015	benders decomposition (0.06); cost-benefit allocation (0.06); north sea offshore grid (0.06); coalitional operation (0.06); power system flexibility (0.06)
8	Microgrids	13	2012	microgrids (0.05); micro-grid (0.05); cost-benefit (0.05); elasticity (0.05); incentives (0.05)
9	Biofuel Supply Chain	8	2015	game theory (0.04); strategy selection (0.04); rin (0.04); government regulations (0.04); decentralized decision-making (0.04)

From 2015 to 2018, there are many cluster-level connections, indicating high co-citation frequencies of papers and close connections of papers across different clusters. There are multiple vertical lines between clusters #0 IES, #2 Game Theory and #5 HEM. Cluster #1 Government is more associated with clusters #0 IES and #2 Game Theory. Yu M (2016) under cluster #2 Game Theory is closely related to multiple articles under clusters #0 IES, #3 EGT, and #5 HEM. Cluster #3EGT has multiple connections with clusters #1Government and #4 Subsidy. Banez-Chicharro F (2017) under cluster #7 TEP is closely linked to multiple articles on clusters #0 IES and #2 Game Theory. Under the cluster #8 Microgrids, Montuori L (2014) had a relatively significant relationship with the two articles under cluster #2 Game Theory, and we believe that they may have had an impact on each other. Zhang HM (2017) under cluster #9 BSC is closely linked to multiple articles in clusters #0 IES and #1 Government.

We analyze important co-cited documents from two perspectives: centrality and frequency. The co-cited documents are ranked according to their frequencies and centralities respectively. The ranking results are shown in Tables 3 and 4. Documents with high frequencies are cited more frequently in other documents in the cluster, while documents with high centralities are cited more frequently in documents in different clusters. That is, the former represents the degree of horizontal connection, and the latter represents the degree of vertical connection. According to the frequency, the most important document in the co-cited document network is Chen WT (2018), with a total of 14 citations and a centrality of 0.05. In their 2018 paper, Chen WT et al. applied evolutionary game theory to examine the strategies of manufacturers in response to various combinations of carbon taxes and subsidies [7]. First, Chen WT et al. developed an evolutionary game theory model of the interaction between the government and manufacturers based on static carbon taxes and subsidies and then analyzed the evolutionary behavior of the government and manufacturers under three additional models, namely dynamic taxes and static subsidies, static tax and dynamic subsidy and dynamic tax and dynamic subsidy and finally reached the conclusion that the bilateral dynamic tax subsidy mechanism is more effective [7]. Using the Stackelberg model, Yu M et al. developed a novel Demand-Response (DR) model for electricity trading between a utility company (1 leader) and multiple users (N followers) and proposed an iterative algorithm to achieve the Stackelberg equilibrium state and determine the optimal power generation and power demand for the leader and N followers [8]. The research of Yu M et al. showed that this method can effectively flatten the peak demand and fill the vacancy of the low demand and significantly reduce the mismatch between supply and demand [8].

Table 3. List of co-cited articles with co-citation frequency ≥ 10 times.

Count	Centrality	Year	Reference
14	0.05	2018	Chen WT, 2018, J CLEAN PROD, V201, P123, DOI 10.1016/j.jclepro.2018.08.007
13	0.01	2018	Zhang CH, 2018, APPL ENERG, V220, P1, DOI 10.1016/j.apenergy.2018.03.010
13	0.04	2016	Lo Prete C, 2016, APPL ENERG, V169, P524, DOI 10.1016/j.apenergy.2016.01.099
11	0.01	2017	Wei F, 2017, APPL ENERG, V200, P315, DOI 10.1016/j.apenergy.2017.05.001
11	0.03	2014	Soliman HM, 2014, IEEE T SMART GRID, V5, P1475, DOI 10.1109/TSG.2014.2302245
10	0	2017	Wu B, 2017, J CLEAN PROD, V141, P168, DOI 10.1016/j.jclepro.2016.09.053
10	0.15	2016	Yu M, 2016, APPL ENERG, V164, P702, DOI 10.1016/j.apenergy.2015.12.039
10	0.03	2017	Madani SR, 2017, COMPUT IND ENG, V105, P287, DOI 10.1016/j.cie.2017.01.017
10	0.04	2017	Motalleb M, 2017, APPL ENERG, V202, P581, DOI 10.1016/j.apenergy.2017.05.186

Table 4. List of co-cited articles with centrality ≥ 0.07.

Count	Centrality	Year	Reference
10	0.15	2016	Yu M, 2016, APPL ENERG, V164, P702, DOI 10.1016/j.apenergy.2015.12.039
3	0.14	2018	Motalleb M, 2018, ENERGY, V143, P424, DOI 10.1016/j.energy.2017.10.129
5	0.13	2015	Cintuglu MH, 2015, IEEE T SMART GRID, V6, P1064, DOI 10.1109/TSG.2014.2387215
2	0.1	2012	Samadi P, 2012, IEEE T SMART GRID, V3, P1170, DOI 10.1109/TSG.2012.2203341
6	0.1	2017	Zhu LJ, 2017, APPL ENERG, V196, P238, DOI 10.1016/j.apenergy.2016.11.060
8	0.1	2017	Fan RG, 2017, J CLEAN PROD, V168, P536, DOI 10.1016/j.jclepro.2017.09.044
6	0.09	2012	Mei SW, 2012, IEEE T SUSTAIN ENERG, V3, P506, DOI 10.1109/TSTE.2012.2192299
7	0.09	2014	Su WC, 2014, APPL ENERG, V119, P341, DOI 10.1016/j.apenergy.2014.01.003
8	0.08	2018	Fan SL, 2018, APPL ENERG, V226, P469, DOI 10.1016/j.apenergy.2018.05.095
4	0.07	2017	Banez-Chicharro F, 2017, APPL ENERG, V195, P382, DOI 10.1016/j.apenergy.2017.03.061

We divide the research evolution process in the field of game theory on energy and natural resources from 2010 to 2021 into three periods in order to conduct a detailed literature study:

(1) Early stage of development (2010~2014). The most important cluster in the early development is #8 Microgrids, which only developed in this period and soon entered a period of silence. Combining co-citation frequency, strength and centrality, the most important document in this cluster is Montuori L (2014). Montuori L et al. studied the microgrid provided by biomass gasification power plant and compared it with other power generation technologies, obtained different solutions for balancing power generation and consumption through scenario simulation and finally better integrated with demand response renewable energy [9]. Anh SJ (2013) and Aalami HA (2010) were the most intense papers (Degree = 10) and the most co-cited papers (Freq = 3), respectively. Anh et al. focused on the power dispatching problem of distributed generators to realize the optimal operation of microgrid [10]. In order to reduce the electricity price, to solve the problem of transmission line congestion and to improve market liquidity, Aalami HA analyzed the demand response mechanism and conducted a simulation study on the load curve of the Iranian power grid on peak days in 2007. The simulation results confirmed good performance of the model [11]. To sum up, the research process of the leading documents in the cluster #8 Microgrids is similar. The purpose of the research is to maximize the benefits of all parties under limited resource constraints. Combined with the demand price elasticity of economics and the user benefit function, the simulation analysis of different scenarios is carried out, and the optimal mechanism is finally obtained. The second largest cluster is #2 Game Theory, and the two most important papers in the early development stage of this cluster are Soliman HM (2014) and Su WC (2014). The former has a total of 11 citations, degree of 0 and a centrality of 0.03. The latter has a slightly lower citation frequency of 7, but its centrality is as high as 0.09, and its degree is as high as 17. Soliman et al. studied the problem of demand-side management (DSM) when customers are equipped with energy storage equipment and discussed two games:

a noncooperative game between residential energy consumers and a Stackelberg game between utility providers and energy consumers, which elucidates the interplay between storage capacity, energy demand, number of users and system performance as measured by the total cost and peak-to-average power ratio (PAR) [12]. Su WC et al. innovatively proposed a game theoretic framework for the next-generation retail electricity market for distributed residential electricity suppliers, formulating a set of mathematical models of retail electricity market participants with many local and global constraints [13]. The literature under the cluster #2 Game Theory explores game theory more and conducts an in-depth analysis of energy supply and demand based on a variety of game theory frameworks. In addition, except for clusters #0 and #6, which did not appear in the early development period, other clusters cited papers in 2013~2014. The vast majority of research topics in the field of game theory research in energy and natural resources have been officially initiated.

(2) Fast growing stage (2015~2017). During this period, cluster #8 Microgrids finally terminated, #2 Game Theory maintained its good momentum from the previous period, #6 GBT kicked off but did not yet enter its peak, and the rest of the clusters finally entered a period of rapid development, and the average publication year of most clusters was concentrated in 2016–2017. First, the two most important papers in cluster #0 Integrated Energy Systems (IES) in this period are Wei F (2017) and Motalleb M (2017), with total citation frequencies of 11 and 10, centralities of 0.01 and 0.04, and degrees of 12 and 8, respectively. Wei F et al. analyzed the multi-energy trading (MET) problem in the integrated energy system (IES) based on a new game model which is derived from the hierarchical Stackelberg game, and proved for the first time that there is a unique Stackelberg equilibrium in the MET problem [14]. Motalleb M et al. constructed a theoretical model of competition among demand response aggregators, which ultimately provided sellers with a game theoretically sound decision procedure that facilitated the prediction and analysis of bids for energy sales in the market [15]. Under cluster #1 Government, the most important document is Madani SR (2017), with a total citation frequency of 10, degree of 22 and centrality of 0.03. In this study, a government-led game model with two competitive green and non-green supply chains as followers was established. For the first time, the pricing policy, green strategy and governance tariff in supply chain competition were clarified, and it was proven that the improvement in the government decision making and the impact of the subsidy rate are significantly greater than the tax rate [16]. Cluster #2 Game Theory has two of the most important papers published in this period, Lo Prete C (2016) and Yu M (2016). Lo Prete C (2016) has a total citation frequency of 13, degree of 19, and a centrality of 0.04. Yu M (2016) has a total of 10 citations, degree = 12 and a centrality of 0.15. Using a cooperative game theory framework, Lo Prete C et al. modeled the economic incentives for market participation in the cooperative development of microgrids in minigrids served by regulated utilities, which explores how to correct for utility pricing market failures [16]. In cluster #3 EGT, the most important article in this period is Wu B (2017) with a co-citation frequency of 10 and degree of 11. Wu B et al. constructed a low-carbon strategy evolution model of the game between the government and enterprises in the context of complex networks, analyzed how enterprises compete and transform in the Newman–Watts small-world network, and proved that enterprises' expectation on policies such as government subsidies and supervision can set the speed of dissemination of low-carbon strategies [17]. The co-citation frequencies of major papers in clusters the #4 Subsidy and #5 Home Energy Management (HEM) are significantly weaker than important papers of the previous clusters. Among them, the most important literature is Chen ZY (2016) with a co-citation frequency of 6, degree of 18 and centrality of 0.02. The substitution elasticity of energy sector and non-energy sector factors and China's consumption preferences for energy and non-energy bulk commodities prove that a small carbon tax on production links can help increase total social welfare [18]. In

summary, we find that in the rapid development stage, more game theory models are applied in the research field of game theory on energy and natural resource. The topic of microgrid is greatly reduced while topics such as integrated energy systems were greatly enhanced. In addition, the carbon tax incentive mechanism between government and enterprises has begun to be widely discussed, and green strategies have become one of the hot topics of research.

(3) Explosive development stage (2018~2021). Based on the number of published papers, we can see a surge of papers from about 40 per year in the second stage to about 100 per year. On the one hand, clusters #7TEP and #9BSC disappeared in this stage and cluster #2 Game Theory gradually entered into the mature stage. On the other hand, other research topics have maintained their high popularities from the previous stage. Cluster #6 GBT is an emerging theme in the third stage. The most important documents under cluster #0IES were published in this period: Zhang CH (2018) has a co-citation frequency of 13, degree of 16 and centrality of 0.01. This paper studies the P2P energy trading model, proposes a hierarchical system architecture model to identify and classify the key elements and technologies involved in P2P energy trading, and proves that P2P energy trading can promote the local balance of production and consumption [19]. Cluster #3EGT also has a very important document, Chen WT (2018). During this explosive development stage, Chen WT et al. applied evolutionary game theory to examine the strategies of manufacturers in response to various carbon tax policies [7]. Cluster #6GBT is the youngest cluster, and its most important document at this stage is Zhang LP (2019) with a co-citation frequency of 5, degree of 17 and centrality of 0.04. Zhang LP et al. studied the evolutionary game model of technology diffusion within the manufacturer alliance under the background of China's low-carbon policy and simulated the impact of carbon trading market, environmental tax and innovation subsidies on the green technology diffusion of manufacturing enterprises in China's Barabasi-Albert model [20]. The third-stage research continues with the precedent subjects of green policy and carbon tax themes, goes much more in-depth and is no longer limited to the Stackelberg model but has introduced more uncommon games. In addition, the third stage is also characterized with new topics, such as P2P transactions.

3.3. Keyword Analysis of Literature

The keyword clustering function in CiteSpace software can be used to analyze the evolution process of literature keywords under the topics of game theory on energy and natural resources. The document keyword clustering function of CiteSpace software can calculate the occurrence frequency, centrality and degree of the document data keywords, analyze the data similarities, group the data based on the extraction results and pick up the core themes of data groups. We conduct keyword analysis on research topics from January 1990 to December 2021, set the time slice to 1 year, and the selection criteria are set as follows: $k = 25$, LRF = 3.0, L/N = 10, LBY = 5 and e = 1.0. The results are shown in Figure 3. In total, there are 698 valid documents, 601 nodes and 2986 connections. The value of density is 0.0166. Modularity Q is equal to 0.5114, which indicates that the boundaries of each research topic are quite clear and that a certain degree of field differentiation is quite obvious. Weighted mean silhouette S is equal to 0.8163, indicating that the intra-cluster homogeneity is strong, and each cluster has a recognizable uniform theme. Harmonic mean (Q,S), which is equal to 0.6288, refers to the reciprocal of the arithmetic mean of the reciprocal of the Q value and the S value. This value represents the overall degree of cluster differentiation and the degree of homogeneity within the cluster, indicating that the overall structure of the clustering network we obtained is reasonable. Keyword clustering analysis results are shown in Figure 3.

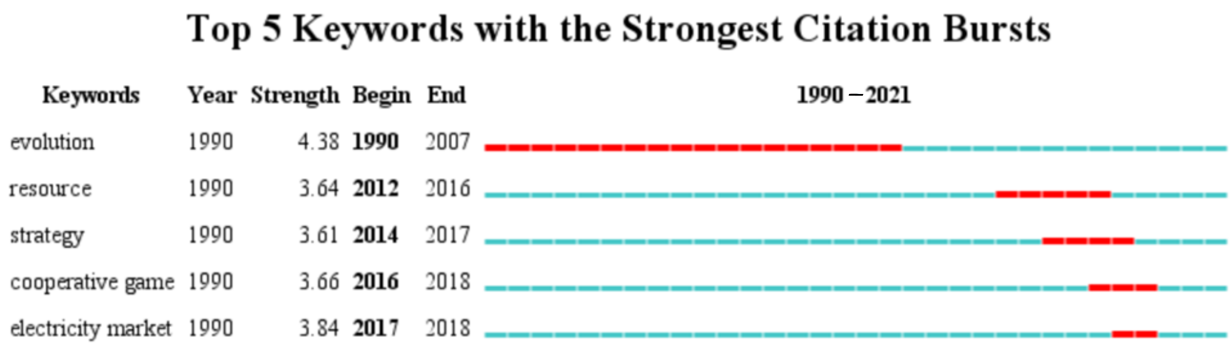

Figure 3. Highlights of the top 5 keywords.

Combining the obtained clustering network of 601 keywords and the keyword highlighting map with the in-depth analysis of literature co-citation clustering in Section 3.2, we extracted the nine main themes under this study and classified them as three categories: (1) Research objects: electricity market, integrated energy system and carbon emissions; (2) Research questions: demand response and demand side management, energy price model, government policy and subsidy mechanism; (3) Game model: Stackelberg Games, evolutionary games and cooperative games. Analyzing the WoS core collection, in addition to the above-mentioned subjects, we can add nine more themes, such as "electricity market" and "integrated energy system". After a new round of analysis of the obtained literature data, focusing on analyzing head documents of more than 10 citations and taking into account of tail documents, we have come to some conclusions as follows:

3.3.1. Research Objects

1. Electricity market. There are a total of 131 articles under this topic. Microgrids is an important category of electricity markets. With regard to energy sources, wind energy and renewable energy are very hot research topics. As a new energy source with high uncertainty, wind energy and conventional power producers can determine their profits through game theory in the bilateral reserve market. Large-scale grid integration of distributed renewable energy is emerging as a promising solution to reconfigure current grid infrastructure and ensure energy supply reliability. Since distributed renewable energy was incorporated into existing grid infrastructure, the economic operation of new, more complex retail electricity markets has become a research hot spot. The research issues mainly include demand side management (DSM) and cost allocation. The DSM model is the most common solution when energy supply is limited. DSM can be used to coordinate supply and demand and improve system reliability, as well as expand the capacity constraints of existing grid infrastructure. In addition to the Stackelberg model, the commonly used game models also include the Cournot model. When a game theoretic framework is introduced into a DSM model, the usual goal is to study fluctuations in the load curve and reduce the peak-to-average ratio in order to maximize returns for both retail electricity market users and residential electricity suppliers. In this scenario, game theory is often applied to the exploration of dynamic pricing strategies. Dynamic pricing strategies can encourage consumers to participate in peak reduction. In addition, game theoretic models can also be applied to coalition, collaboration, and profit distribution problems in home microgrids. In addition, the profit distribution problem of the participants in the electricity market supply chain can also be solved with game theory. Load demand, transmission expansion and energy storage are also common directions of exploration. Short-term hot topics such as P2P and blockchain technology also affect the research direction of the electricity market.
2. Integrated energy system. A total of 50 articles is sorted out under this topic, which can also be seen as a sub-topic of the electricity market topic. Extending the electricity market mechanism to the distribution system, modeling the corresponding

energy trading process for different agents such as wind farms, solar power plants and demand aggregators is the main integration mode of an integrated energy system. Research focuses include improving the operational performance of power distribution systems, coordinating the collaborative interactions of energy systems, and designing novel dynamic energy management strategies. We can store energy from multiple sources in one aggregator. The competition model between demand response aggregators uses a lot of game theory model frameworks. The Stackelberg model is the most widely used one, with similar application scenarios described in the above section of the electricity market. In addition, in the context of smart grids, researchers have also explored the concept of smart building clusters, which allows multiple smart buildings to operate jointly for optimization purposes. In addition to electricity supply networks, building distributed heating networks are also within the scope of this topic. Combining energy system optimization with revenue distribution schemes for heating networks is also a common research direction.

3. Carbon emissions. There are a total of 97 articles under this topic. This topic is closely related to topics of environmental pollution and resource consumption. In the field of game theory on carbon emissions and energy and natural resources, the mainstream research direction is to use game theory methods to test and predict the behavioral strategies of governments and manufacturers in response to carbon tax and subsidy policies and to simulate carbon emissions trading markets with the purpose to achieve the greatest social benefit on the basis of protecting the environment. In addition to carbon taxes and technology subsidies, other government interventions include direct tariffs and tradable licenses on green and non-green products. Technological innovation and bank-to-business green loans are also often introduced into game models. For example, based on the analysis model of game theory, quantitative simulation of the development of new energy vehicles and green credit is carried out. In addition, other environmental policies and measures have also been explored, such as the establishment of a Stackelberg model to explore the impact of waste battery recycling on energy conservation and emission reduction.

3.3.2. Research tasks

1. Demand response and demand side management. There are a total of 72 articles under this topic. This topic is closely related to electricity markets and integrated energy systems. Users adjust their electricity consumption behaviors according to electricity prices and other policies for the purpose of reducing electricity load and ensuring stable power supply, which is demand response. The load management method of the power company is demand side management. Demand response is divided into two categories: price-based and incentive-based. Price-based demand response includes pricing by time, pricing of real-time, and pricing of peaks, while incentive-based demand response includes direct load control, interruptible compliance, demand-side bidding and emergency power demand response. The mainstream research direction is to use the game theory model to study response behaviors of power users to different policies in order to maximize social benefits by means of reducing user costs, reducing peak demand, stabilizing power supply of power grid and reducing environmental pollution while satisfying consumption constraints. In addition to the Stackelberg model, the common game theory methods are evolutionary game theory models. In the study of users, the diversity of users and the feasibility of hierarchical management can also be considered, and the heterogeneity of demand flexibility can also be reflected in the noncooperative game framework. In addition to the traditional power grid, the introduction of distributed energy and renewable energy smart grid is the current research trend. The demand response model of the electricity market has also been extended to the gas market.
2. Energy market price model. There are 134 articles under this topic. The energy market price models mainly include electricity and non-electricity price models. Since

electricity cannot be stored, it is quite different from the pricing models of gas and oil. Pricing models for energy commodities such as natural gas and oil have little to do with game theory and are therefore not considered further in this section. The electricity pricing model is closely related to the electricity market and demand response topics discussed above. The electricity market has the characteristics of price spikes, mean reversion (prices can quickly return to the mean level from spikes) and strong volatility. The commodity price model of electricity cannot be derived from traditional production, storage, distribution and other links. Therefore, it is the most mainstream research method to simulate the game process from the perspective of market participants.

3. Government policies and subsidy mechanisms. There are 118 articles under the policy topic and 82 articles under the subsidy topic. The topics of carbon emissions research and evolutionary games are closely related to the topics of government policies and subsidy mechanisms, and many papers appear repeatedly. Government policies mainly include taxation of carbon emissions, tax relief for energy-efficient companies, subsidies for green technologies and tradable licenses for products. When studying policy effects, researchers often employ evolutionary game models, using multi-stage game models to simulate the behavioral strategies of governments and other market players. In addition to carbon emissions, green technologies such as smart energy-efficient homes and electric vehicles are also popular research directions.

3.3.3. Game Model

1. The Stackelberg model. A total of 81 papers used the Stackelberg model. The Stackelberg model, which positions market players as leaders and followers, is widely used in the field of energy and natural resource game theory research. The Stackelberg game framework is suitable for various scenarios in the field of energy economics, such as in the grid-building demand response model, where Stackelberg can successfully cope with demand fluctuations while maximizing the total benefit. In addition to traditional grids, smart grids composed of multiple energy aggregators are also applied to the Stackelberg model with constraints such as transaction prices and scale constraints. In addition, in a multi-layer game model, Stackelberg can also be applied to only one layer. For example, in a multi-level integrated energy system composed of natural gas companies (upper tier), multiple energy hubs that supply electricity or heat (middle tier) and multiple users (lower tier), the Stackelberg game method can study the multi-level integrated energy system energy scheduling and operating strategies for all participants. The two-layer interaction model is also the mainstream model. In the upper layer, the distribution network operator decides the transaction price and quantity of each microgrid according to the solution of the lower layer problem under the premise of considering the constraints; the process is a Stackelberg model.
2. Evolutionary games. There are a total of 101 articles under this topic. Evolutionary games no longer assume that the participants are rational, but, similar to biological evolution, under the condition of incomplete information, the game equilibrium is finally reached through continuous trial and error. For example, in carbon tax research, the evolutionary behavior of manufacturers in response to a combination of government taxes and subsidies is a hot research topic. In the study of climate and environmental policy, heterogeneity in the behavior of firms or governments in response to policies can also be simulated by multi-step game models to design incentives, reform regulatory regimes and improve market outcomes. Evolutionary game models can also be used to simulate the process of green technology diffusion. The participants in the model can be two parties, namely the government and the manufacturer, or multiple parties, such as the government, energy companies and downstream energy users. In the study of electricity market and gas market, researchers also proposed some pricing methods based on evolutionary game theory. The electricity

market and gas market are a nonlinear complex economic system/multi-agent system with multiple interacting agents (government agent, local gas distribution operator agent and end user agent). Combining the evolutionary game theory model with the demand response model, we can simulate the behavior of participants in different scenarios and obtain optimization results.

3. Cooperative game. There are a total of 137 articles under this topic. A cooperative game is one in which the participants cooperate with each other and fight against each other in the form of a group. Cooperative games are also called positive-sum games; that is, the total social benefit increases when the equilibrium is reached. Cooperative games mainly appear in new energy management systems. Multi-agent distributed energy management systems often consist of cooperative games involving multiple agents. In addition, the application of noncooperative games in the framework of energy management is also a hot research direction. In the bidding game on the demand side, the advantages and disadvantages of the cooperative game and the competitive game are also the research focus. Depending on the heterogeneity of end users (residential, commercial, and industrial), hierarchical demand-side management models can also be introduced into cooperative or noncooperative game models. The design of the battery energy storage system can also use the cooperative game model, using a variety of batteries as the participants of the cooperative game model, and the cost and profit are established in the corresponding game strategy space. We summarize our findings in Figure 4.

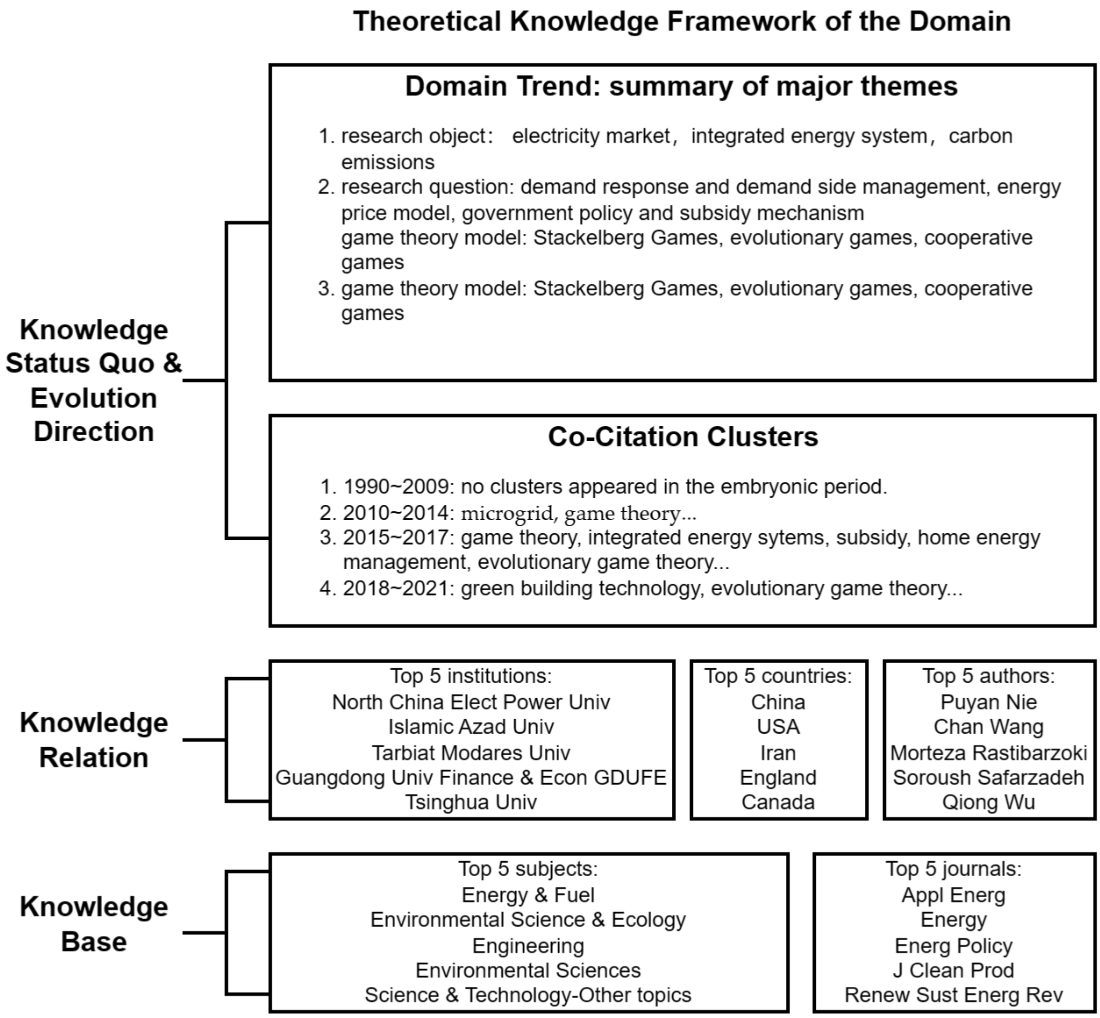

Figure 4. Knowledge framework of the domain.

4. Conclusions

In this paper, we use CiteSpace software to conduct a bibliometric analysis of the research literature under the topics of energy, natural resources and game theory in the Web of Science Core Collection. We roughly divide the topic of game theory of energy and natural resources into four stages: (1) the embryonic stage from 1990 to 2009, when only a small number of new papers came out and the research was not large-scale; (2) the early stage from 2010 to 2014, which is also named as "microgrid" period; (3) vigorous development from 2015 to 2017, when major themes propped up and the evolutionary game process between government and enterprises became a research hot spot; and (4) further development from 2018 to 2021, when the earlier research direction continued with more than 100 new papers per year and more in-depth research. Combined with the literature co-citation analysis and keyword analysis, we summarize the three major directions and nine themes of this research field: (1) Research objects: electricity market, integrated energy system and carbon emissions; (2) Research questions: demand Response and demand side management, energy price model and government policy and subsidy mechanism; and (3) Game model: Stackelberg game, evolutionary game and cooperative game. So far, the research and development of energy and natural resource game theory from 1990 to 2021 has been sorted out. Giving the three major development crises that the world is currently facing, the financial crisis, the energy crisis and the climate crisis, we believe that the energy crisis and extreme climate will become new hot topics in the next two years. The game method will be more realistic and practical, and the decisions made by countries around the world in dealing with the three major crises will also provide a more authentic basis for our empirical analysis. The impact of climate disasters on the energy economy is also an issue worth exploring. We believe that research that combines energy, natural resources, the environment and game theory will eventually help human development. On the one hand, our paper is innovative, because it fills an important gap in the research field, because we believe that a bibliometric study on game theory on energy and natural resources can provide researchers and policymakers with important new perspectives and insights. On the other hand, we still have our limitations. We could expand our research scope by including more keywords than "energy" and "natural resources", so that we could generate a more inclusive review on the game theory of major subgroups of sustainability. For example, we could expand our interest into sustainable agriculture. We leave this work to future studies.

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Conflicts of Interest: The authors declare no conflict of interest.

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