

# Visual Analysis of Carbon Emissions in Steel Industry Based on CiteSpace

Desheng Xu

Inner Mongolia University of Technology

Ke Yang

Inner Mongolia University of Technology

Wei Duan (✉ [duanwei1246@imut.edu.cn](mailto:duanwei1246@imut.edu.cn))

Inner Mongolia University of Technology <https://orcid.org/0000-0002-3132-314X>

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## Research Article

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# Abstract

This paper analyzes the research characteristics and development context of carbon emissions in the steel industry, which will provide reference for future carbon emissions research and practice in the steel industry in China. Based on the “Web of Science Core Collection” (hereinafter referred to as SCIE) database, this paper used CiteSpace software to make a bibliometric analysis of the literatures related to carbon emissions in the steel industry from 1991 to 2020 in terms of countries and regions, major publishing institutions, high-yield authors, keywords and time zone views. The results show that: 1) Scholars and research institutions in different countries and regions form a close cooperation network according to their geographical location;2) The research forces with China, the United States, the United Kingdom and Japan as the core have provided key research support and contributed major research results to the carbon emission field of the steel industry;3) Climate change, production technology and future scenario analysis are the three main research topics;4) In the future research stage, the comprehensive application of various disciplines such as technical and economic analysis, scenario analysis and environmental climatology will become the forefront of the research on carbon emissions in the steel industry.

## Introduction

The Fifth Assessment Report of IPCC pointed out that man-made greenhouse gas emissions lead to the continuous deterioration of global climate, which poses a serious threat to the stable development of human beings and nature (Stocker 2014). Industry is the main body of economic activities, plays an important role in the greenhouse gas emissions, according to BP world energy statistics yearbook (2019) data statistics, in 2019, industry accounted for 33% of the world's energy consumption and 40% of CO<sub>2</sub> emissions in turn (Yu et al. 2021), and the iron and steel industry as one of resource-intensive industries, is a key field of greenhouse gas emissions, accounting for about 33.8% of the total industrial emissions and 7% of the world's total CO<sub>2</sub> emissions (Yuan et al. 2020). Therefore, carbon emission reduction activities of the steel industry play a vital role in its own sustainable development and global carbon emission control (Talaie et al. 2020). At present, China is the world's largest steel producer and consumer. In 2019, China's steel consumption totaled 907.5 million tons, accounting for 51.3% of the world's total consumption. Crude steel production totaled 996.3 million tons, ranking first in the world, accounting for 53.3% of the world's total production. Pig iron production totaled 809.4 million tons, accounting for 63.2% of the total pig iron production in the world (BP Company 2019). In addition, China's steel industry mainly consumes coal and coke energy, accounting for 89.18% of the total energy consumption of the steel industry (Wang et al. 2017), which makes the steel industry become one of the key sources of China's CO<sub>2</sub> emissions, accounting for about 15% of the total national CO<sub>2</sub> emissions (Zhang et al. 2018). In recent years, with the annual increase of CO<sub>2</sub> emissions in China's steel industry, its development has also been faced with serious environmental problems (Xu et al. 2017). In order to cope with China's increasingly severe environmental challenges and achieve the goal of carbon peak and carbon neutral before 2030 and 2060 in turn (Hu 2021), it is necessary to conduct in-depth research on carbon emissions in the steel

industry. What is the collaborative network of research journals, institutions, authors, and countries that have been involved in the analysis of carbon emissions from the steel industry for nearly three decades? How do the research topic evolve? How do they relate to each other? What are the latest research frontiers? The discussion of these problems is of great theoretical and practical significance for researchers to grasp the research hotspots in this field systematically and to enhance the efficiency of scientific research.

With the help of CiteSpace visualization analysis software, this paper adopted the method of bibliometric analysis to make a visual metrological analysis of the relevant literatures on carbon emissions of steel industry from 1991 to 2020 in SCIE database by using cooperative network map, keyword co-appearing, clustering and Timezone time map. This paper revealed the research hotspot and development trend of the current and future, aiming to provide reference for future prospective research on carbon emissions in China's steel industry.

## Materials And Methods

In order to comprehensively analyze the characteristics and frontier hot of carbon emission research in iron and steel industry, this paper used CiteSpace (version 5.7.R3) software to conduct scientific econometric analysis on related literature. CiteSpace is gradually developed under the background of scientometrics, data and information visualization, and is a visual analysis software for visual description and trend display of literature (Li and Chen 2016). By using CiteSpace to draw the map of cooperative network, keyword clustering and time zone view, the basic characteristics of research in this field and the evolution path of the topic can be explored (Huang et al. 2020), and the research hotspots and trends can be sought.

Generally speaking, the main stages of research development in each field are determined according to the evolution process of the research topic, which in turn is promoted by both the knowledge base and the research frontier (Chen 2020). Therefore, this paper used CiteSpace software to draw a visual analysis map. Through detailed interpretation and analysis of each map, this paper explored the evolution process and rules of carbon emission research in the steel industry, found out its active themes and frontier hotspots, and objectively analyzed and commented on the research panoramic view in this field.

In this paper, an advanced retrieval was conducted on CNKI database, with "steel industry" and "carbon emissions" as the retrieval topics, the time set as "unlimited year" to "2020", and the journal source categories set as "SCI source journals", "EI source journals" and "CSSCI". A total of 20 related literatures were retrieved. Due to the small number of domestic literatures and considering the representativeness of samples, this paper used Web of Science as the literature retrieval system and selected SCIE database for advanced retrieval. The relevant literature retrieved was downloaded and saved as a plain text file in the form of "full record", which was used as the data sample for analysis in this paper.

## Results And Discussion

## Overview of Research Characteristics

Through the analysis of the basic characteristics of carbon emission research in the steel industry, the development of the research in this field can be grasped as a whole, and the academic circles' attention to this field and its research value can be understood.

## Research Records Distribution

Through sorted out the published papers from 1991 to 2020, it is found that the distribution of the published papers related to carbon emissions in the iron and steel industry showed an overall increasing trend. As shown in Figure 1 below, some researchers began to pay attention to carbon emissions in the steel industry in the early 1990s, and corresponding research results emerged. In recent years, it has attracted widespread attention. In 1991, Italian scholar Gretz, J, et al first made relevant research in this field and put forward their opinions, and they thought that steel production is one of the most important source of carbon dioxide pollution, as a large user of coal and other forms of energy, in order to cope with the threat of global warming, it is necessary to control coal consumption and seek alternative energy (Gretz et al. 1991). Perhaps because its early research mode is still in the initial stage of exploration, the active promotion of practical actions has not triggered a strong academic boom, and the research on carbon emissions in the steel industry has not been widely paid attention by scholars from all walks of life. This continued until the early 2000s, after which the number of discoveries in the field began to increase. Especially in 2020, the annual number of published papers on carbon emissions research in the steel industry reached a peak of 69. The proposed idea of carbon peak and carbon neutral goal (Chen 2020) made scholars and research institutions around the world paid more attention to this research field, and a large number of new theories, new methods and new technologies continued to emerge, and the number of published papers grows rapidly.

## Analysis of the Major Sources

The continuous development and growth of carbon emission research in the steel industry in the past 30 years has benefited from the continuous support of international journals of various disciplines. Table 1 lists the journals that published more than 4 research articles in this field, including energy, environmental engineering, metallurgy and ecology, etc., with strong comprehensive disciplines. More than half of the major source journals are in JCR 1 area, among which the number of publications of *Energy* is the highest with an impact factor above 6. Other top six journals, such as *Energy Policy* and *Journal of Cleaner Production*, all have an impact factor above 7. The most prominent one is that the 5-year impact factor of *Applied Energy* has reached 9.086. This indicated that the carbon emission research of iron and steel industry has been widely concerned by the mainstream academic journals, especially the authoritative energy journals. Thus it can be seen that although the carbon emission research field of the steel industry started late, with the increasingly severe global climate change situation (Isson et al. 2020),

scholars and authoritative professional journals from all walks of life are gradually paying more attention to it.

**Table 1** Journals with more than 4 papers on carbon emission research in the steel industry

Source journal name	Number of papers/ article	Percentage/%	Impact factor (2019)	5-year impact factor
Energy	16	13.8	6.082	6.046
Energy Policy	14	12.1	5.042	5.693
Journal of Cleaner Production	10	8.6	7.246	7.491
Resources Conservation and Recycling	9	7.8	8.086	7.589
Applied Energy	6	5.2	8.848	9.086
Environmental Science & Technology	6	5.2	7.864	8.543
International Journal of Greenhouse Gas Control	6	5.2	3.639	3.698
Sustainability	6	5.2	2.576	2.798
Energies	5	4.3	2.702	2.822
Journal of Iron and Steel Research International	5	4.3	1.213	1.357
Steel Research International	5	4	1.81	1.769

### Analysis of Main Research Forces and Cooperation

In order to have a deeper understanding of the specific research situation in the field of carbon emissions in the steel industry, this part made a bibliometric and statistical analysis on the major publishing regions, publishing institutions and high-yield authors, and explored the internal relationship between the literatures in this field.

### Analysis of Main Publishing Countries and Regions

In order to explore the cooperation characteristics of publishing countries in the carbon emission research of the steel industry, CiteSpace software was used to conduct a quantitative analysis of the literature extracted from SCIE. Country was selected in the Node Type and the distribution network map of publishing countries and regions was obtained as shown in Figure 2 below. After statistics, it is found that a total of 41 countries and regions have published relevant literatures (due to the small nodes in some regions with a small number of published papers, they are not shown in the figure), mainly

distributed in Asia, Europe, Oceania and North America. The top ten countries and regions were sorted out. As shown in Figure 3, all countries except China are developed countries, which also echoes the economic and cultural development pattern of the world today.

The size of the node (circle) in the network map of the country and region where the paper is issued represents the amount of the paper it publishes and the size of nodes means the number of articles it publishes. In addition, the thickness of the connection lines indicates the degree of cooperation. In the picture, we can see obviously, China has the largest number of nodes. It is the only country that has published more than 100 papers on carbon emissions in the steel industry, up to 157 papers, and it is the core force of research in this field. As the world's largest energy user in the steel industry and one of the major industrial CO<sub>2</sub> emitters, China has increasingly strict requirements for carbon emission reduction in recent years, and relevant scholars have paid more and more attention to the research in this field (Peng et al. 2018). At the same time, the major publishing countries and regions have formed a close cooperation network with China, the United States, the United Kingdom and Japan as the core, including Germany, Sweden, Australia, Finland, the Netherlands and Italy. Except for China, the key scientific research force of carbon emission research of the steel industry mainly comes from western countries, led by the United States. The cause of the phenomenon may have two aspects, on the one hand, because of the steel industry carbon emissions research is by the European scholars Gretz, J., AKIMOTO, H and SUZUKI, M and others take the lead in put forward and carry out related research (Gretz et al.1994; Akimoto and Narita 1994; Suzuki et al. 1995);On the other hand, due to the limited level of industrial development and weak scientific research strength in Africa, South Asia and Southeast Asia, etc., they do not pay much attention to this field (Abdelaziz et al. 2017).

### **Analysis of Major Publishing Research Institutions**

By sorting out the statistics of the international research institutions in the field of carbon emissions in the steel industry, the top 20 research institutions are listed as shown in Table 2 below. Among them, Chinese Academy of Sciences (Chinese AcadSci) published the highest number of papers, with 26 papers. The first paper in this field was published in 2007. Through the decomposition method of Malmquist index, Wei, Y. M., et al. found that due to the technological progress and improvement of technical efficiency, the energy efficiency of China's iron and steel industry increased by 60% from 1994 to 2003, which greatly reduced the carbon emissions of the steel industry (Wei et al. 2007).Secondly, the number of published papers of research institutions in the United States, Sweden, the United Kingdom and Australia follow closely, and most of them are national universities and colleges.This indicates that a large proportion of the scientific research force is stored in higher education institutions. Although this can make use of the best academic advantages to promote the development of carbon emission

research in the steel industry, at the same time, other research institutions should be actively encouraged to join in this field to continuously expand the depth and breadth of research in this field.

**Table 2**Top 20 scientific research institutions of carbon emission research in iron and steel industry

Issuing organization	Number of papers / article	Start year
Chinese AcadSci	26	2007
Xiamen Univ	15	2016
Northeastern Univ	13	2011
Chalmers Univ Technol	12	2013
Tsinghua Univ	12	2006
Univ Chinese AcadSci	11	2014
Jiangxi Univ Finance & Econ	8	2016
Univ Sci & Technol Beijing	7	2017
Lawrence Berkeley Natl Lab	6	2002
Lulea Univ Technol	6	2007
NatlInstEnvironm Studies	5	2003
Univ Cambridge	5	2010
China UnivGeosci	5	2011
Beijing Normal Univ	5	2012
Beijing Inst Technol	5	2009
CSIRO	4	2011
JFE Steel Crop	4	2006
Natl Cheng Kung Univ	4	2007
UnivNaclAutonoma Mexico	4	2002
Abo AkadUniv	4	2010

In addition, this paper uses CiteSpacebibliometric software to generate a network map of research institutions of carbon emission in the steel industry (Fig.4), which can indicate the cooperation between major publishing institutions and further explore the distribution of scientific research forces in this field. In the network graph, nodes represent the number of articles published by research institutions, and the connecting lines between nodes represent the degree of cooperation among research institutions. As can be seen from Figure 4, on the whole, there is a certain degree of cooperation among major scientific

research institutions, and the closely connected scientific research institutions are geographically close to each other. For example, China and Japan in Asia, the United States and Mexico in the Americas and other countries and regions have close cooperative relations. Only some underdeveloped countries and regions have weak cooperative relations between their research institutions.

### **Analysis of Main High-yield Authors**

In this paper, the authors of carbon emissions research in the steel industry are sorted out and summarized, and the number of published papers, nationality, institution and research scope keywords of the top 10 most productive authors in this field are statistically analyzed, as shown in Table 3 below. It is intuitive to find that nearly half of these major prolific authors are from China, led by Professor Lin Boqiang of Xiamen University. Professor Lin Boqiang had published 14 papers in total. He has made a key contribution to the research on industrial energy conservation and carbon emission reduction in China and represents the forefront of scientific research and development in this field in China (Lin et al. 2017; Lin and Xu 2018; Lin and Xu 2018). At the present stage, China is experiencing rapid industrialization and urbanization, resulting in a sharp increase in energy demand (Xu and Lin 2016). He emphasized that in the context of energy shortage, environmental pollution and energy cost constraints, energy conservation and emission reduction in the steel industry will become an important strategy for China's transformation to a low carbon economy (Lin and Du 2017). He was followed by Filip Johnsson of Chalmers University of Technology in Sweden with nine and Johan Rootzen of the University of Gothenburg with five. Filip Johnsson, Johan Rootzen and Professor Lin differ in their geographical scope due to differences in nationality, but their research aims are similar. In the *Paris Agreement*, Sweden promised to reduce greenhouse gas (GHG) emissions to zero by 2045 (Karlsson et al. 2020). Filip Johnsson and Johan Rootzen expected to achieve substantial emission reductions in energy-intensive industries through carbon capture and storage, so as to fulfill the commitment and achieve sustainable development goals (Johnsson et al. 2020; Johnsson et al. 2020).

**Table 3** Top 10 authors of carbon emission research in iron and steel industry

Author	Number of papers/article	Nationality	Organization	Research keywords
Boqianglin	14	China	Xiamen University	Energy economy; Energy policy; Technical economy, etc
Bin Xu	9	China	Jiangxi University of Finance and Economics	Steel industry; Carbon dioxide emissions; Panel data model, etc
FilipJohnsson	9	Sweden	Chalmers University of Technology	Carbon capture; Industrial CCS; Economic analysis, etc
Johan Rootzen	5	Sweden	University of Gothenburg	Carbon emission reduction; Climate change impact; Low carbon technology; Sustainable transformation; Scenario analysis, etc
E Worrell	4	U.S.A	Lawrence Berkeley National Laboratory	Steel industry; Carbon emission reduction; Energy efficiency, etc
Ida Karlsson	4	Sweden	Chalmers University of Technology	Carbon emission reduction; Greenhouse gas emissions; Sustainable transformation; Value chain; Supply chain, etc
Ali Hasanbeigi	4	Norway	Southeast University of Norway	MEA; Steelmaking; CCS; Cost estimation, etc
Yong Geng	4	China	Shanghai Jiaotong University	Iron and steel industry; Environmental economic model; Technology upgrading; Carbon trading, etc
Guibing Hong	4	Taiwan, China	Taipei University of Technology	Iron and steel industry; Construction industry; Taiwan; Energy saving; Energy audit, etc
RenjingXu	3	China	Nanchang Institute of Technology	Iron and steel industry; Carbon dioxide emissions; Quantile Regression, etc

In addition, several collaboration groups of authors have been formed in the field of carbon emission research in the steel industry, among which the collaboration among the highly productive authors is more prominent. In order to more intuitively represent the cooperation system among scholars, this paper used CiteSpace software to generate a map of author cooperation network (Fig.5) for analysis. It can be seen from this map that only a few scholars have formed a cooperative network, among which the most extensive group is centered on E Worrell of Lawrence Berkeley National Laboratory, including L Price and N Martin, etc. They looked at the low cost energy efficiency and carbon reduction opportunities in the US

steel industry (Worrell et al. 2001). The most closely collaborated group is Lin Boqiang and Xu Bin. They identified the key influencing factors of carbon dioxide emissions in China's steel industry from the perspective of regional geographical differences, and provided certain theoretical support and practical guidance for realizing carbon emission reduction in China's iron and steel industry and formulating effective environmental protection measures (Xu et al. 2017; Xu and Lin 2018).

## **Hot Spots and Cutting-edge Analysis**

Through keyword co-occurrence, clustering and Timezone analysis of literature data, we can better grasp the hot topics and research frontiers in the field of carbon emissions in iron and steel industry, and clarify its development vein and future research direction.

## **Keywords Co-occurrence Analysis**

Keywords are the words that express the concept of the central theme of a literature, and the keywords cited jointly by multiple scientific literatures are keyword co-occurrence. It can show the correlation between the research keywords of carbon emissions in the steel industry very intuitively, and can also explore the research focus and hotspots by observing the word frequency and centrality ranking (Shi and Li 2019). A research hotspot is generally defined as a key topic jointly discussed by closely related scientific literatures in a certain period of time. It is a representative vocabulary to describe the core content of an article, and the frequently co-occurring keywords reflect the hot topic of the research (Li and Chen 2018).

Running CiteSpace, set Node Type as Keyword, and the time range was 1991-2020, the network cutting method was Pathfinder, Pruning networks and Pruning the merged network, selected 1 year time slice, selected keywords for Node Type, defaulted for other options, imported the selected literature data, and got Keyword co-emerging map (Fig.6). As shown in Fig. 6, the co-occurrence graph of key words in carbon emission research of the steel industry has a total of 451 nodes, 918 connections, and a network density of 0.009. Among them, the size of the keyword node corresponds to its frequency.

In addition, the mediating centrality of each keyword can be obtained from the keyword co-occurrence graph. The node with high centrality is the bridge connecting each keyword, and the higher the value of the keyword is, the more critical the keyword is in its research hotspots. The top ten keywords with the highest frequency and the highest intermediary centrality were sorted out through the keyword co-occurrence map of carbon emissions research in the steel industry, as shown in Table 4. Summing up the two overlapping keywords, divided into three categories: carbon emissions, efficiency and China, they can be regarded as the most important connecting hub of hot keywords in the research field of carbon emissions in the steel industry.

**Table 4** Frequency and centrality of top ten keywords in Carbon Emission Research of iron and steel industry

Ranking	High frequency keywords	Frequency	First year	Key words of heart type in Senior High School	Intermediary centrality	First year
1	Co <sub>2</sub> emission	110	1997	Carbon dioxide emission	0.35	1992
2	Steel industry	73	2007	Co <sub>2</sub> emission	0.17	1997
3	Iron	67	1992	China	0.15	2002
4	Carbon dioxide emission	51	1992	Intensity	0.14	2002
5	China	44	2002	Iron and steel industry	0.13	2000
6	Consumption	43	2006	Model	0.12	2000
7	Industry	43	1997	Bioma	0.11	2009
8	Efficiency	42	2007	Blast furnace	0.10	2006
9	Reduction	42	2014	Carbon dioxide	0.10	1994
10	Energy	41	2002	Efficiency	0.08	2007

### Analysis of Hot Research Topics

Keywords clustering can deepen the co-occurrence relationship of keywords and calculate a group of keywords with a closer relationship, so as to form a topic clustering containing multiple groups of words. In order to further investigate the knowledge structure of carbon emissions in the steel industry and explore the research hotspots, this paper conducted cluster analysis on the key words. Run the software to obtain the correlation clustering map (Fig. 7). From the clustering map, we can see that the Modularity module value (Q value) is 0.8166, greater than 0.3, indicating that the clustering results are significant. And Mean Silhouette: the Mean contour value (S value) of the clustering is 0.9306, greater than 0.7, indicating that the clustering is highly credible. Scholars closely focused on carbon dioxide emissions and steel industry research, formed a total of 10 keywords cluster research hotspots. In the following, the clustering shown is sorted out and analyzed, and three hot research topics are formed.

Topic 1: Climate change-oriented carbon emissions from the steel industry. Topics in this category include Cluster #3 Climate Change Policy and Cluster #6 climate change. The key words include climate change policy, carbon emission, dynamic modeling, integrated steel mill, multi-sector, attribute analysis, co-integration method, etc. at the present stage, Climate degradation is now one of the most serious threats to human habitat, and changing it will require fundamental changes in our daily social and economic lives. Steel production is a special case of economic activity, which is not only related to combustion, but also closely related to greenhouse gas emissions (Mayer et al. 2019). In many developed

countries, global climate change has been widely concerned. In order to protect the environment, they have taken more and more measures to deal with greenhouse gases in heavy industries such as steel industry and manufacturing industry (Mert et al. 2018). Among developing countries, China is the country that pays the highest attention to climate change, and the steel industry plays an important role in mitigating global climate deterioration (Li et al. 2019; An et al. 2018). As the world's largest steel producer and consumer, China bears the primary responsibility for energy conservation and emission reduction in the steel industry, and is a key force in reversing the current climate deterioration. China should actively participate in global climate regulation actions. In terms of steel production and supply, low-carbon technology should be promoted in time and clean energy should be used. In terms of steel consumption demand, alternative environmental protection materials can be selected to increase investment in scientific research and reduce the necessary amount of steel, so as to reduce emissions of CO<sub>2</sub> and other air pollutants.

Topic 2: Production technology-oriented carbon emissions from the steel industry. Topics in this category include Clusters #0 Iron and Steel Industry, Clusters #1 Steel Scrap, Clusters #2 Coal and Clusters #5 Manufacturing Industry, etc. Keywords include Empirical Analysis, Steel Sector, Industry Processes, Sustainable Iron, Critical Factor, etc. In order to mitigate global warming and climate deterioration, major industrial sectors, such as the steel industry, as one of the most important contributors to man-made CO<sub>2</sub> emissions, should not only find more efficient environmental cleaning solutions to reduce CO<sub>2</sub> emissions, but also ensure the efficient operation of the solutions and low treatment costs (Chisalita et al. 2019). In the past 10 to 15 years, some large steel manufacturing countries and the research plan of EU is ongoing or already completed, including oxygen blast furnace, utmost ground biomass replace coke, instead of carbon hydrogen, carbon dioxide capture and storage (CCS) and other new technologies, these technologies through production facilities and a total modernization of energy system, and adopt new pioneering method, can make "world steel" in use to achieve a reduction of 0.4-0.5 tons of carbon dioxide per ton of steel level (Holappa 2020). Increasing efforts to reduce carbon emissions from the source of the production line and improving the level of production technology are all important links to effectively control carbon emissions in the steel industry.

Topic 3: Carbon emission study of steel industry based on future scenario analysis. This kind of hot topic includes cluster #4 Scenario Analysis, and the main keywords include atmospheric modeling, chemical evolution, revisiting China's CO emission, etc. The climate targets agreed in Paris in 2015 make deep decarbonization of energy and emissions intensive industries essential. Through the scenario study on the zero emission path of the European steel industry, it is found that its carbon emission reduction effect is mainly dependent on technological choice, major macro-economic state and regional characteristics, but the potential socio-economic development and climate policy trajectory have a poor reflection on carbon emission reduction (Sahoo et al. 2019). China, as the largest CO<sub>2</sub> emitter in the world, has been actively promoting the development path of carbon emission reduction, and has made a commitment to reach the carbon peak in 2030 in combination with the *Paris Agreement* (Li and Li 2020). Wei P.B. et al. even established the LEAP policy model, and found that under the policy context of capacity upgrading

and energy saving technology research and development, carbon emission reduction in the steel industry has a great prospect and advantage (Bachner et al. 2020; Lu et al. 2020). In the future, with the rapid development of the global economy, the demand for steel will greatly increase, and the research and development of new technologies and the adjustment of energy structure to cope with the future climate change situation are urgent. Carbon emission reduction in the steel industry needs long-term regulation and control. It is an important strategic measure to forecast the future scenario and make corresponding adjustments in time, and it is also a hot topic of research at the present stage.

## Frontier Analysis

In order to further explore the future research frontier hot spots in the field of carbon emissions in the steel industry, it is necessary to analyze the evolution trend of the research hot spots. In this paper, CiteSpace software was used to generate the Timezone map (Fig.8). Combined with the current development status of carbon emission research in the steel industry, the evolution process of the hot research topics was analyzed and summarized to predict the future research trends. Among them, the Timezone map focuses on the evolution of research hotspots over time, which can more clearly explain the update status of each research hot spot and its correlation with each other (Wei et al. 2017).

According to Figure 8, the research history of carbon emissions in the steel industry from 1991 to 2020 is divided into three periods: ☐ From 1991 to 2000, this period was the initial stage of research, dominated by CO<sub>2</sub> emission and iron and steel industry, and there were few active research hot topics. Main reason for the related research in this field is headed by the developed countries such as Canada and Mexico were the first to put forward, these countries are in a stage of rapid promotion of industrialization, the demand for energy is also a large increase. And the steel industry, a big user of coal and other forms of energy, is a key target for reducing carbon dioxide emissions (Chen et al. 2015). Under such a background, it is urgent to carry out research on carbon emission of steel industry. Although there are few kinds of research topics in this stage, the research hot spot lasts the longest and is still a hot topic in academic circles. ☐ From 2001 to 2013, the research hotspots of carbon emissions in the steel industry exploded, including energy efficiency, consumption, air pollution source, hydrocarbon, technology, climate change policy and China, etc. At this time, the research in this field was in the rapid development stage. With the gradual acceleration of global economic growth and increasingly close economic links between countries, the corresponding demand for steel industry is also increasing, the carbon emissions generated are also rising at a very fast rate, and the problem of air pollution is increasingly aggravated (Walsh 1992; Sheinbaum and Rodriguez 1997). In order to prevent further deterioration of this phenomenon in a timely manner, reducing carbon dioxide emissions produced in the industrial process, improving the energy efficiency of the steel industry, improving energy conservation technology, wasting heat utilization technology and using of hydrogen energy for energy substitution had been put on the agenda (Arens et al. 2017; Liang et al. 2009; Moynahan and Allwood 2012). ☐ From 2014 to now, this period has been in a stable development stage, and the hot research keywords in this stage include quantitative assessment,

techno economic analysis, scenario analysis and environmental benefit, etc. The possibility of achieving zero-emission steelmaking can be investigated by using the techno-economic analysis method. It is found that the combination of CCS (carbon capture and storage) and biomass substitution in blast furnace can effectively reduce CO<sub>2</sub> emissions (Le et al. 2011); And through scenario analysis, it is found that compared with traditional energy, the renewable energy and the innovation of ironmaking technology also shows a strong competitive advantage in terms of greenhouse gas emission reduction and economic cost. In the future, feasible low-carbon path and alternative strategy of renewable energy should be sought based on this (Fujji et al. 2012; Sun et al. 2012). In addition, methods such as Life-cycle assessment (LCA) and Long-term short-term memory (LSTM) also provide theoretical support for carbon emission reduction research in the steel industry (Toktarova et al. 2020; Yang et al. 2021; Shatokha et al. 2020). It is obvious that the research in this stage mostly adopts quantitative economic analysis. Compared with the previous stage, the research method is more scientific and the research content is more in-depth. It is no longer limited to the surface of things, but focuses on in-depth analysis of the essential causes of carbon emissions in the steel industry and looking for new development paths.

Through a review of the carbon emission research and development history of the entire steel industry, From the initial proposal of the research topic to the increase of research attention in this field due to global climate change, and then to the application of quantitative economic analysis in this research at the present stage, the research level has been deepened and the research hotspots have gradually increased. And the carbon peak and carbon neutral proposed has triggered the world's scholars to the steel industry carbon emission research field deep thinking. Therefore, under such an environment, in the coming decades, carbon emission research of steel industry will form a breakout point in the academic circle, and the comprehensive application of various econometric analysis, technical and economic analysis and environmental climatology in this field will be the frontier hotspot of future research.

## Conclusions

This paper taken carbon emission of iron and steel industry as the research topic, and used the bibliometric analysis software CiteSpace to make a visual analysis of the related literatures in scie database from 1991 to 2020. Based on the analysis of the statistics of the major source journals, the cooperation map of the publishing countries and regions, the network map of the main publishing institutions and high-yield authors, keyword co-occurrence, clustering, Timezone view and other maps, the characteristics, research topics and frontier hot spots of carbon emissions research in the steel industry were summarized.

The results show that:

(1) In terms of the major research forces of carbon emissions in the steel industry, scholars and research institutions in China, Sweden, the United States and the United Kingdom have formed a close cooperation network based on their close geographical relationship. With China, the United States, the United Kingdom and Japan as the core, they have provided key scientific research support and contributed major research

results to the carbon emission field of the steel industry. In particular, the Chinese Academy of Sciences and Xiamen University in China have led the way in the number of published papers, and they are an important driving force for the research in this field. However, the cooperation between their institutions still needs to be improved. Therefore, in the future, we can strengthen the participation and cooperation of other research institutions and enterprises, expand the scope of research, and learn from each other's research experience and results.

(2) In terms of hot spots and frontiers of carbon emissions research in the steel industry, they are mainly classified into three research orientations: climate change-oriented research, production technology-oriented research and future scenario analysis-oriented research on carbon emissions in the steel industry. From 1991 to 2020, the research focus of carbon emissions in the steel industry continued to focus on four major issues, namely carbon dioxide emissions, energy use, air pollution and climate policy. The research levels and methods have been continuously deepened. And the carbon peak and carbon neutral targets have attracted wide attention from scholars in this field. Therefore, in the future research stage, there will be an outbreak period in the field of carbon emissions in the steel industry, and the research direction can focus on the comprehensive application of various technical and economic analysis, scenario analysis and environmental climatology.

## Declarations

- Ethics approval and consent to participate

Not applicable.

- Consent for publication

Not applicable.

- Availability of data and materials

Not applicable.

- Competing interests

The authors declare that they have no competing interests.

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- Authors' contributions

Desheng Xu: conceptualization, funding acquisition, resources, supervision, validation, writing-review and editing, and visualization. Ke Yang: conceptualization, data curation, formal analysis, investigation, methodology, software. Wei Duan: writing-review and editing.

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# Figures

Number of published articles/article

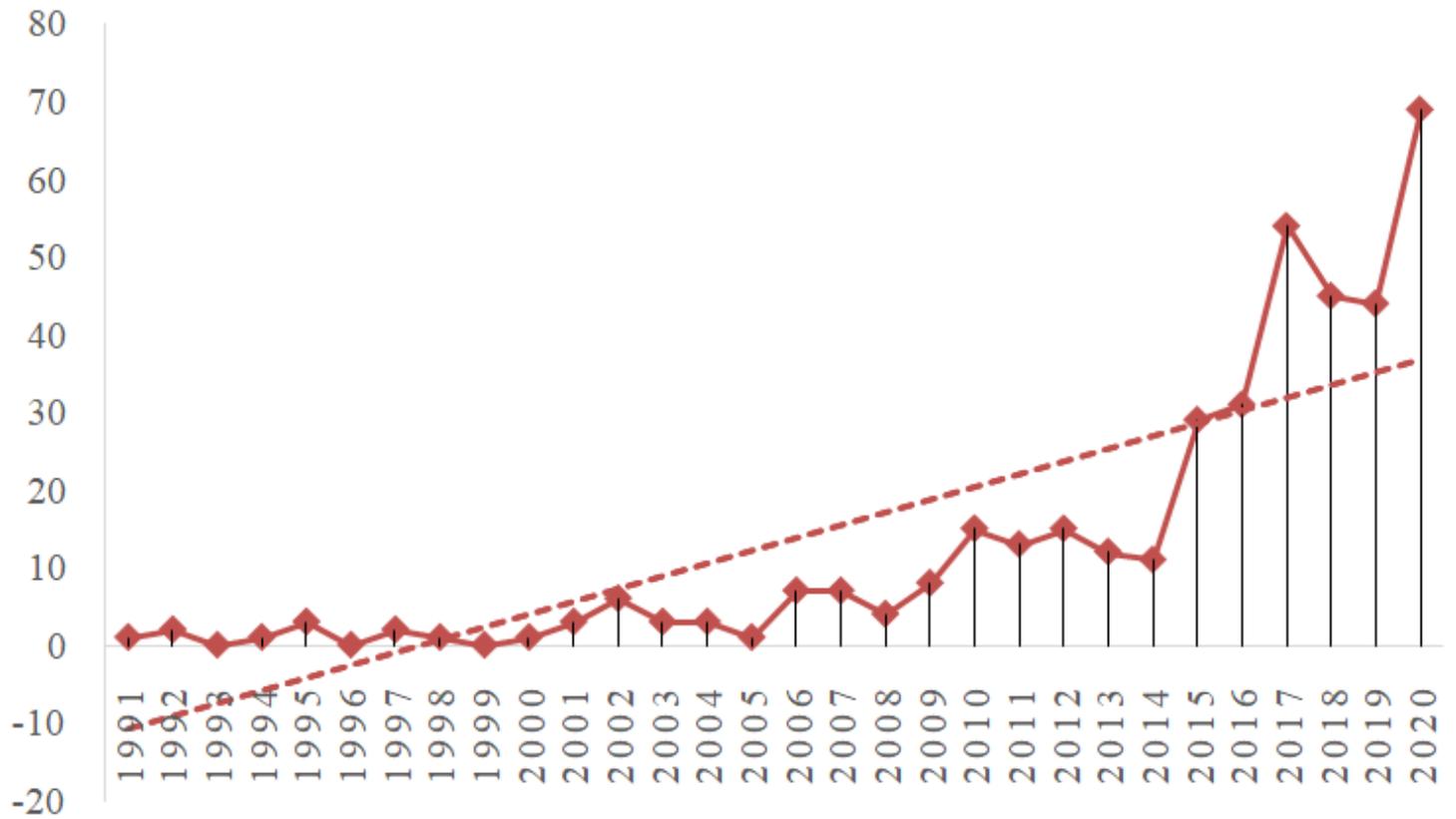


Figure 1

Distribution of carbon emissions research papers in the steel industry

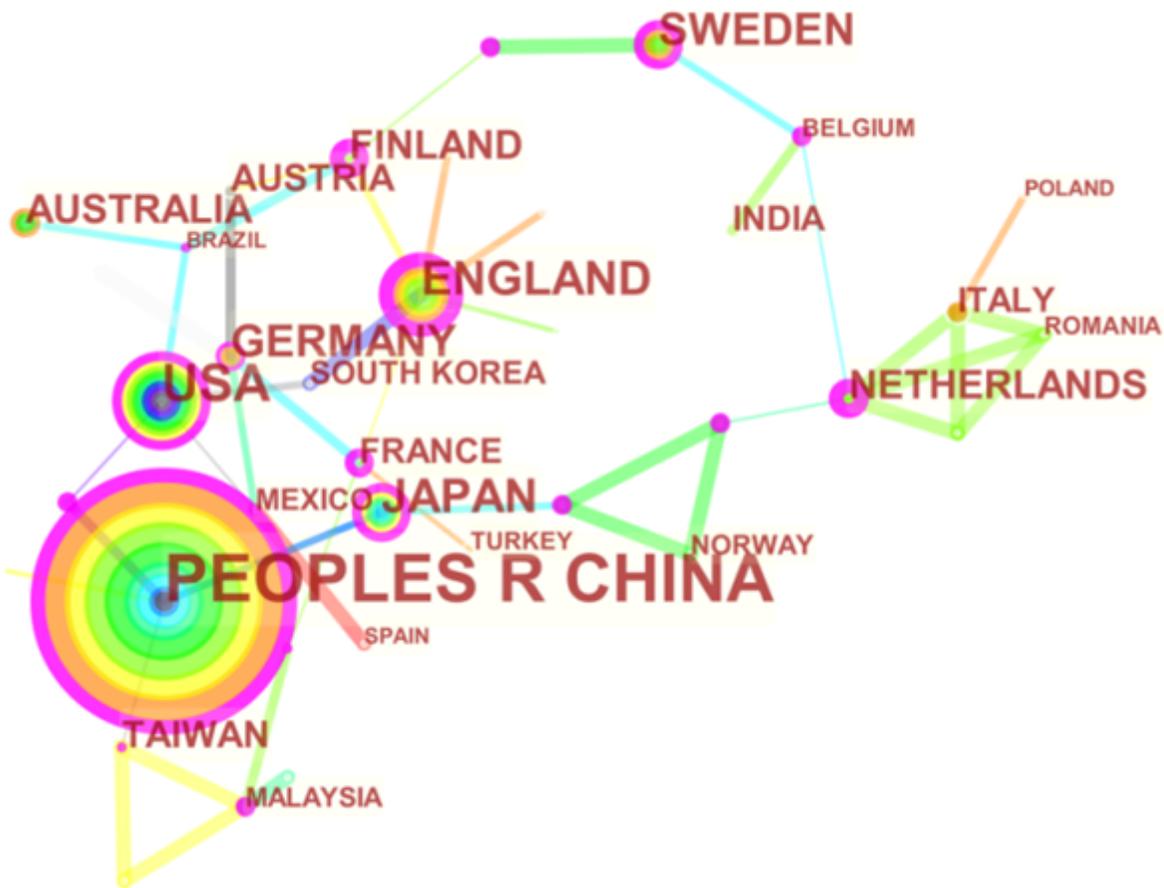
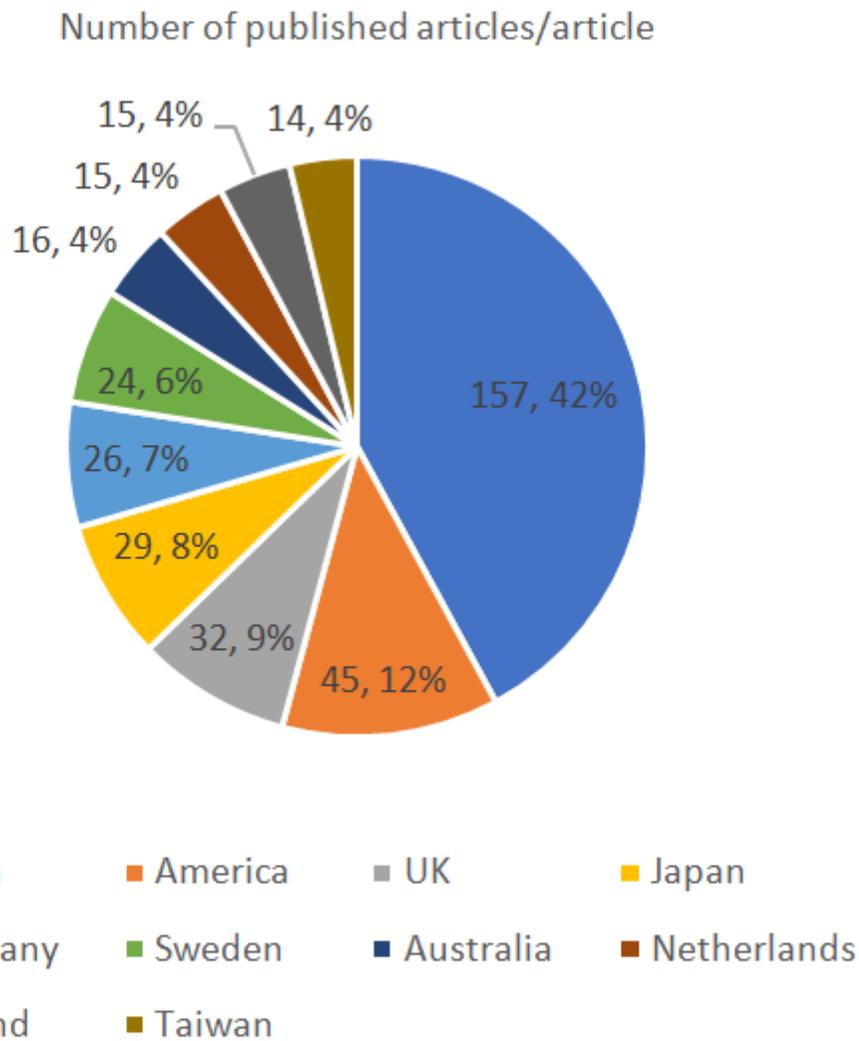


Figure 2

Distribution network map of the publishing countries and regions



**Figure 3**

Top 10 countries and regions of carbon emission research in iron and steel industry

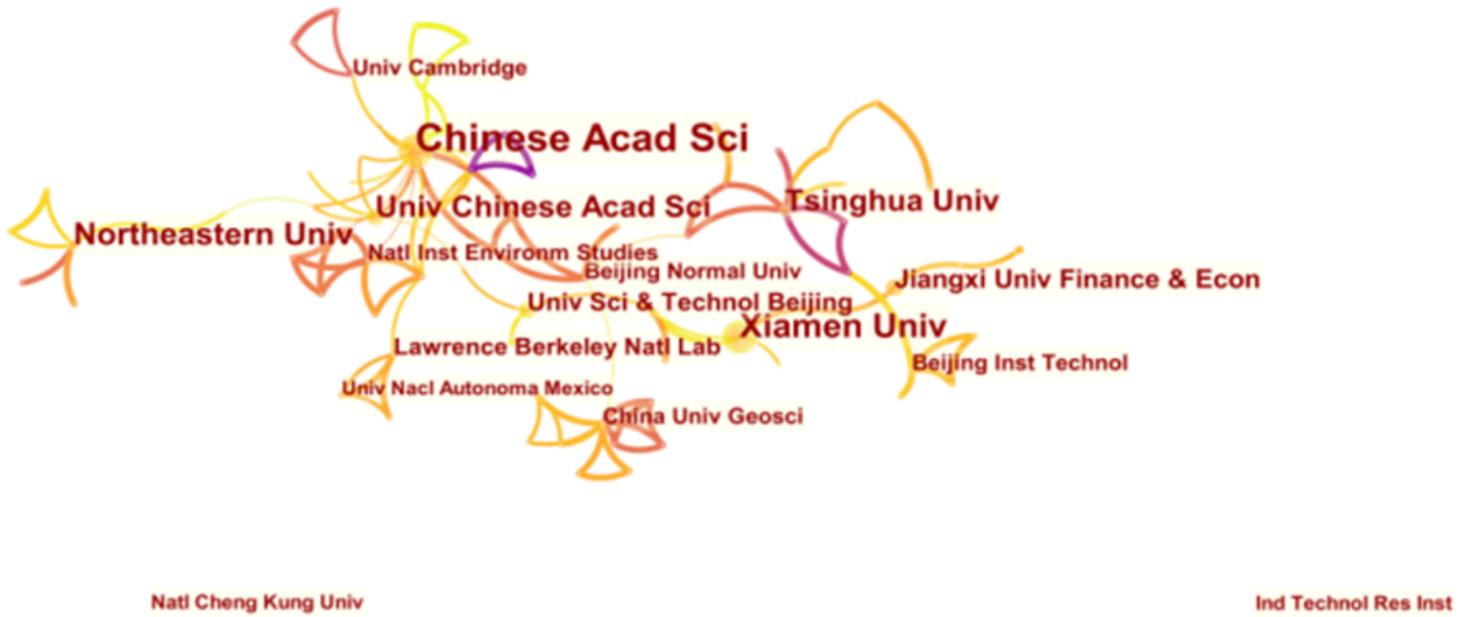


Figure 4

Distribution network map of carbon emission research institutions in iron and steel industry

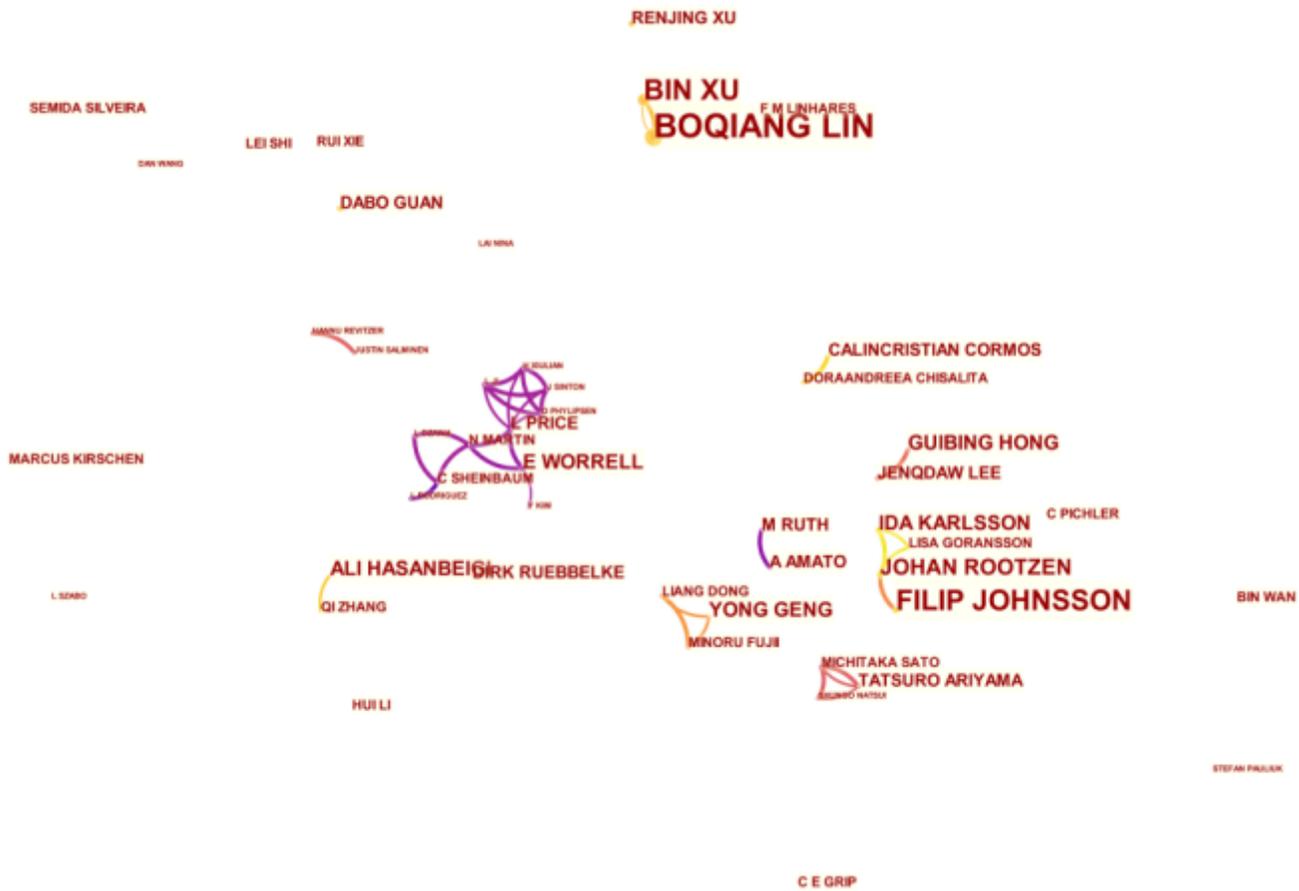
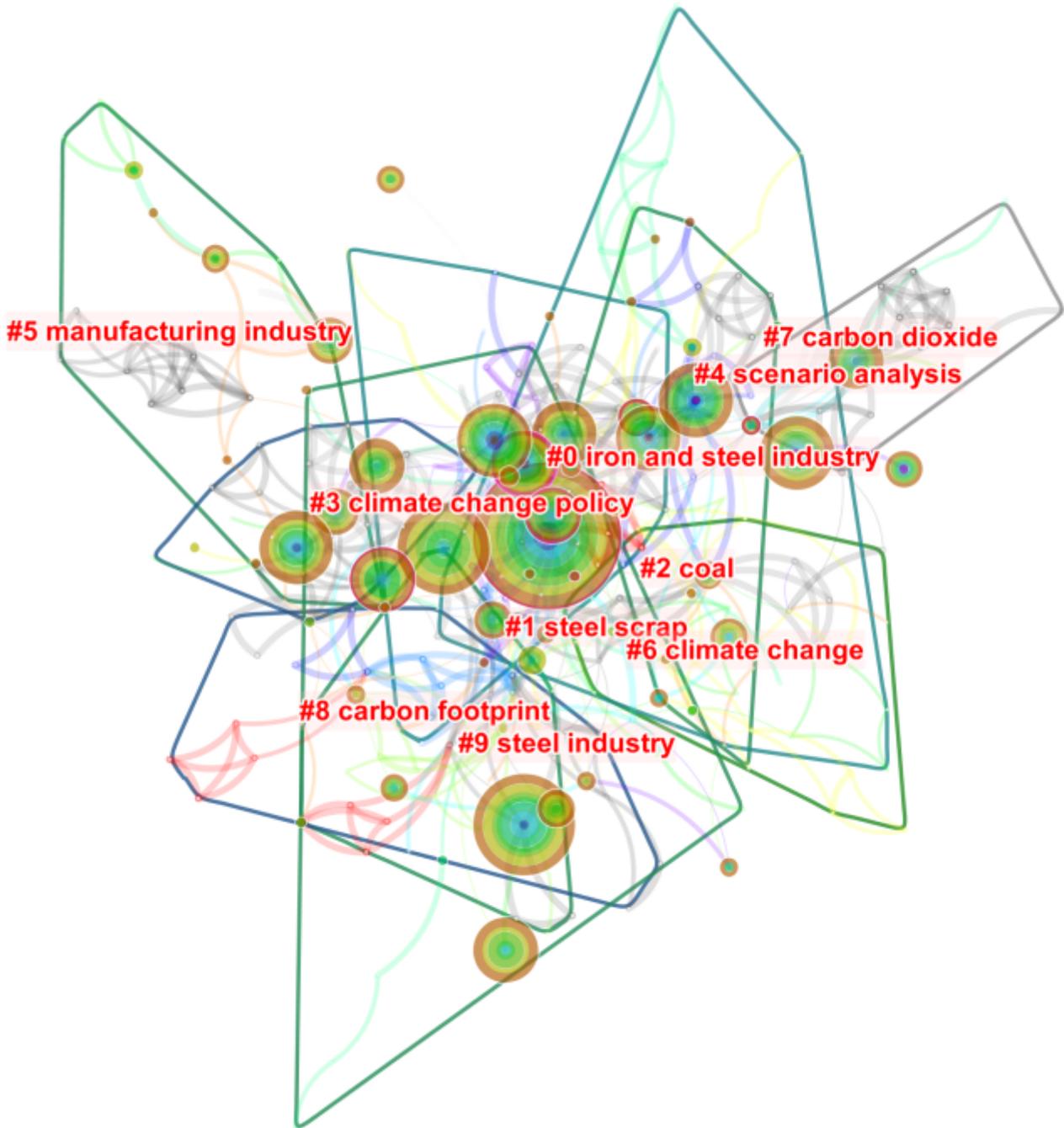


Figure 5

Map of cooperation network of carbon emission research authors in iron and steel industry





**Figure 7**

Keywords clustering map of carbon emission in iron and steel industry

