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Scientific Data-Driven Evaluation on Academic Articles of Low-carbon Economy

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Abstract: Low-carbon economy has played an important role in green energy economics in last two decades. The number of studies conducted on low-carbon economy has increased steadily since 1990 and now in a fast-growing stage of its academic articles' production life cycle. An increasing number of scholars have paid their attentions to low-carbon economy research. Hence, the low-carbon economy has been an important and popular topic in the past 30 years as evidenced by numerous papers in journals listed in several subject categories in the Web of Science (WoS) online database. This research reviewed more than 14,000 bibliographic records from the Science Citation Index and Social Science Citation Index of WoS. In this work, paper citations, subject categories, cited journals, top countries, productive institutes, authors, cited references and publications' citations or research collaborations are analysed from published literature. We have found that the top three productive journals in low-carbon economy research are *Energy Policy*, *Renewable and Sustainable Energy Reviews* and *Journal of Cleaner Production*. The U.S. has an apparent advantage in the quantity and quality of low-carbon economy research. In addition, the U.S. is in the centre of international collaboration networks, including two top productive institutes, which summarized as *University of California Berkeley* and *Carnegie Mellon University* accordingly. An overall trend of the developing analysis of low-carbon economy research can provide a clear knowledge map and deep understanding of academic research on low-carbon economy.

Keywords: Scientific data driven evaluation; Low-carbon economy research; Quantitative assessment; Academic impact; Citation influence.

1. Introduction

An increasing number of studies have focused on greenhouse gas (GHG) emissions because such emissions have caused severe crises and conflicts, such as climate change and environmental pollution, which threaten the stability of the world's climate, economy and even the existence of humankind. Emission problems are primarily caused by the heavy dependence of global energy systems on fossil fuel (Jiang et al., 2013). Although expectations about the cost of global warming remain a debatable issue, the consensus among scientists is that GHG emissions created significant risks of climate change (Glaeser and Kahn, 2010). With increasing emissions of carbon dioxide (CO_2), the greenhouse effect and frequent global catastrophic climate change have seriously threatened the balance of natural ecosystems and the living environment of human beings (Zhou, 2010). To reduce CO_2 emissions effectively whilst maintaining economic growth, different countries have established new development paths in different ways, among which the low-carbon economy is one of the most widely advocated (Höhne et al., 2007). The development of the low-carbon economy resulted from the concern of the international community for the severe crises and conflicts caused by climate change and environmental pollution (Yan et al., 2017). The low-carbon economy has become a priority in recent years and has gradually become the focus of the academic community and politicians. Therefore, the development of the low-carbon economy is an irreversible global trend.

The causes and consequences of climate change and environmental pollution are global, and national governments should take action to address these problems. Effective responses to climate change require a collective global efforts and transition to a sustainable low-carbon economy (Dagoumas and Barker, 2010). Global concerns about the effects of climate change are widely recognised, and individual countries have undertaken different strategies to mitigate climate change. These strategies have led to extended negotiations towards the ratification of the Kyoto Protocol, which provides an international framework for reducing GHG emissions. Since the implementation of the Kyoto Protocol in 2005, a call for full-fledged measures to address global warming on a global scale has been initiated (Shimada et.al, 2007). The European Union (EU) and several individual countries have committed themselves to the implementation of policies to reduce GHG emissions (Dagoumas and Barker, 2010). The United Kingdom (UK) set a ground breaking climate change mitigation policy with the publication of a long-term national CO_2 reduction target of 60% by 2050 compared with 2003

(DTI, 2003). Several countries in Europe, including Germany (80%), France (75%) and the Netherlands (80%), have also adopted highly ambitious long-term targets (Kawase et.al, 2006). In the Japan–U.S. Joint Message on Climate Change Negotiations, Japan agreed to a long-term target of an 80% reduction in GHG emissions by 2050 compared with 2012 (Ashina et.al., 2012). The critical situation of global climate change requires emerging economies to participate in these collective efforts. Climate change and energy security are addressed in China's long-term development strategy (Hu and Lee, 2008). The search for low-carbon development trajectories contributed not only to improving the global climate but also to enhancing China's long-term energy security and competitiveness (Richerzhagen and Scholz, 2008). In 2009, the Chinese government set a goal of reducing the emission intensity (CO_2 emissions per unit of Gross Domestic Product (GDP) in 2020 by 40%–45% relative to the amount in 2005 (Wang et.al, 2011). Many reforms will be implemented in future, and these include low-carbon policy guidance, adjusting the industrial structure, setting rigorous energy-saving targets, optimising the energy structure and encouraging a low-carbon lifestyle among the public (Zhou et.al., 2012).

The term "low-carbon economy" was first mentioned in UK government documents in the white book titled "Our energy future: create low-carbon economy" in 2003 (DTI, 2003). Since then, the low-carbon economy has become increasingly popular. However, the term has no internationally agreed upon definition (Mulugetta and Urban, 2010). Different countries and organisations have different interpretations. In existing literatures, a number of concepts relevant to the low-carbon economy, such as low-carbon energy (Li et.al, 2012), low-carbon transport (Harto et.al, 2010), low-carbon society (Shukla et.al, 2008), low-carbon city (Phdungsilp, 2010), low-carbon community (Jiang et.al, 2013) and low-carbon tourism (Scott et.al, 2010), have been discussed a lot. A common feature of the low-carbon economies of different countries is the use of a small amount of carbon to promote economic growth in the future (Mulugetta and Urban, 2010). The low-carbon economy is a development trend that aims to reduce energy consumption and pollutant emissions, improve energy utilisation rates and establish environmentally friendly economic development mechanisms to yield high economic outputs, and create a high standard of living standard as well as provide good quality of life (Wang, 2011).

Exploration of the dependencies between sustainable development in specific countries and the low-carbon economy has elicited considerable research interest recently. Many studies have been conducted to analyse CO_2 mitigation pathways (or pathways towards a low-carbon society) at global (Ekholm et.al, 2010) and

regional/national scales (Kannan, 2009). Low-carbon energy, also known as non-fossil energy, has experienced rapid growth since 2005 due to the efforts to optimise energy mix and reduce GHG emissions. Promoting renewable energy to address climate change concerns is a priority of many countries, and increasingly binding and restrictive legislation has been established (Protocol, 1998). Consequently, wind farms, solar panels, technologies for carbon capture and storage and related developments, such as electricity network upgrades and extensions, are now being developed and deployed globally (Batel et.al, 2013). Previous research has also discussed the potential energy security implications of the national low-carbon fuel standard (NLCFS) (Leiby and Rubin, 2013), and issues in strategic energy security have again entered the limelight. The success of low-carbon development may not be as simple as allocating funds, building infrastructure or developing new technologies (Bai and Liu, 2013). These schemes should be based on a thorough understanding of residents' low-carbon awareness and behaviour at the same time.

The current and foreseeable development direction of modern society forecasts that climate change and environmental pollution will continue in the future and become increasingly complex due to the interconnection with economic development fields, such as energy, transportation and industry. In the case of P.R. China, energy linkages have become more challenging, costlier, more complex more reliant on long-distance transport within national consumers, more dependent on foreign supply chains of oil, gas and coal compared with the situation in the past (Shealy and Dorian, 2010). However, the transition towards a sustainable low-carbon economy requires radical changes to systems for providing low-carbon energy research and other efforts, such as technologies, infrastructures and institutions associated with and accessed by individuals, communities and businesses. This transition involves a deep understanding of, and major changes to the practices of energy use, innovation and deployment of low-carbon technologies and broad changes in the mix of industries within national and global economies (Foxon, 2011). These changes require stable economic growth whilst mitigating further climate change and ensuring that socioeconomic systems remain within ecological limits, which require an understanding of the connections among these integrated system components, their dynamics, the defined transition and the potential "levers" involved in "transitioning" (Moloney et.al, 2010).

The development of the global economy measured in GDP is highly related to energy consumption because worldwide industrialisation leads to CO_2 emissions. The positive correlation between GDP and low-carbon economy research output demonstrates that the green industry is an important developing subject that is

currently rooted in societies globally. The negative correlation between CO_2 emissions and low-carbon emissions is due to many technologies and industrial policies developed to inhibit CO_2 emissions to protect our planet. In the new century, the global GDP increased quickly, and CO_2 emissions were controlled to a certain level compared with those in the previous years. Low-carbon economy research has hence attracted much attention and has played an important role in global economic development. The amount of low-carbon economy research increased rapidly even during the global financial crisis in 2008.

The primary purpose of this research work is to identify study priorities and potential structure holes in the research agenda in the field of low-carbon economy with scientometric method. The scientometric analysis is a technique that the mathematical formulae and visualization tools are employed to allow for a broader yet concise capturing and mapping of a scientific knowledge area by identifying structural patterns and tracing salient research frontiers (Olawumi, 2018). The scientometric analysis is always described as one of the most used methods to evaluate and examine the research development and performance in a given research filed. Publications on low-carbon economy productivity were analysed carefully in this paper by scientometrics analysis, under which the co-occurrence matrix of certain meta-text such as authors, institutes, countries or journals, references created and mapped by knowledge networks tools (Lyu et.al, 2015). The following section introduces scientometric data and the data collection methodology employed in this study, the scientometric techniques such as co-author analysis, co-citation analysis and clustering analysis would be adopted below. Scientometric analysis has been applied in scientific study as a quantitative analysis method for years. Its statistical outcomes can measure the contribution of scientific publications within a specified theme and describe the current research trends that can be used to identify the objectives of future studies (Albino et.al, 2014). The findings are presented in section 3, and the last section provides an academic discussion, conclusions and policy implications.

2. Materials and Methodology

To examine research outputs and their citation impacts, high-level academic articles and their citation links were collected and studied using scientometric method. The scientometric method has been used widely to analyse scientific production and research trends in many branches of study (Fahimnia, et.al, 2015). The scientometric analysis is described as one of the most used methods to evaluate and examine the research

development and performance of journals, academics, universities, countries in an identified research field (Konur, 2012, Hood and Wilson, 2001). As a detailed method in scientific data-based bibliomaniac study, paper productivity, subjects, journals, countries, institutes, references and related citations were thoroughly discussed via a quantitative analysis. Data on articles' citations were derived from a scientific dataset, in this process the scientometric method was employed to summary the citations at subjects, journals and authors, institutes or countries level in details. With a statistical method, the main indicators related to research impact, such as total citations, citations per paper, and impact factor (IF), were employed for a thorough analysis. Scientometric techniques have been adopted in this study including (i) co-author analysis, co-citation analysis and clustering analysis; and (ii) scientific data visualization and knowledge networks mapping via scientometric software (NetDraw and HistCite) based on co-occurrence matrix from the dataset.

Scientific big data-based analysis, as a quantitative and visual method, has been successfully applied to various research fields, including innovation activity in a company (Chappin and Ligtvoet, 2014), socio-technical change (Hsieh and Chang, 2009), evolutionary analysis of collaboration networks (Yin, 2013), development of grey system theory research (Cadez S, 2013) and institutional pressure and knowledge creation (Siegmeier and Möller, 2013). Considering the apparent significant advantage in trend-spotting and visualising technology, a large amount of literature regarding scientometric or bibliometric analysis has been published in energy analysis areas, such as biofuel fields (Zhang et.al., 2016), carbon taxes (Holland et.al., 2009), renewable energies (Chen, et.al., 2017) and alternative energy (Mao et.al., 2015). Moreover, scientometric and bibliometric analysis has been used as a meaningful tool for the study of energy and fuel research priorities and trends in P.R China (Chen et.al, 2016), renewable energy research progress in Mexico (Alemán-Nava et.al, 2014) and energy in Spain (Montoya et.al, 2014). However, minimal attention has been provided to the study of global trends in low-carbon economy research.

The data source in this research is the WoS offered by Clarivate Analytics, and data for this work were searched by using the search terms ("low carbon*" or low-carbon* or "greenhouse* gas* reduct*" or "carbon* reduct*" or "carbon* mitigat*" or "carbon* efficienc*" or "carbon* performanc*" or "carbon* productivit*") and (develop* or econom* or transit* or policy* or industry*). A total of 14,176 articles and 450,191 references were retrieved from SCI and SSCI databases. The references were published in 143,156 journals by 189,463 authors.

3. Results Analysis and Discussion

To determine the effects of low-carbon related outputs, highly relevant data and calculations with further analysis were provided and performed respectively. Figures and tables are used to describe the number of citations and citation trends of low-carbon economy research from the SCI and SSCI databases. Publications (as an indicator of scientific performance) and their citations (as indicators of research impact/influence) are commonly accepted indicators in quantitative analyses of scientific research performance. For a given paper in a citation database, such as SCI or SSCI, "times cited" means the number of times the paper been cited, and "number of references" signifies the other papers cited in the published paper, which forms the research basis for the given research output. These two elements of metadata were analysed to obtain findings on low-carbon economy research.

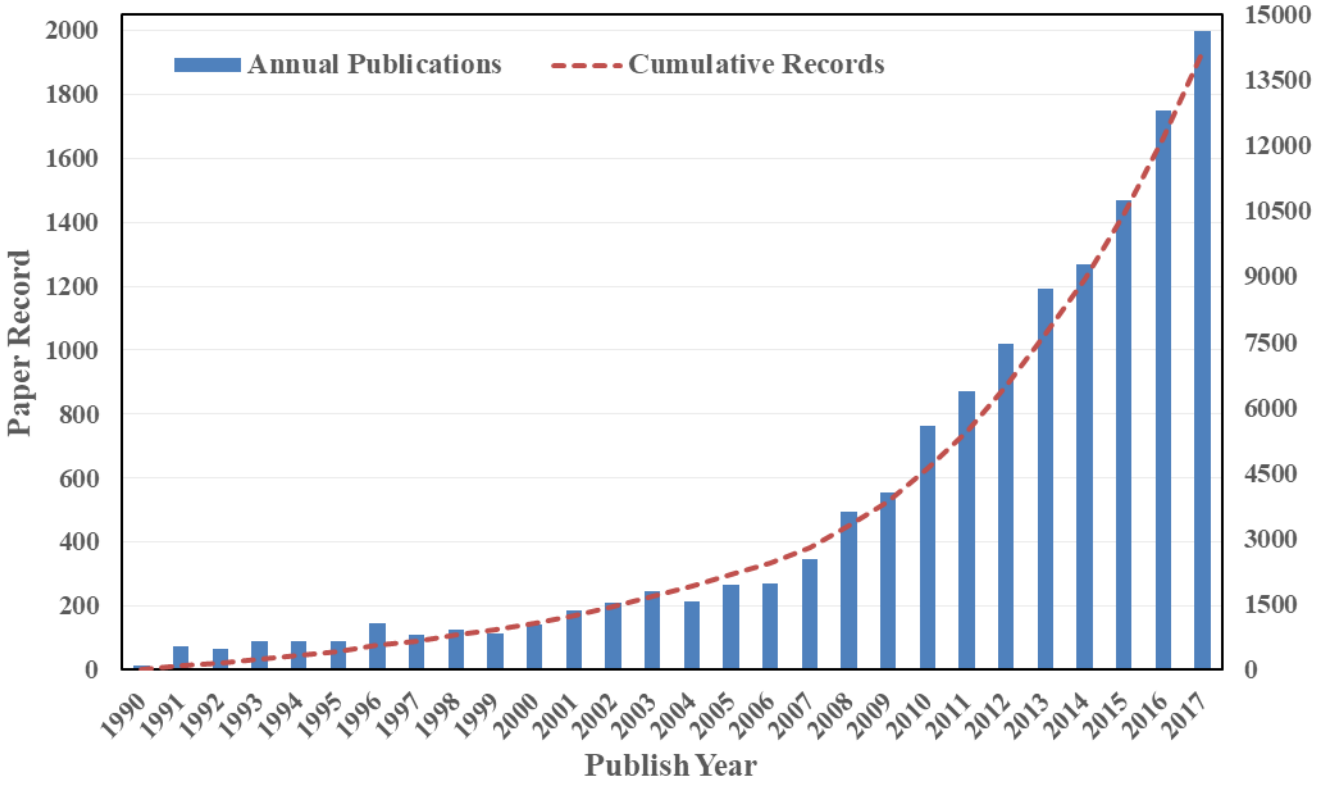

Figure 1. Global Low-carbon Economy Research Outputs and Increase Trend

In summary, attention should be focused on the most viable path towards achieving a low-carbon economy. Low-carbon economy research refers to those outputs of a green economy without pollution. Research records obtained from the Clarivate Analytics are shown in Figure 1. Publication records were collected from SCI and

SSCI databases. From 1990 onwards, the publication records exponentially increased by 40 times. Given that most countries were already concerned with environmental pollution, low-carbon economy research began to be a popular topic from the 1990s, and a global carbon emission protocol was implemented in 2005.

Papers related to low-carbon economy were cited 288,621 times, and such citation links are important in the assessment of the research impact in this work. Furthermore, articles related to low-carbon economy obtained from WoS were used to investigate present and future citation trends in Table 1.

Table 1 Research Outputs and Their Citation Records for Low-carbon Economy

No.	PY	TP	NA	TC	NR	AU/TP	TC/TP	RE/TP
1	1991	73	201	1651	1774	2.75	22.62	24.3
2	1992	67	199	1884	1877	2.97	28.12	28.01
3	1993	88	255	1761	2080	2.9	20.01	23.64
4	1994	88	252	2236	2487	2.86	25.41	28.26
5	1995	88	232	1678	2333	2.64	19.07	26.51
6	1996	146	396	3673	4469	2.71	25.16	30.61
7	1997	109	331	2294	2840	3.04	21.05	26.06
8	1998	124	378	3674	4084	3.05	29.63	32.94
9	1999	115	367	3419	3762	3.19	29.73	32.71
10	2000	143	457	6317	4546	3.2	44.17	31.79
11	2001	187	570	7303	5612	3.05	39.05	30.01
12	2002	209	638	6329	5673	3.05	30.28	27.14
13	2003	245	781	8032	8112	3.19	32.78	33.11
14	2004	214	749	6784	6345	3.5	31.7	29.65
15	2005	268	845	9546	8530	3.15	35.62	31.83
16	2006	271	875	12943	9544	3.23	47.76	35.22
17	2007	346	1208	15446	13229	3.49	44.64	38.23
18	2008	496	1639	19902	16900	3.3	40.13	34.07
19	2009	555	1917	20075	21132	3.45	36.17	38.08
20	2010	762	2427	23908	32075	3.19	31.38	42.09
21	2011	872	3033	23011	36622	3.48	26.39	42
22	2012	1020	4176	23214	46593	4.09	22.76	45.68
23	2013	1194	4550	26186	56152	3.81	21.93	47.03
24	2014	1270	4875	20322	61594	3.84	16	48.5
25	2015	1467	5778	18123	75057	3.94	12.35	51.16
26	2016	1748	7178	12599	90841	4.11	7.21	51.97
27	2017	1999	8226	6175	111778	4.12	3.09	55.92

PY: Publish Year; TP: Total Publications; NA: Number of Authors; TC: Total Citations; NR: Number of References; AU/TP: Author per Paper; TC/TP: Citation per Paper; RE/TP: Reference per Paper.

In the scientometric trend of low-carbon economy research, as the number of authors and references increased from 1991 to 2017 greatly, the publication and citation records grew quickly and significantly at the

same time. The citation records decreased in the last five years due to citation delay, which is a normal phenomenon in citation based research. The number of total citations was typically at a higher level in the exponential growth curve over time compared with the most recent publications. An important characteristic of the scientometric trend is that from the average data, the number of authors and references increased from less than three to more than four, and the number of references doubled from 25 to 50. The average number of times these papers were cited increased from 22.62 in 1991 to 47.76 in 2006 and then decreased due to citation delay. This result indicates that an increasing number of scholars are focusing on low-carbon economy research. These research outputs exerted a great impact in the last 27 years around the world.

3.1. Times Cited Performance Study

In the citation index databases of SCI and SSCI, the count of references and times cited were recorded to trace the citation pathways. With the detailed scientific publication data, abundant information on the low-carbon economy can be obtained through a scientometric study. The basic citation information was listed from references and times cited records.

3.1.1. Annual Reference Distribution

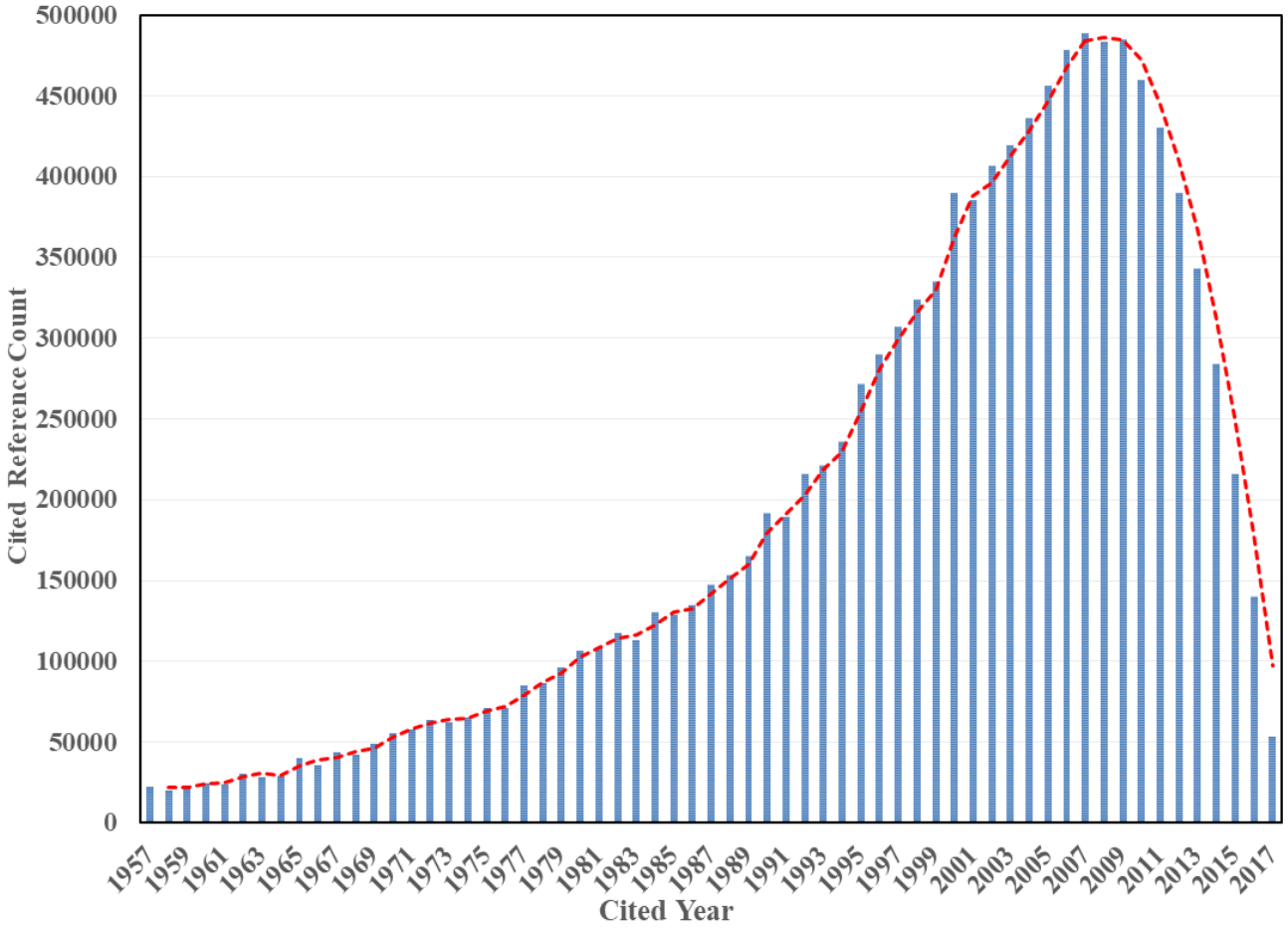

Figure 2. Annual References Distribution in Low-carbon Economy Research Papers

References related to low-carbon economy publication were collected from 1957 to 2017 and are shown in Figure 2. The reference information combined with information from the SCI and SSCI databases were used to examine the reference and citation behaviours. The total references ranged from only 21,197 in 1957 to more than 488,748 in 2007. Few researchers paid attention to the low-carbon economy before the 1990s, but after 1995, the number of references increased rapidly. The growth trend presented a curve that decreased rapidly after reaching its peak in 2007. Many scholars paid attention to newly published low-carbon economy papers, and their distribution from 1998 to 2007 rose quickly. Several typical papers were quoted more than once, and the ratio between reference counts and reference records showed the average strength of the year paper cited. In those references, papers published 3–5 years ago were referenced more than five times, which was more than that of early publications. This finding shows a significant characteristic distribution in the references of scientific papers.

3.1.2 Time Cited Frequency Study

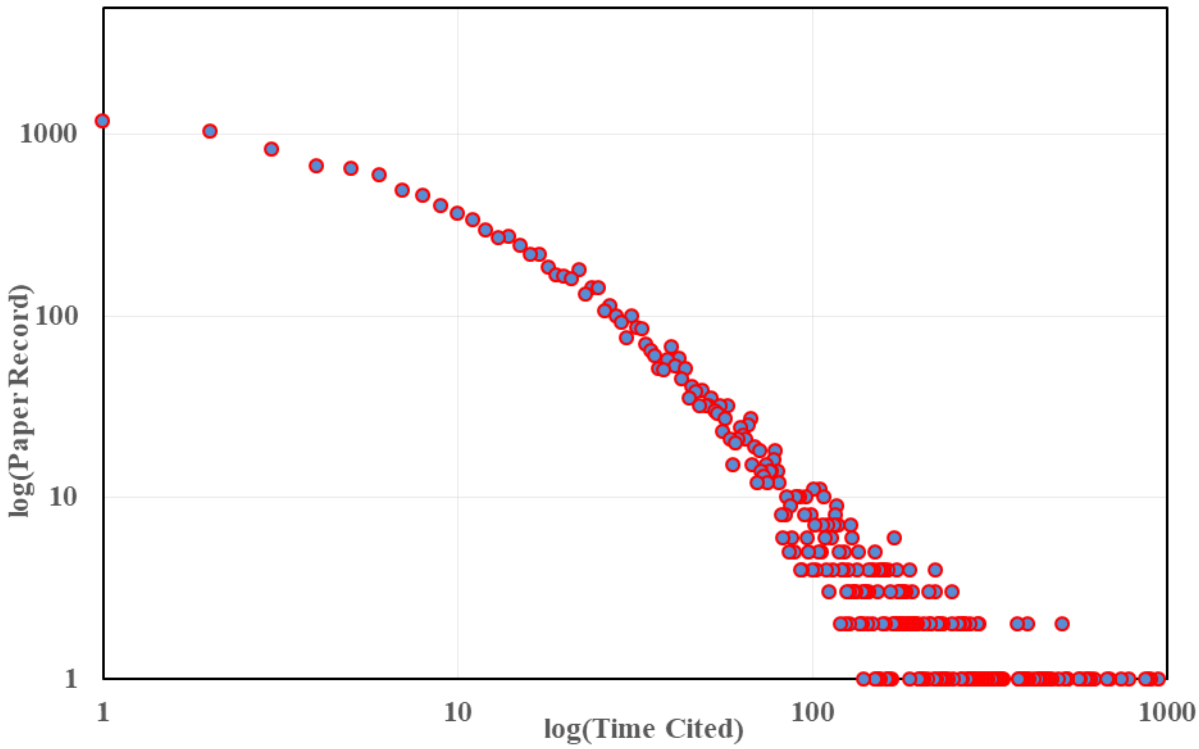

Figure 3. Times Cited Distribution in Low-carbon Economy Research Papers

Times cited and the total number of citations was provided in the database and are visualised in Figure 3. Figure 3. indicates that most articles were rarely cited at a low frequency of not more than five times. Specifically, more than 1,500 articles (10% of all papers) had a reference number of zero. Most papers were cited at the middle level, with citation times of 5–18 and with total articles of more than 5,000, which constitute 35% of all papers. Only a small number of articles proved to be highly cited papers with good quality and high recognition in the low carbon research scientific community. After a visualisation of the citation and its size, the log-log distribution was obtained. Times cited and the paper numbers maintained a power law distribution because the double-logarithmic curve formed as a straight line. The more citations a paper received, the smaller the distribution of those papers was. This distribution trend is consistent with that in papers in most scientific fields. According to this distribution, high-level research work outputs can be selected based on their citations, and this criterion was used to evaluate low-carbon economy papers in the next section followed.

3.2. Influence of Research Outputs

The impact of a single paper is limited, whereas many outputs can influence numerous researchers and attract the attentions of many scholars because they signify the rule of creation in society. Thus, the subjects and journals were reviewed to understand the research influence in the domain of the low-carbon economy.

3.2.1. Subject Citation Distribution

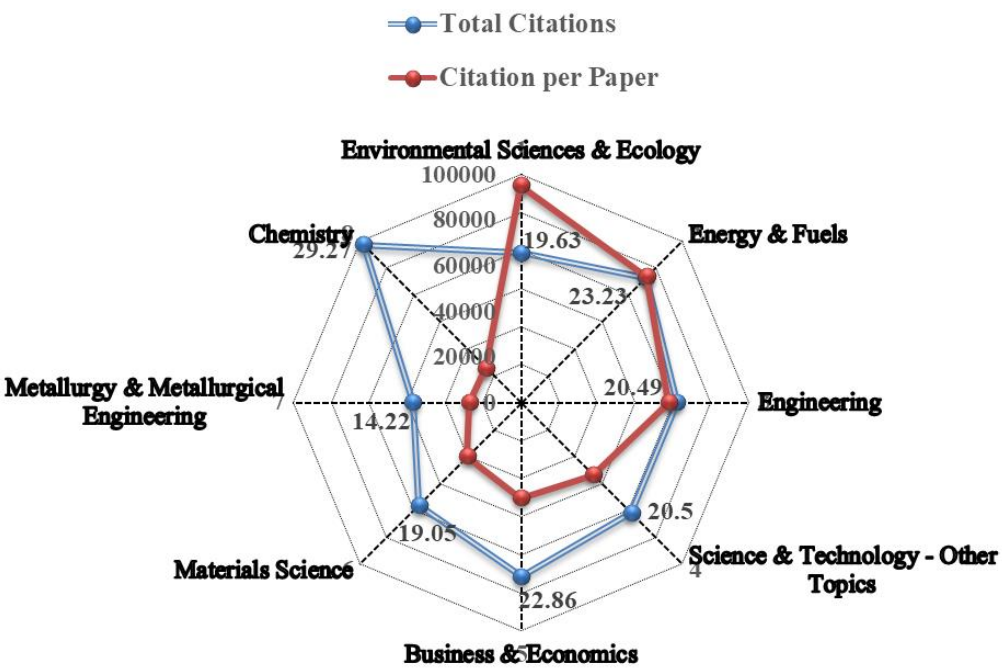

Figure 4. Total Citation and Citation per Paper in Most Distributed Subjects

The papers related to the low-carbon economy were published in many types of journals and are classified into 23 subjects in the WoS platform. According to the subject category classification of Clarivate Analytics in the Journal Citation Report (JCR), the publications are listed in several subjects that are ranked by the number of papers. The papers' citation impacts are shown in Figure 4. Researchers devoted more attention to environmental science and ecology research, which demonstrates the growing concern about climate change and environmental problems with an increasing realisation of a severe crisis. Chemistry occupies the dominant position in the paper citations in low-carbon economy research, and Energy and Fuels are in the second position, followed by Business and Economics. These subjects are the most cited in low-carbon research, but their

citations per paper are at a modest level compared with those of Environment Science and Ecology, Energy and Fuel, as well as Engineering and other topics. The papers in the latter subjects obtained an average citation count of more than 20 times per paper, particularly multi-disciplinary papers in "science and technology-other topics". The reason is that low-carbon economy research is not a single discipline and has attracted attentions of researchers from many other subjects in the entire science and technology circle.

3.2.2. Journal Citation Distribution

The impact of specific subject papers can be understood from the distribution of their citations in different subjects as above. The influence of the journals can also be analysed through the journals of low-carbon economy publications, for which the journal can be considered a special cluster of papers with a similar topic.

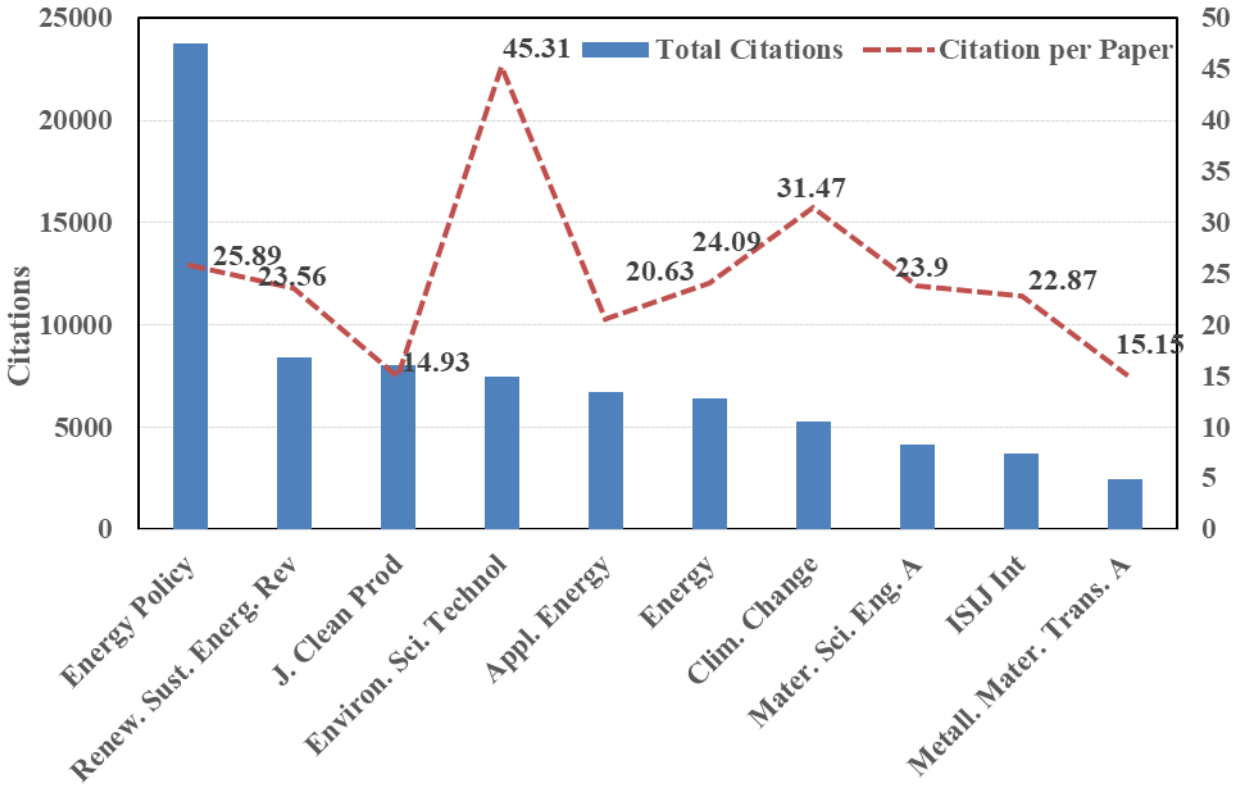

Figure 5. Top 10 productive journals and their citations' distribution

The top 10 productive journals are displayed in Figure 5. *Energy Policy* has an absolute advantage in total citations and with most number of publications. *Energy Policy* has a higher time cited per paper partly due to its large number of publications in recent years. The journal of *Energy Policy* was statistically the most productive and the main contributor to low-carbon economy research from 1990 to 2017. *Renewable and*

Sustainable Energy Reviews ranks second in total citations, with the higher citation per paper record in this analysis item. Other journals, such as *Applied Energy* or *Energy*, following but have a relatively lower level of citations per paper. The journal of *Environment Science and Technology* has the most citations per paper, which illustrates its high research level in low-carbon economy research domain. The cited papers and their journal performance are presented and it was found, many authors cited articles published in multiple disciplinary journals, such as *Science*, *Nature* and PNAS, aside from articles in journals in a professional field. A difference exists between *Energy Policy* and other journals published before the 1990s. However, papers published in *Energy Policy* experienced an impressive growth after 2000 and demonstrated a fluctuating trend of rising and falling, which also indicates the journal's performance in the future. In addition, the gap between *Energy Policy* and other journals has widened. Current performance shows that this journal has overwhelming superiority and will likely be the most productive for a long period. Overall, papers in every realm of low-carbon economy research citations showed an upward trend during this period.

3.3. Citation Analysis of Research Base

Low-carbon economy research exerted a strong impact on human cognition, but of importance are questions of why and how this occurred. Through a co-citation analysis, the origin of knowledge can be clearly identified by using the visualised clusters formed in the knowledge networks. Journal co-citation analysis (JCA) and author co-citation analysis (ACA) methods were employed in this work to provide critical answers to the questions issued above.

3.3.1. Journal Co-citation Analysis (JCA)

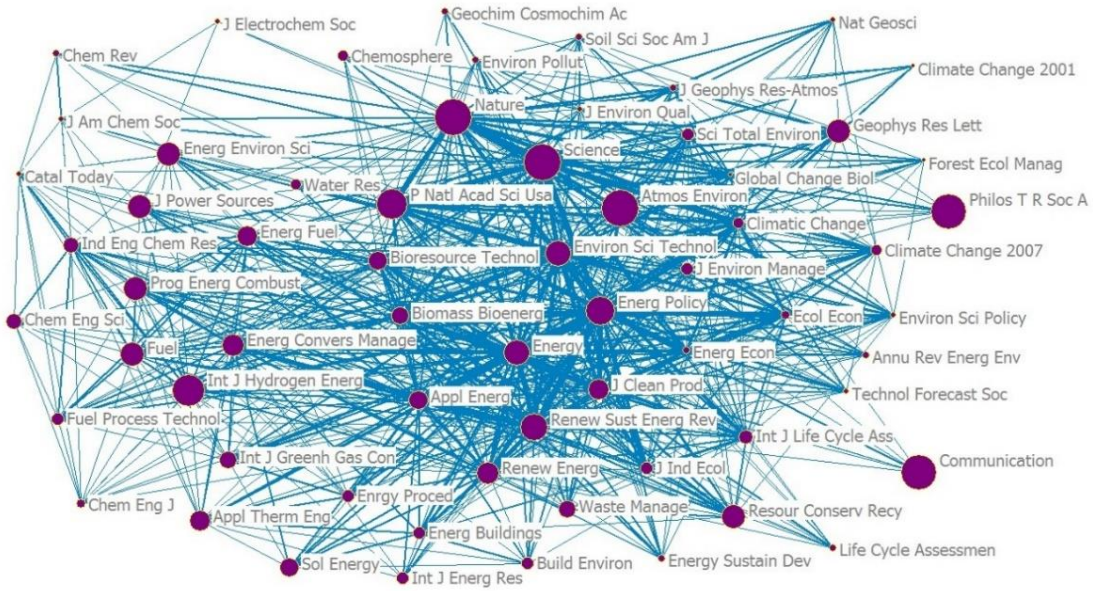

Figure 6. Journal Co-citation Network for Low-Carbon Economy Research

To obtain further information on the citation impact and research base, the JCA method was employed to help to understand the origin and destination of knowledge. Figure 6. of the Journal Co-citation Network reveals that the top 10 cited journals in the previous section are also found in the central position in the co-citation network. In addition, *Atmosphere Environment* and *International Journal of Hydrogen Energy* belong to a co-citation core area centring on *Energy Policy*. *Atmosphere Environment* and *International Journal of Hydrogen Energy* are concerned with low-carbon economy research, especially in the field of low-carbon policies. Another co-citation core area focuses on fuel, such as located in the journals as *Fuel*, *Energy Fuel* and *Energy Conversation Management*, which form a sub-entre in the journal co-citation map. Co-cited journals are the research base in the field of low-carbon economy research, which providing critical original knowledge clusters in their research history.

3.3.2. Author Co-citation Analysis (ACA)

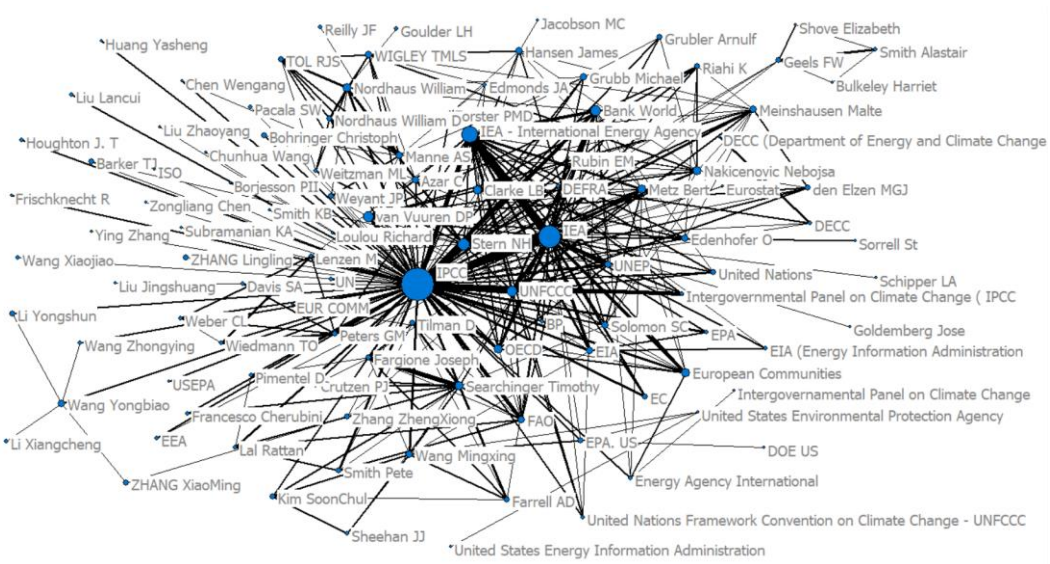

Figure 7. Author Co-citation Network for Low-carbon Economy Research

The co-cited authors for productive works are presented in Figure 7. The authors were much close to the cluster in collaboration networks. ACA social networks of the low-carbon economy showed that their research cooperation was close and strong. Several international organizations, such as *Intergovernmental Panel on Climate Change* (IPCC), *International Energy Agency* (IEA) and *Organization for Economic Cooperation and Development* (OECD), published a large number of research articles and were highly co-cited as authorities. Except for the UN or EU organizations, many active and productive authors were also co-cited for many times. Authors' co-cited frequency showed a significant centrality pattern in Figure 7. Component analysis revealed that the scholars' group could be regarded as a backbone in this field. Nevertheless, the author productivity analysis could be biased because two or more authors may have the same initials (e.g. Wang, YB) or authors may use different names in their publications (e.g. surnames were changed after women authors being married). In this work, all cited authors were cleared and classified before preparing the visualisation map and ACA analysis as the main nodes in the co-citation network.

3.4. Survey of Collaboration Trends

Collaboration provides inspiration and innovation to scientists and makes their knowledge highly influential in academic circles. Through collaboration networks survey, the impact of low-carbon economy research can

be traced and examined clearly.

3.4.1. Country-level Collaboration

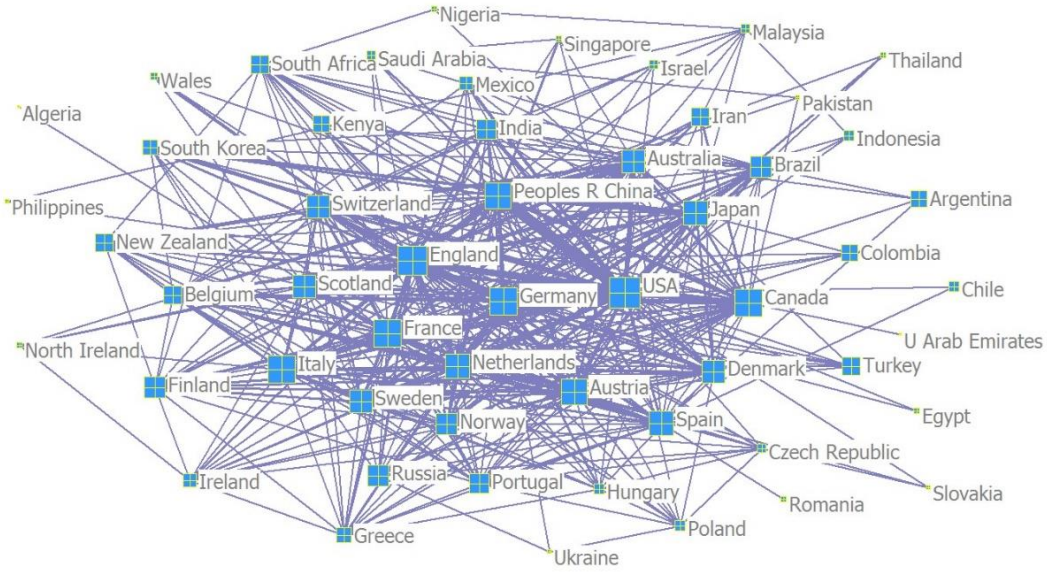

Figure 8. Collaboration Network among Countries in Low-carbon Economy Research

Figure 8 displays the low-carbon economy research cooperative network country map, from which the national/regional cooperative relationship and national/regional cooperation degree can be discovered and understood. The line thickness between countries or regions reflects their degree of cooperation. The U.S. is the most productive country in the research on low-carbon economy among all countries and is located at the core position in the networks of corporations. England, Germany, the Netherlands, France and P.R. China are also at the heart of the network. They cooperate frequently with one another in this globalization era. The U.S. published the largest number of papers and occupies the core position in the collaboration network. India, Australia, Japan, Canada, Spain, Norway, Sweden, Italy, Switzerland and Scotland are in the peripheral layer. Being the largest developed country in the entire world, the U.S. enacted its own climate change policy targets and mitigation regulations. Thus, many scholars in the U.S. still have paid attention to the field of low-carbon economy research. In developing countries, such as P.R. China, the search for low-carbon development trajectories contribute not only to the global climate but also to the long-term energy security and competitiveness of their economy.

Next, an exercise was carried out to determine the number of authors in different countries and the most

publishing countries on low-carbon economy research. China (9,620 authors), USA (7,770), England (3,936), and Germany (2,502) are the four biggest contributing countries on the low-carbon economy research publications. Authors from England and Canada receive the highest productivity (0.31 articles per author), followed by Australia and India (0.29 articles per author).

3.4.2. Institute-level Collaboration

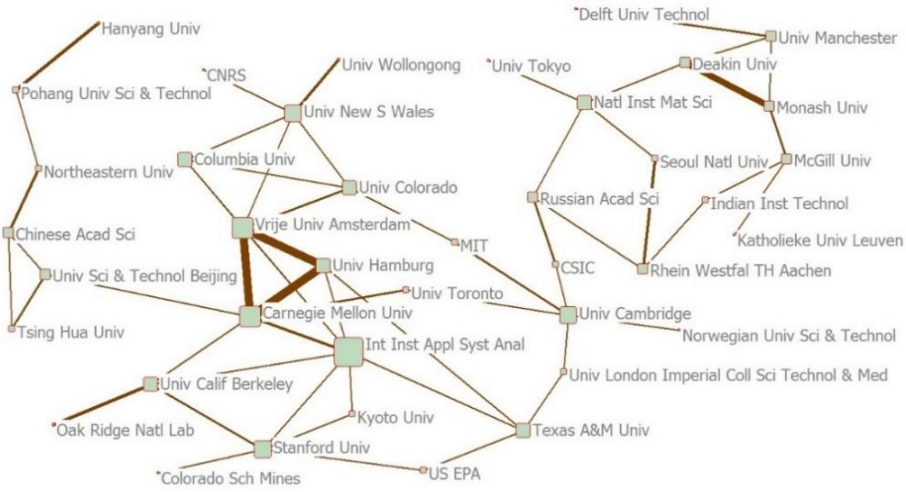

Figure 9. Collaboration network among institutes in low-carbon economy research

Figure 9. shows the cooperation networks of organizations in low-carbon economy research. According to the degree of cooperation among these institutes, several of them, such as *Vrije Universiteit Amsterdam*, *Universität Hamburg* and *Carnegie Mellon University*, are in the core status of the network because they cooperated frequently. These organizations play an important role in the process of knowledge transfer process in low-carbon economy research worldwide. The *International Institute for Applied Systems Analysis* (IIASA) is the central institute in the collaboration network shown above. IIASA focuses on common problems that might be encountered all over the world; examples of these problems include environment, ecology, energy and population, all of which are research hotspots of the low-carbon economy. Several institutions, such as *Delft University of Technology*, *Katholieke Universiteit Leuven*, *Colorado School of Mines* (CSM) and *Tsing Hua University* are scattered on the fringe of the network because they cooperated minimally and produce a small number of papers, so they need more efforts to collaborate with other institutes from the entire world.

3.5. Citation Impact of Literatures

The citation impact at the country, institute and paper levels was thoroughly analysed from macro-, meso- and micro-perspectives in this paper. The citation impacts of the most productive countries and institutes are provided below, according their outputs as well as research influence.

3.5.1. Country Citation Cognition

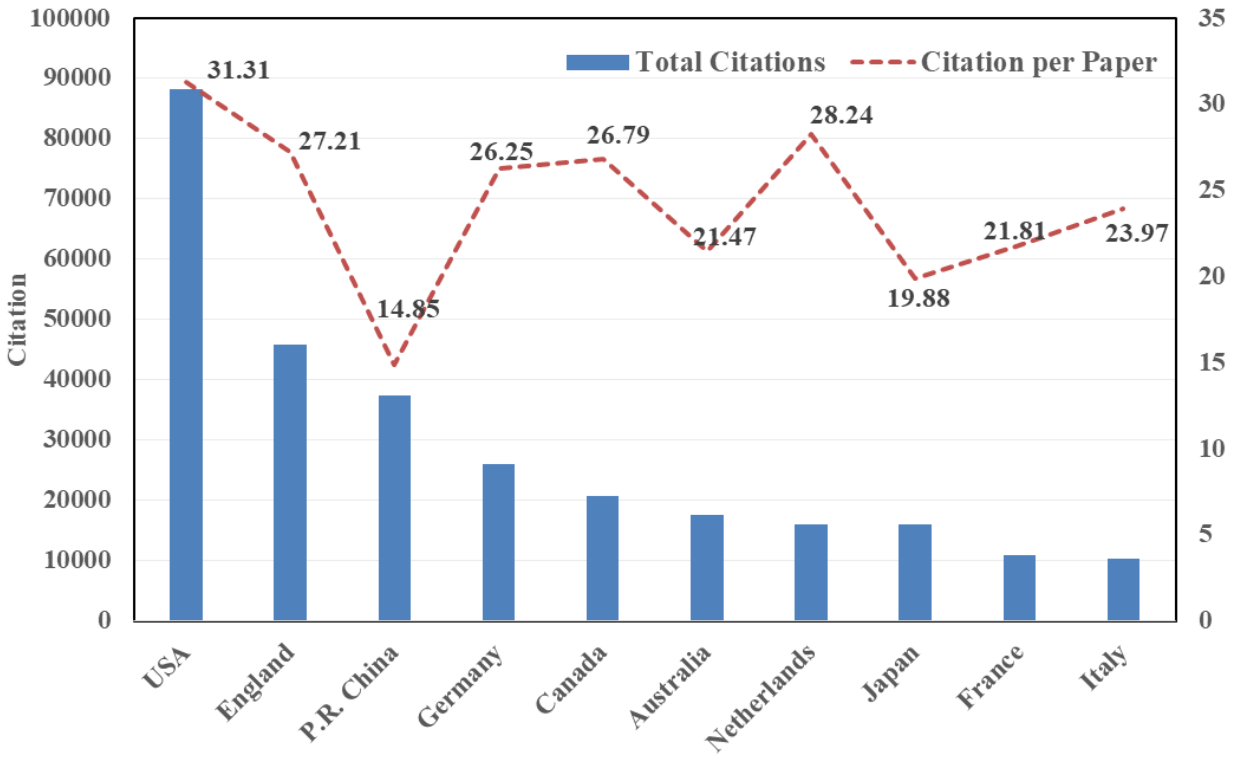

Figure 10. Total Citation and Citation per Paper in Productive Countries

The total citations and citations per paper frequencies in the field of low-carbon economy research from the top 10 countries are shown in Figure 10. The U.S. had the highest total citation counts, far outstripping the other nations in the past years, followed by England, P.R. China, Germany and Canada. The countries ranked by citations per paper listed in a descending order, are separately the U.S., the Netherlands, England, Canada, and Germany. The U.S. is also top-ranked in the issued number of papers, total citations and high citations per paper, demonstrating its dominance in the field of low-carbon economy research. This performance indicates the high quality of the papers published in the U.S. The Netherlands, whose citation per paper is 28.24, ranked second with a modest citation per paper. P.R China holds the third place in the total citations but has the lowest citations

per paper in this research domain. Germany and Canada are highly ranked in total citations and citations per paper, illustrating their good performance in low-carbon economy research in these years.

3.5.2. Institute Citations Cognition

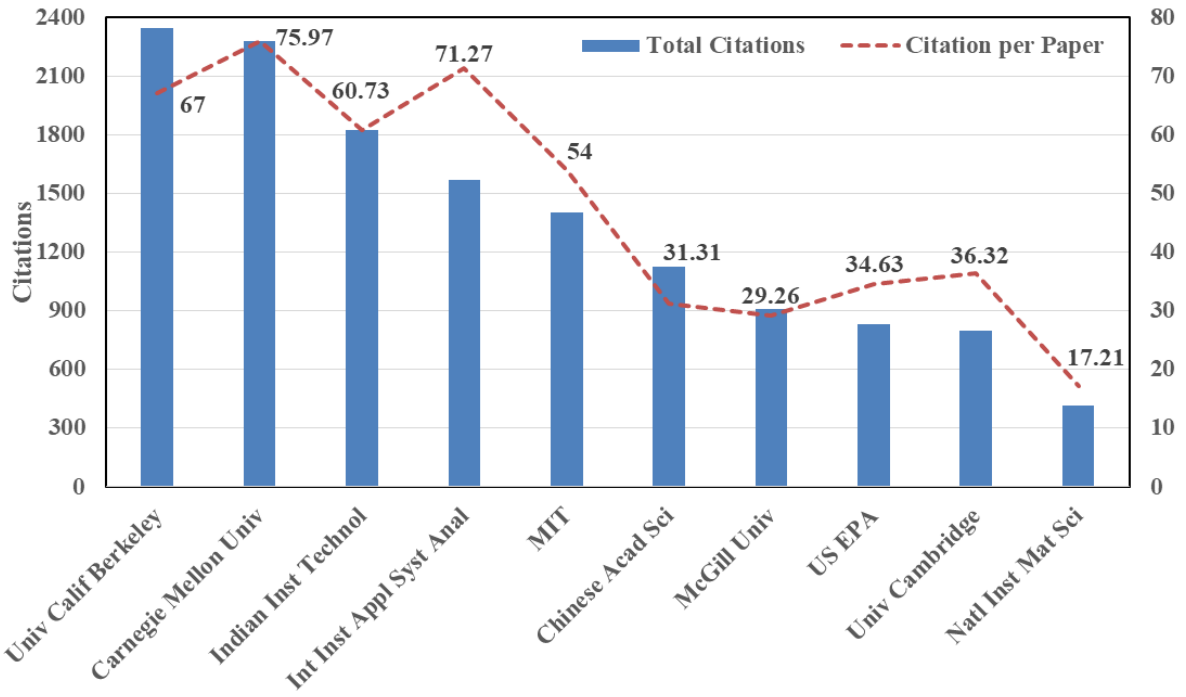

Figure 11. Total citation and citation per paper in productive institutes

Figure 11. shows the top 10 institutes around the world in terms of total citations and citations per paper in the field of the low-carbon economy. *University of California Berkeley*, *Carnegie Mellon University* performed well in total citations and far exceeded other institutes, followed by the *Indian Institute of Technology*, *International Institute for Applied Systems Analysis*, *Massachusetts Institute of Technology* and *Chinese Academy of Sciences, McFill University*. The ranking of citations per paper in a descending order is *Carnegie Mellon University*, *International Institute for Applied Systems Analysis*, *University of California Berkeley* and *Indian Institute of Technology*. Most of the top institutes are from the U.S, which indicates that top institutes from America have played an essential role in promoting the extension and maturation of the low-carbon economy. It also implies that the U.S has not only invested the most resources on research on low-carbon economy but also occupies a dominant position in this area. The productive institutes, such as *Carnegie Mellon University* and *International Institute for Applied Systems Analysis* have a high quantity of citations per paper. Their research results have received great recognition. The number of citations per paper is less than the number

of total citations. Productive institutes, such as *University of California Berkeley*, perform well in article numbers and attach importance to publishing research results on the low-carbon economy. Chinese institutes are not top-ranked, and thus the institutes in P.R. China need to strengthen and improve their research on low-carbon economy research.

3.6. Scientific Citation Network Study

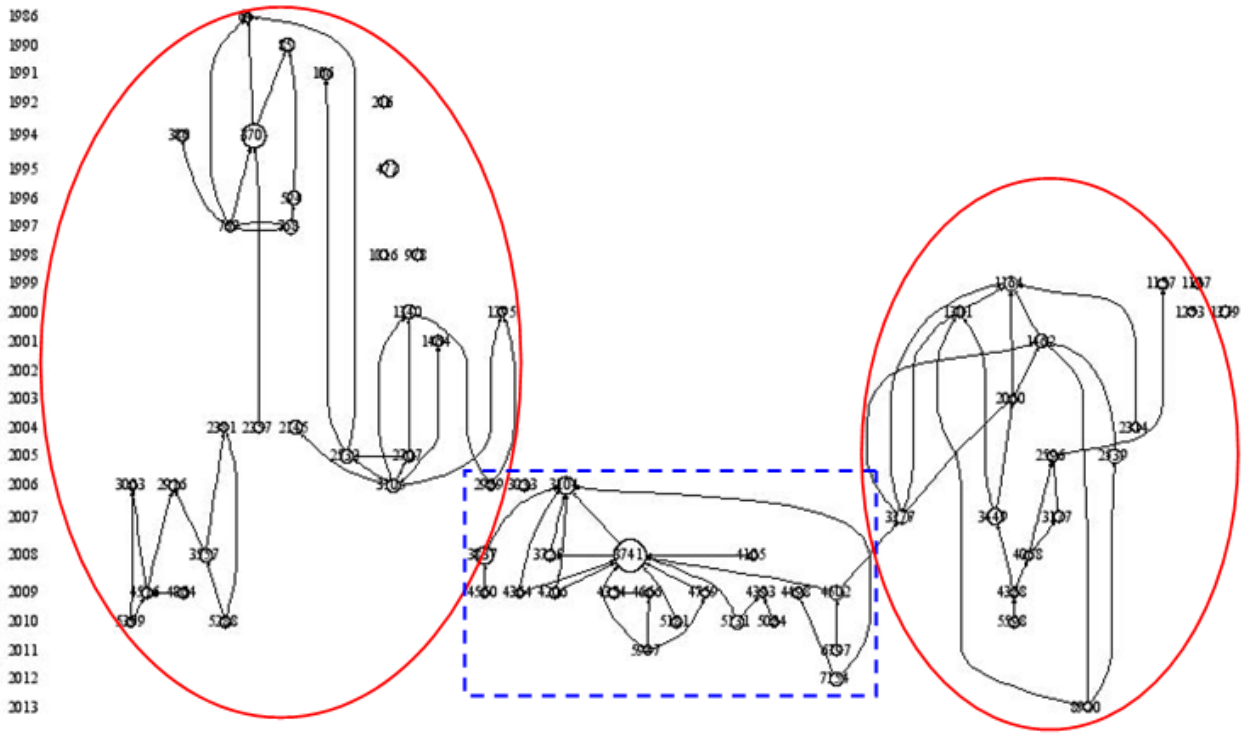

Figure 12. Citation Network for Low-carbon Economy Research

By examining the citation network above, it can be traced the citation history in low-carbon economy research from 1986 to 2013 as in Figure 12. Recently published papers cited former ones and then a citation network formed, in which a time series of the citations traces the citing pathways. All related papers can be divided into three parts from the figure above with the time axis on the left. The left part shows research work in low carbon, the middle part reflects the public concern about pollution and the right part contains the low-carbon economy policy research. To see the node information clearly, all the nodes are numbered in Figure 12. The citation point's parameters are also provided in Table 1. The citation scores in the local and global means of citation times calculated in the research domain or discipline and from all domains and subjects. As shown in Table 2, it can be concluded that paper no. 64 is the ground-breaking work in low-carbon economy research.

Paper no. 370 cited paper no. 64, and it was cited many times after publishing. Along with the development of research, other papers were cited by newly published papers in the 20th century, which means further knowledge was gained in low-carbon economy research followed. In recent works, paper no. 3741 paper (published in Science) attracted the most citations. In this citation network, paper numbers 5288, 7154 and 8920 are in the bottom end, and they cited many other classical papers, to perform the up-to-data research work in low-carbon economy research.

Table 2 The Nodes' Parameters in the Citation Network of Low-carbon Economy

Rank	Paper No.	Author / Date / Journal	LCS	GCS
1	64	Ushioda K, 1986, *Mater Sci Tech Ser*, V2, P807	17	46
2	370	Ray Rk, 1994, *Int Mater Rev*, V39, P129	88	334
3	1194	Yada H, 2000, *ISIJ Int*, V40, P200	22	92
4	1340	Park Kt, 2000, *Mat Sci Eng A-Struct*, V293, P165	28	146
5	1462	Manne As, 2001, *Nature*, V410, P675	27	132
6	1478	Liu G, 2001, *Scripta Mater*, V44, P1791	28	159
7	1541	Wrage N, 2001, *Soil Biol Biochem*, V33, P1723	21	635
8	1785	Rao Ab, 2002, *Environ Sci Technol*, V36, P4467	36	651
9	1832	Heller Mc, 2003, *Biomass Bioenerg*, V25, P147	17	188
10	2060	Hyman Rc, 2003, *Environ Model Assess*, V8, P175	18	37
11	2314	Mcfarland Jr, 2004, *Energ Econ*, V26, P685	17	67
12	2381	Mcginn Sm, 2004, *J Anim Sci*, V82, P3346	19	172
13	2539	Shine Kp, 2005, *Climatic Change*, V68, P281	34	201
14	2596	Chen Wy, 2005, *Energy Policy*, V33, P885	24	67
15	2707	Song R, 2005, *Acta Mater*, V53, P4881	22	131
16	3047	Nemet Gf, 2006, *Energy Policy*, V34, P3218	18	198
17	3741	Fargione J, 2008, *Science*, V319, P1235	162	1486
18	5288	Eckard Rj, 2010, *Livest Sci*, V130, P47	24	135
19	7154	Williams Jh, 2012, *Science*, V335, P53	27	119
20	8920	Bond Tc, 2013, *J Geophys Res-Atmos*, V118, P5380	18	637

LCR: Local Citation Score; GCS: Global Citation Score

Conclusion and Policy Implications

The impact of the global research performance of the low-carbon economy was evaluated based on scientific data from SCI and SSCI databases through scientometric methods. Contributions in low-carbon economic research can be summarized into two parts. The first involves discussion and summary about the evolution and characteristics of low-carbon economy. The second is research suggestions, which can range from policy implications to possible actions to improve low-carbon economy research and reduce GHG emission in the future.

(1) Discussion and Summary

Low-carbon economy has attracted the attention of many researchers from different subjects all over the world in the last decade. The findings can be used to study global research trends and applied to achieve the effective concentration of low-carbon economy in the future. Our work analyzed the extension of low-carbon economy research from scientific publications to summarize the rapid application of research outputs and reveal the key and popular methods in this research subject. The low-carbon economy research outputs were examined from paper records, subjects, journals, countries, institutes, authors and their citations. Excellent interdisciplinary scientists have promoted the research of low-carbon economy in the last two decades. Researchers should pay attention to core papers, institutes, and journals to facilitate their green pursuit.

Low-carbon economy research presented an upward trend based on the scientific data research results, given that SCI and SSCI paper production increased rapidly in the last two decades until now. The number of low-carbon economy papers increased from less than 100 in 1990 to 1, 999 at the end of 2017. In recent years, several countries, such as the U.S., England, P. R. China and Germany, have provided outstanding contributions to research on the low-carbon economy. The U.S. ranked first in terms of the quality and quantity of papers. Institutes, such as *University of California Berkeley* and *Carnegie Mellon University*, produced the most papers in the field of low-carbon economy in the world. Meanwhile, the core journals of *Energy Policy*, *Renewable and Sustainable Energy Reviews* and *Journal of Clear Production* published the most papers in recent years. Researchers should pay attention to the recent direction and new publications in these top journals to study the low-carbon economy well as they collected most influential academic research results.

By using a scientometric method, the relationships of the subjects, journals and citations and the order by

time and space were analysed and discussed in this work. The figures and tables describe the entire distribution and interesting regulations of the low-carbon economy research outputs in the world. This work provides better understanding on the low-carbon economy effectively and helps scholars study in their potential research. Researchers should pay attention to the core papers, institutes and journals to help their working on green pursuing in this planet.

(2) Policy Implications

A set of recommendations based on our findings are provided to improve low-carbon economy research and applications. (i) Research policy that encourages cooperation among different subjects and directions can promote the interdisciplinary and cross-directional research of low-carbon economy. (ii) The communication and collaboration among different countries and regions, particularly the actors on the verge of the collaboration network, should be promoted to accelerate knowledge diffusion and reduce knowledge gap. (iii) The influence of international organizations (e.g., IPCC, IEA, and OECD) as coordination centers and knowledge hub for developing low-carbon economy should be enhanced. (iv) Joint research programs should be established and findings of research institutes and industry in different regions should be shared to expand the transformation and application of low-carbon economy. (v) Knowledge and findings on the low-carbon economy research are also important to influence the policy-making and actions of governments to address climate change and environment pollution.

This study aims to provide guidance to those who aspire to investigate the low-carbon economy using big scientific data-driven evolution through citations or references analysis. However, the introduction of the shortcomings of this study and new challenges of low-carbon economy is also necessary. Numerous papers on low-carbon economy are dispersed in a limited number of databases. Thus, several high-quality papers may not have been analyzed in the current research. Accordingly, future studies should focus on additional databases, such as those on patent data analysis, to determine the key advances on low-carbon technologies in the world. These studies should also focus on the number of patents, citations, and co-citations, among others, to determine the relationships among all technologies. Lastly, future studies could show a complete and vivid image of the low carbon economy research from another perspective.

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