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Current Status and Prospects of Integrated Assessment Models (IAMs) in the Context of Carbon Neutrality: A bibliometric perspective

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ABSTRACT

With the proposal of “carbon neutrality”, research on global warming mitigation and low-carbon transformation of energy system has been widely focused. The Integrated Assessment Model (IAM) is an important model for studying energy supply and demand, and making strategic decisions in terms of economics and policy, which can formulate reasonable and effective low-carbon development plans based on energy policies, energy structures and energy technology development levels. However, there is no knowledge mapping domain of IAMs in the context of carbon neutrality, which makes it difficult for researchers to follow the hotspots and select the appropriate IAM. In this paper, 11770 unique research papers on IAMs were retrieved from the Web of Science core database and analyzed by bibliometric mapping using VOSviewer and CiteSpace. Knowledge mapping is used to visualize the countries/regions, researchers, and journals that have made major contributions, and to analyze the network of collaborative relationships between them. The results show that the growth of relevant IAMs research is large and has been studied from multiple perspectives on climate change. Keyword analysis shows that research hotspots include "climate change", "life cycle assessment" and "sustainability assessment"; in the burst detection, "machine learning" has been widely incorporated into research over the last two years. The paper also discusses the interplay between scientific research and policy, pointing out that policy guidance is complementary to IAMs research. This study can provide the IAMs with recommendations for future development decisions on low carbon development issues.

Keywords: Integrated assessment model, Knowledge mapping, Citespace, VOSviewer, Carbon neutrality

1 INTRODUCTION

Energy production and consumption are closely related to socio-economic development and environmental protection. To solve these problems, countries need to achieve economic transformation as soon as possible[1], develop a scientific and rational energy development plan[2,3], and integrate all aspects of the energy transition from energy resource development to end-user consumption[4,5]. Integrated Assessment Models (IAMs) are strategic and forward-looking, which are an important method for studying energy supply and demand, and for making strategic economic and policy decisions. The construction of IAMs draws on theories and analytical methods from many disciplines and has become a key tool for analysing the future of the social environment[6].

There is a large body of work examining the development of integrated assessment models in terms of structural composition[6], model coupling[7], and model uncertainty[8]. Few have examined the knowledge mapping domain of IAMs. However, these are important for researchers and laypersons to understand the history and development of IAMs. To fill these gaps, all relevant English language scientific publications were downloaded from Web of Science (WOS) and analysed in this paper using VOSviewer and Citespace. The aim of this paper is to visualise keywords, topics, authors, and institutions through bibliometric analysis to clearly depict the overall research area of IAMs, to identify emerging patterns in the field, and to suggest the

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importance of IAMs for carbon neutrality from a policy perspective.

The following section describes the development of IAMs and reviews mainstream IAMs; the methodologies used in this paper are briefly described in Section 3; the research results are interpreted in Section 4; the findings are discussed in Section 5; and finally, the conclusions of this study are stated in Section 6.

2 LITERATURE REVIEW

2.1 A brief overview of IAMs

2.1.1 Development of IAMs

Although the IAMs are widely accepted, there is no clear definition of what IAMs are, and it is difficult to give a very precise definition[9]. Rotmans et al.[10] noted that many studies on the economics of climate change are linked to climatology, ecology, regional science, and engineering. In fact, any model that combines multidisciplinary models to study macro issues of climate change can be called an IAM.

IAMs dealing with climate change first appeared in the 1970s[11,12], and these models only included atmospheric CO_2 concentration and temperature changes as environmental variables in the model. As the models evolved and their functionality was gradually improved, many technical details[13-15] were added to the models and an increasing number of early assessment models emerged. Later some IAMs also added modules for land use, water cycle, and air pollutants to study the specific impacts of climate change[16].

The IAMs have become a common tool for assessing the management of climate change, Schumacher[17] makes some recommendations for the use of IAMs in climate change policy; scholars have also summarised the link between climate change and integrated assessment[18]; Skea et al.[19] found that the IAMs link future trends in socio-economic and technological development to global climate change. These suggest that IAMs are effective in describing the environmental, social, and economic factors that drive climate change and climate policy, and in suggesting appropriate policy recommendations and improvements[20].

2.1.2 The progress of mainstream IAMs research

The earliest IAMs originated in the 1970s, when the 1973 oil crisis led to a significant increase in oil prices, and attempts to increase energy diversity led to an increased focus on energy planning and management, resulting in the creation of various IAMs (Table 1).

Due to space limitations, the literature reviews have been omitted.

Table 1 Mainstream IAM features

Model	Region	Range of model	Method
MESSAGE	Global	Energy, Economy, Policy, Environment	Optimization
GCAM	Global	Energy, Environment	Simulation
AIM	Asia-Pacific	Energy, Economy, Policy	Simulation
IMAGE	Global	Energy, Policy, Environment	Simulation
EPPA	16 regions	Economy, Policy, Environment	Optimization
REMIND	11 regions	Energy, Economy, Policy, Environment	Simulation

2.2 Knowledge mapping

With the development of knowledge mapping, there have been a large number of scientific mapping methods[21], the most popular ones being VOSviewer and Citespace methods. The former was developed in 2009. The latter was developed by Dr. Chaomei Chen[22] in 2004. Before running either software, it is necessary to filter and download the text files of the required relevant literature from WOS.

2.3 The interplay of policy and science

The influence of policy and scientific research is reciprocal; firstly, policy can influence research, and there is an extensive literature showing that the introduction of policy drives the production and use of research results. Weiss et al.[23] point out that scientific research is only used as a political act to meet desired policy requirements, and that scientific discoveries are more useful to the government departments that provide the funding[24]. Thus, from this perspective, scientists are more likely to engage in scientific research in the service of policy.

On the other hand, there are many studies that show how scientific research can influence policy making. The results of scientific studies have a decisive influence on the formulation and implementation of policies, such as the way in which government departments use urban planning principles[25] and the formulation of policy

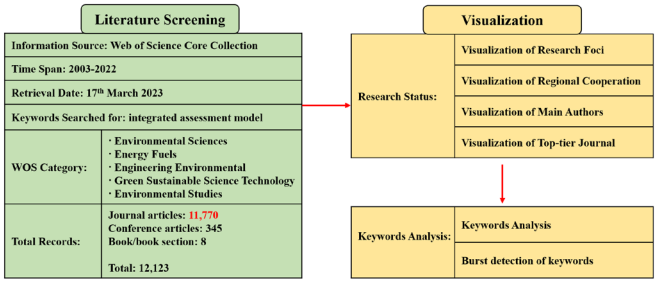

Fig. 1. Diagram of the employed methodology

requirements[26]. This is particularly evident in the context of carbon neutrality[27] , where many policy reports have been produced under the auspices of various IAMs. It is therefore increasingly necessary to analyse the interaction between IAM research and policy.

3 METHODOLOGY

There are a total of two steps in the bibliometric analysis, namely literature screening and knowledge mapping. These steps are explained and summarised in detail below and summarized in Fig. 1.

3.1 Literature Screening

This study covers 20 years, from 2003 to 2022, and screens the core ensemble database of WOS. The keyword "integrated assessment model" was searched, and only journal papers were excluded from the search, a total of five WOS categories related to climate change, and the total number of papers obtained was 11770.

3.2 Visualization

As shown in Fig. 1, the visualization step is divided into two steps, starting with a collaborative visual analysis of the current state of IAMs research, which is important for understanding academic communication and knowledge diffusion[28]. Next, keyword analysis is performed, which mainly includes keyword co-occurrence analysis and keyword burst detection.

4 RESULTS AND DISCUSSION

The results show that the number of publications increases rapidly from 2003 to 2022 (Fig. 2), from which it can be seen that IAMs started to develop gradually in 2004, and the rate of development increased gradually after 2010, peaking after 2017 and reaching a peak in 2021 with a total of 1678 publications.

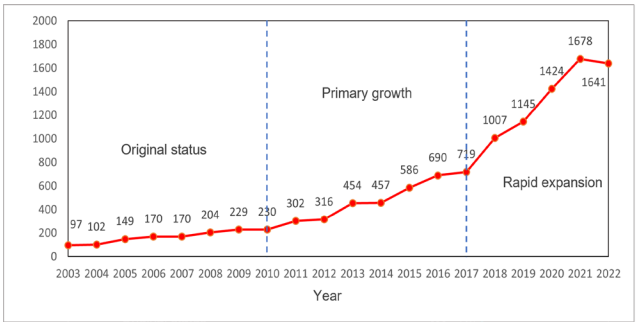

Fig. 2. The number of publications about IAMs

4.1 Research foci

The cluster visualization network of the selected samples in this study is shown in Fig. 3, and the top 7 clusters are shown in the figure, and the information

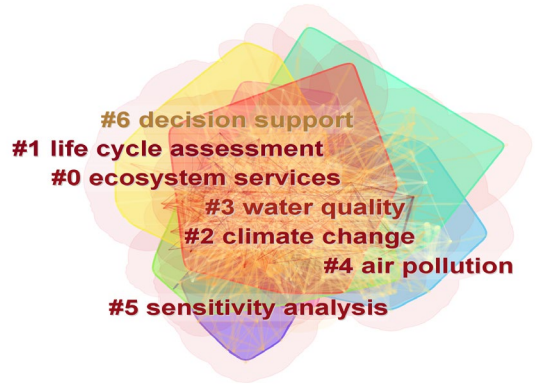

Fig. 3. Cluster network of IAMs research domain

related to each cluster is listed in Table 2. The second column of the table represents the number of literature in each cluster, which shows that IAMs are widely used in the context of carbon neutrality for ecosystems and climate change. The third column, "Silhouette", measures the degree of homogeneity of the clusters, and the closer the score is to 1, the higher the consistency of the research topics involved in the papers[29]. As can be seen in Table 2, the scores ranged from 0.687-0.901, indicating that the studies in each cluster were closely related and the results were reliable. The fourth column indicates the average publication time of the articles in the clusters [30].

Table 2 Summary of the top 7 clusters

ID	Size	Silhouette	AVG.Year	Label
0	142	0.71	2007	Ecosystem services
1	112	0.728	2009	Life cycle assessment
2	107	0.69	2006	Climate change
3	95	0.687	2006	Water quality
4	86	0.746	2006	Air pollution
5	19	0.893	2008	Sensitivity analysis
6	17	0.901	2006	Decision support

4.2 Regional Cooperation

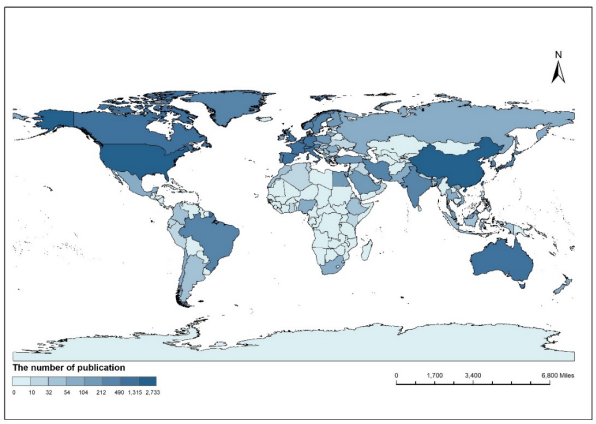

Fig. 4. Number of publications in different country/region

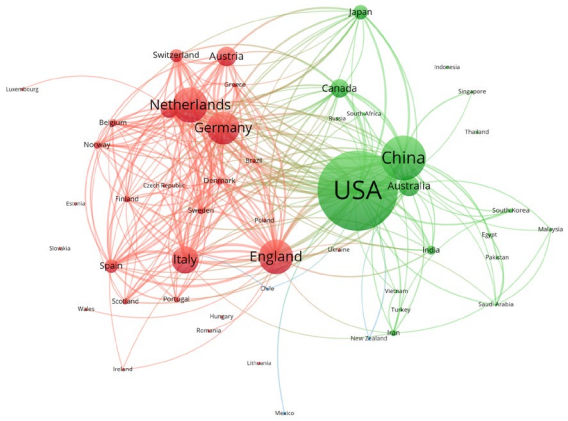

Fig. 5. Regional cooperation network (based on citations)

All 11,770 results came from 162 countries/regions, and the top 50 countries/regions in terms of total number of citations were selected for visual analysis of publication source countries using VOSviewer (Fig. 5). The larger the node in the graph, the more the country's publications are cited, and the thickness of the line is proportional to the degree of collaboration, the thicker the line, the closer the collaboration between countries. When analyzing the total number of citations, the Netherlands, which ranks sixth in terms of the number of publications, ranks third in terms of total citations, with a total of 41,828, demonstrating its strength in the field of research. Among the top ten countries in the publication, only China is a developing country, while the remaining nine countries are all developed countries.

4.3 Main authors

It can be seen that the author with the highest number of publications is Van Vuuren Detlef P., which shows the depth of research in this field. And the fact that the author is a Dutch scientist explains the very high number of citations to publications from the Netherlands

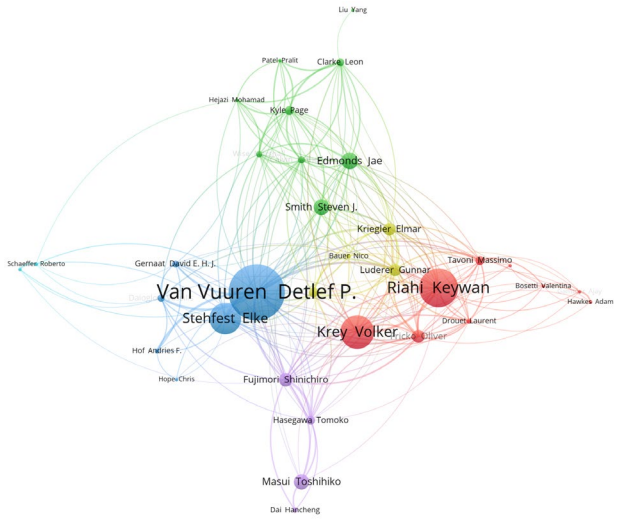

Fig. 6. Co-authorship network (based on citations)

as a whole, as Van Vuuren Detlef P. alone has 10626 citations. The top 40 authors in terms of number of publications were selected from among all publication authors and their collaboration network visualization was analyzed using VOSviewer (Fig. 6).

4.4 Top-tier journals

The top 10 journals were selected and presented in a table (Table 3). The most popular journal was the Journal of *Cleaner Production*.However, *Sustainability*, which ranks second in terms of the number of publications, is missing, and it can be concluded from Table 3 that it has only 5909 citations. It is worth noting that *Climatic Change* received more citations with fewer publications, with an average frequency of 75.4 citations per publication.

Table 3 The number of publications in different journals

Journal	PUBs	CITs	Avg. CITs	Percentage
Journal of Cleaner Production	614	17404	28.3	5.22
Sustainability	574	5909	10.3	4.88
Science of the Total Environment	558	18154	32.5	4.74
Applied Energy	294	11497	39.1	2.50
Environmental Modelling Software	279	13394	48.0	2.37
Energies	264	2098	7.9	2.24
Water	263	2591	9.9	2.23
Energy	245	7028	28.7	2.08
Climatic Change	236	17797	75.4	2.01
Ecological Indicators	225	6951	30.9	1.91

4.5 Keywords analysis

Therefore, 29,971 keywords (author keywords only) were extracted from 11770 articles in this study. Knowledge mapping of symbiotic networks is visualized using VOSviewer software. The keywords with high research value were further screened to generate a co-occurrence network view of keywords (Fig. 7). Each node represents a keyword, and some non-keywords are not shown to avoid overlap. The size of the circles indicates the frequency of each keyword. Usually, the relevance of close keywords is stronger than that of far keywords, and the color indicates the categorical clustering of keywords. The results show that the keywords show obvious clustering characteristics, among which cluster 3, "integrated assessment models" and "climate change" show obvious correlation, indicating that IAMs are widely used in climate change research(Fig. 7).

4.6 Burst detection of keywords

From 2003 to 2022, the software detected a total of 65 strong emergent keywords, and the top 20 keywords

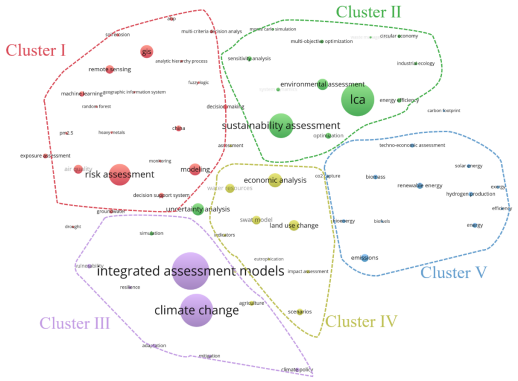

Fig. 7. Keywords network (based on citations)

with relatively high "Strength" were selected and plotted in Table 4. The higher the strength, the more focused the research is. The second column of the table indicates the time when this keyword first appeared, and the last column indicates the time span during which the corresponding keyword was studied intensively. The time with the lightest color indicates that the corresponding keyword has not yet appeared, and when the color becomes darker, it means that the keyword was noticed for the first time, and when it turns red, it means that the corresponding keyword was noticed and studied intensively. From the table, we can see that "machine learning" has been in the spotlight on since 2020, and the strength is 26.82, indicating that it has received a lot of consideration and study. The third-ranked term, "decision support", has been a hot topic since 2004, indicating that the guiding role of IAMs for policy has been respected by researchers.

Table 4 Top 10 keywords with the strongest citation bursts

Keywords	Year	Strength	2003-2022
machine learning	2020	26.82	
integrated assessment	2003	23.93	
decision support	2004	21.21	
science	2005	20.22	
economics	2008	20.11	
construction	2020	18.36	
circular economy	2019	16.34	
analytic hierarchy	2008	16.26	
mitigation	2011	15.46	
benefits	2006	15.44	

5 CONCLUSIONS

In this paper, an overview of the mainstream IAMs is first discussed; and then a bibliometric analysis of 11770 articles screened from Web of Science using CiteSpace and VOSviewer visualization software yields some very meaningful conclusions：

1） Research on IAM has developed very rapidly after 2017, with the highest number of publications in 2021, 1678;

2） Current research in the field of IAMs is mainly focused on environmental areas such as ecosystems, climate change, and supporting policy making, and machine learning has been a big hit in the field of IAMs in the past two years;

3） For IAMs research is mainly concentrated in developed countries and China, with very close collaboratives within Europe and between the US and China, with the highest number of publications coming from the US (2733), followed by China (2496). There is closer collaboration between researchers from the same country/region or research institution. And the main researchers come from developed countries, where the researcher with the highest number of publications is Van Vuuren Detlef P. from Utrecht University, with a total of 95 publications and a total of 10626 citations;

4） Life cycle assessment and GIS as a very important tool in IAMs research is reflected in many studies;

5） Articles on IAMs research are mainly from journals such as Journal of Cleaner Production, Sustainability, and Science of the Total Environment, but the journal with the highest number of citations is Climatic Change.

The paper also discusses the relationship between scientific research and policy, argues for the interplay between scientific research and policy, and points out that the IAMs research provides sound, scientific guidance for IPCC reports and the like.

In general, in the current international carbon neutral context, IAMs have received a great deal of attention and research in the areas of climate change, water pollution, new energies and so on. In the future, with the addition of new technologies such as machine learning and further international cooperation, IAMs will definitely play a more significant role in international climate change governance.

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REFERENCE

[1] Guo JJ, Zhou Y, Ali S, et al. Exploring the role of green innovation and investment in energy for environmental quality: An empirical appraisal from provincial data of China. Journal of Environmental Management, 2021, 292.

[2] Danso A, Adomako S, Lartey T, et al. Stakeholder integration, environmental sustainability orientation and financial performance. Journal of Business Research, 2020, 119: 652-662.
[3] Kim B, Lee S. The impact of material and immaterial sustainability on firm performance: The moderating role of franchising strategy. Tourism Management, 2020, 77.
[4] Nelson S, Allwood JM. The technological and social timelines of climate mitigation: Lessons from 12 past transitions. Energy Policy, 2021, 152.
[5] Kang JJ, Yu CY, Xue R, et al. Can regional integration narrow city-level energy efficiency gap in China. Energy Policy, 2022, 163.
[6] Harfoot M, Tittensor DP, Newbold T, et al. Integrated assessment models for ecologists: the present and the future. Global Ecology and Biogeography, 2014, 23: 124-143.
[7] Zhang H, Liu C, Wang Z. Progress in damage function of integrated assessment models for climate change. Progressus Inquisitiones de Mutatione Climatis, 2018, 14: 40-49.
[8] Golub A, Narita D, Schmidt MGW. Uncertainty in Integrated Assessment Models of Climate Change: Alternative Analytical Approaches. Environmental Modeling & Assessment, 2014, 19: 99-109.
[9] Parker P, Letcher R, Jakeman A, et al. Progress in integrated assessment and modelling. Environmental Modelling & Software, 2002, 17: 209-217.
[10] Rotmans J, van Asselt MBA. Uncertainty management in integrated assessment modeling: Towards a pluralistic approach. Environmental Monitoring and Assessment, 2001, 69: 101-130.
[11] Hafele W, J. Anderer. Energy in a finite world: a global systems analysis. In. Ballinger Cambridge, MA, 1981.
[12] Nordhaus WD. Efficient use of energy resources. In. New Haven, CT: Yale University Press, 1979.
[13] Mintzer IM. A matter of degrees: the potential for controlling the greenhouse effect. In: World Resources Institute. Washington, 1987.
[14] Lashof DA. Policy options for stabilizing global climate: draft, report to Congress. In: United States Environmental Protection Agency, Office of Policy, Planning, and Evaluation. Washington, 1989.
[15] Rotmans J, H. De Boois, R. J. Swart. An integrated model for the assessment of the greenhouse effect: The Dutch approach. Climatic Change, 1990, 16(3): 331-356.
[16] Schneider SH. Integrated assessment modeling of global climate change: Transparent rational tool for policy making or opaque screen hiding value - laden assumptions? Environmental Modeling & Assessment, 1997, 2(4): 229-249.
[17] Schumacher I. THE AGGREGATION DILEMMA IN CLIMATE CHANGE POLICY EVALUATION. Climate Change Economics, 2018, 9.
[18] Mendelsohn R. INTEGRATED ASSESSMENT AND CLIMATE CHANGE. Climate Change Economics, 2020, 11.
[19] Skea J, Shukla P, Al Khourdajie A, et al. Intergovernmental Panel on Climate Change: Transparency and integrated assessment modeling. Wiley Interdisciplinary Reviews-Climate Change, 2021, 12.
[20] Sharma M, Norton BG. A policy decision tool for integrated environmental assessment. Environmental Science & Policy, 2005, 8: 356-366.
[21] Balaid A, Abd Rozan MZ, Hikmi SN, et al. Knowledge maps: A systematic literature review and directions for future research. International Journal of Information Management, 2016, 36: 451-475.
[22] Chen CM. Searching for intellectual turning points: Progressive knowledge domain visualization. Proceedings of the National Academy of Sciences of the United States of America, 2004, 101: 5303-5310.
[23] Weiss CH. The Many Meanings of Research Utilization. Public Administration Review, 1979, 39: 426-431.
[24] Lundh A, Lexchin J, Mintzes B, et al. Industry sponsorship and research outcome. Cochrane Database of Systematic Reviews, 2017.
[25] A P. The mangle of practice: time, agency, and science. In: University of Chicago, 2010.
[26] Jeffery C WJR, Henderson A, Scully R, Lodge G. Taking england seriously: the new English politics: the future of england survey 2014. In. Edinburgh: Centre on Constitutional Change, University of Edinburgh, 2014.
[27] Boswell C, Smith K. Rethinking policy "impact": four models of research-policy relations (vol 3, pg 1, 2017). Palgrave Communications, 2018, 4.
[28] Chen C, Chen Y, Hou J, et al. CiteSpace Ⅱ:Detecting and Visualizing Emerging Trends and Transient Patterns in Scientific Literature. Journal of the China Society for Scientific and Technical Information, 2009, 28: 401-421.
[29] Chen CM, Ibekwe-SanJuan F, Hou JH. The Structure and Dynamics of Cocitation Clusters: A Multiple-Perspective Cocitation Analysis. Journal of the American Society for Information Science and Technology, 2010, 61: 1386-1409.
[30] Yu D, Xu C. Mapping research on carbon emissions trading: a co-citation analysis. Renewable and Sustainable Energy Reviews, 2017, 74: 1314-1322.