# Visualizing the Research of Embodied Energy and Environmental Impact Research in the Building and Construction Field: A Bibliometric Analysis

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**Compared to operating energy, research on the embodied energy of buildings and the related environmental impact remain a largely unexplored area. However, as the operating energy of buildings continues to decrease due to improvements in energy efficiency, the percentage and significance of buildings' embodied energy will increase in life cycle energy use. To address the research gap, this paper uses a bibliometric analysis to conduct a systematic review on embodied energy (EE) and environmental impact (EI) by employing VOSviewer software. This study has two objectives: (1) to identify the current research clusters and disciplines formed and (2) to discuss research development trends and characteristics. Between 1996 and 2019, 320 publications related to the research topic were found on the Web of Science, covering 109 journals and 48 countries. The results revealed two research growth trends: first, a temporal shift of the involved research fields and an extension of the research scopes and, second, the different socioeconomic influences on developing and developed countries' research focus and aims. This review provides a comprehensive understanding of the focus, aims, and trends of this new and fast-growing field of EE-EI research.**

## 1.0 BACKGROUND AND MOTIVATION

In this study, embodied energy refers to energy consumed through the entire life span of a building, including the energy used for raw material extraction, manufacturing, material and product transportation, building construction, maintenance, and repairs during the building's operation. EE also covers the energy used during a building's demolition and end-of-life management [1]. EE excludes the operating energy consumed within a building; for example, the heating, cooling, and lighting [2]. The CEN/TC350 standard on sustainability of construction works dictates kWh as the unit of measurement, which is applied to both direct and indirect energy use [3]. Therefore, in this paper, environmental impact is defined as the multiple categories of impact on the environment associated with embodied energy.

In comparison to embodied energy, operating energy is a well-researched topic. A joint effort by academia, industry, and policy makers has improved operating energy efficiency significantly [4]. Operating energy accounts for the majority share of total life cycle energy and the environmental impact of the existing building stock. Consequently, most policies and regulations have focused on the operational stage of the building while largely ignoring the embodied energy derived from other life cycle stages of the building [5]. For example, the Energy Performance Building Directive (EPBD) solely focuses on operating energy and does not consider life cycle energy use [6,7]. However, recent studies indicate that embodied energy consumption represents up to 10–70% of the life cycle environmental impact of an energy-efficient building [8,9] and 13–57% for a passive house [10].

Regardless of the importance of embodied energy, previously, the body of academic research and measurements to tackle embodied energy and the related environmental impact were not investigated systematically. Additionally, the majority of current legislation excludes the measurement and reduction of embodied energy and environmental impact over a building's life cycle [8]. Although the two are closely linked, environmental impact is investigated indirectly from embodied energy in existing studies. EI is also represented by a carbon emission equivalent [11] to measure a building's contribution to climate change and global warming [12]. In order to effectively reduce EI, it is necessary to first understand the intellectual roots and connections between EI and EE. Since the 1960s, bibliometric analysis has often been used to uncover the knowledge structure and development of research fields [13]. The bibliometric network is often referred to as "science mapping": mapping the research connections, trends, and gaps. To this extent, this paper addresses the research gap and uses a bibliometric analysis to conduct a systematic review of the academic (research) evidence to provide a macroscopic overview of the main characteristics and the disciplines involved in EE-EI research. More specifically, the paper (1) recognizes influential countries, disciplines, and main research foci (i.e., the clusters formed) and (2) identifies the characteristics of the development of EE-EI research on a global scale.

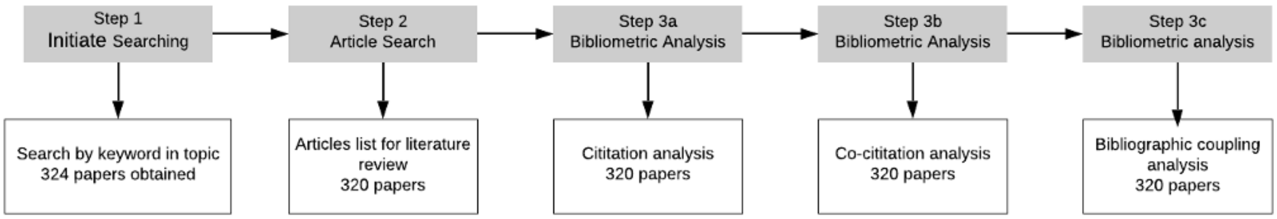


Figure 1. Research flow.

## 2.0 RESEARCH METHOD AND DATA

### 2.1 RESEARCH METHODOLOGY

In this paper, three specific bibliometric methods are applied: citation analysis (CA), co-citation analysis (CCA), and bibliographic coupling analysis (BCA). Citation analysis is often used to define disciplines and emerging specialties through keywords, authors, and journal relationships and to determine the interdisciplinary or multidisciplinary characteristics of research topics [14]. This method is based on the premise that frequently cited papers are likely to have a greater impact and influence on the research subject than those less cited [14]. Co-citation analysis is used to interpret the similarity of content between two publications by counting the number of papers in which both publications have been cited in pair [15]. The more often the two publications are cited together, the closer the intellectual link exists in the authors, disciplines, and research areas. Bibliographic coupling analysis is the opposite of co-citation analysis: two publications are bibliographically coupled if they both cite a third publication [16]. Bibliographic coupling focuses on the overlap in the reference lists of publications. The larger the number of references that two publications have in common, the stronger the bibliographic coupling relation is between the publications. In this study, co-citation and bibliographic coupling are used together to identify the original research interest and future research direction and trends.

### 2.2 REVIEW WORKFLOW

The literature review entailed three steps. In the second step, citation analysis, co-citation analysis, and bibliographic coupling analysis were carried out with VOSviewer software to determine major research clusters or areas and research synergies. CA generally assumes that the number of citations reflects a publication's influence and prominence and its quality or visibility [17,18]. CCA and BCA represent the intellectual contribution and connections. In a VOS-constructed visual map, different cluster maps represent different research areas. The sizes of the nodes indicate the relevance of the items—including research topics, authors, sources, or countries—and the distance between nodes illustrates the intellectual connections. A detailed explanation is provided in section 3.0. In the third step, following the creation of an overview of research activities based on VOSviewer maps and identification of the major active research clusters, an in-depth qualitative review of all studies was conducted to reduce the articles to the five most influential studies (with the most citations) in each cluster. Altogether, 15 papers were thoroughly reviewed to examine the findings and create synergies and conclusions. Figure 1 illustrates the research flow.

### 2.3 DATA COLLECTION

This review used Web of Science (WoS) as the data source, and the specific databases used were Science Citation Index Expanded (SCIE), Conference Proceedings Citation Index Science (CPCIS), Social Science Citation Index (SCI), Emerging Sources Citation Index (ESCI), Conference Proceedings Citation Index-Social Science and Humanities, Book Citation Index-Science, and Book Citation Index-Social Sciences and Humanities. The keywords "embodied energy" and "environmental impact" in topic in the combination of "building" in the title were used for the search. The search results indicated 324 records published in the field of construction building technology, environmental science and studies, engineering, material science, green building technology, energy and fuel, and architecture, among others. The titles and abstracts of the 324 records were carefully screened to ensure data accuracy and relevancy. The author read the abstracts of all 324 papers carefully to make certain the manuscripts were related to embodied energy and environmental impact studies in buildings. Four papers were identified as solely focused on materials production and did not address any application in buildings; therefore, they were eliminated from the collection. After removing the irrelevant articles from the data set, altogether, 320 manuscripts were identified between 1996 and 2019. The first article appeared in 1996, titled "Use of a hybrid energy analysis method for evaluating the embodied energy of building materials," published by a New Zealand researcher. It referenced two early documents: the first was a study conducted by a research group in the United States in 1976, and the other was a report from the Energy Analysis workshop hosted in Sweden in 1974. Both documents were not found in the WoS database.

## 3.0 RESULTS: RESEARCH CHARACTERISTICS

### 3.1 PUBLICATION OUTPUT AND GROWTH TRENDS

Figure 2 illustrates the yearly distribution of the bibliographic records of embodied energy manuscripts over the 13-year period. Until 2009, only a few papers were published annually,

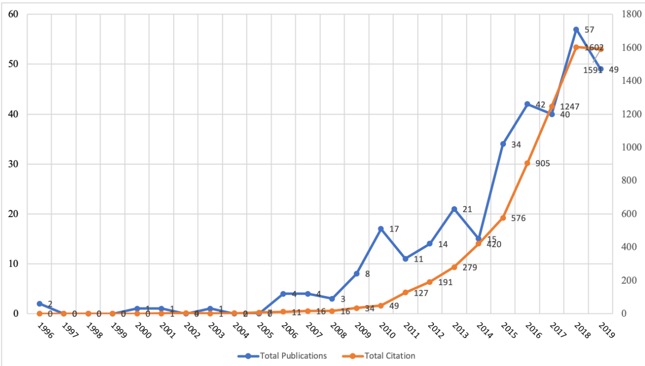


Figure 2. Output and Growth.

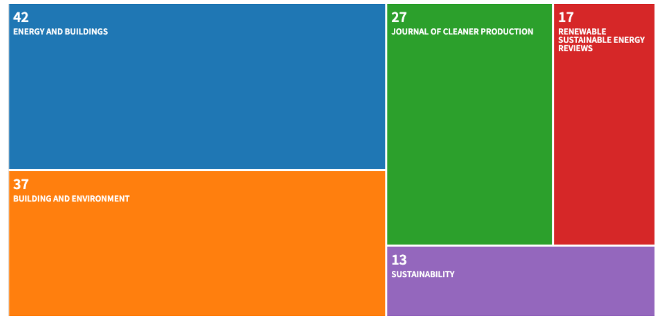


Figure 3. Top five journals with the highest number of EE-EI papers.

with rapid growth beginning around 2015 when the number of annual publications doubled.

All the bibliographic records (including title, abstract, and keywords) were downloaded. References, which are important building blocks of an article's intellectual structure, were also downloaded; a total of 4,021 references were included in the analysis. Of the 320 documents found, 77 (24%) did not have any citations, and 124 (38%) had fewer than ten citations. Table 1 lists the ten most cited articles.

### 3.2 GEOGRAPHICAL AND PUBLICATION SOURCE DISTRIBUTION AND COOPERATION

In total, the 320 publications were published in 109 different journals. This high number indicates a wide variety of disciplines and regions involved. Of the 109 journals, 71 journals (65.1%) only published one paper on the research topic, 9 journals (8.3%) published two papers, and only 6 journals (4.6%) published more than ten papers on the topic. Figure 3 provides information for the top five most active journals that have published papers on EE-EI research. These five journals have contributed close to half of all EE-EI articles (45.3%, n = 145/320). Three key journals are Energy and Buildings, Building and Environment, and Journal of Cleaner Production, with 42, 37, and 27 articles on the topic, respectively. See section 3.4 for more information on the division of research clusters.

EE-EI publications originate from 48 countries, with 27 located in Europe, 13 in Asia, 3 in South America, 2 in North America, 2 in Oceania, and 1 in Africa. Figure 4 illustrates the worldwide distribution of the contributing countries and regions, where 40 countries (81.6%) produced ten or fewer publications, 7 countries or regions (14.6%) produced between eleven and forty papers, and 2 countries (4%) generated more than forty publications. The United States produced the most publications (n = 45), followed by China (n = 43) and the United Kingdom (n = 35). Figure 5 indicates the top five most productive and influential countries on this research topic. Economic advancement does not seem to have contributed to scientific and academic investments, since the top five ranking countries include both developing and developed countries.

The cooperation network among research between countries was analyzed using co-author analysis. The countries in the network included those with at least ten published papers, and countries that did not have a cooperation relation were excluded. Figure 6 illustrates the results of the cooperation network; the size of the circles represents the number of publications, and the thickness of the connecting lines represent the strength of collaborations. The color indicates the collaboration clusters, with four major clusters apparent: the first and biggest (red) is around the United States, the second (yellow) is China, the third (green) is England, and the fourth (blue) is Italy. The cluster surrounding the United States has two major contributors: South Korea and India. This indicates the close cooperation network among the three countries with the United States leading the effort. The same interpretation can be applied to other clusters. The cluster around China has one major contributor, Australia, which is closely tied to the fourth cluster of Italy and Germany. The third cluster centered on England is more distant from the previous three but has a closer collaboration with Canada, which has no direct cooperation with any other countries. This cooperation network demonstrates that the collaboration between countries and authors tends to be geographically correlated and centered on the most influential countries with the most publications output (refer to figure 5 for the top five most influential countries) [19,20]. Additionally, the network demonstrates that the cooperation among researchers is transnational and is not confined by the developing or developed worlds.

### 4.0 DISCUSSION AND CONCLUSION

Two characteristics can be identified in the reach of EE-EI in the past several decades. The first is the temporal shift of involved research fields and extension of the research scope or topics. Bibliographic coupling analysis reveals two primary disciplines contributing to the development and promotion of EE-EI research starting in the early 1990s: the building construction field and environmental science field. After 10 years of development, co-citation analysis indicated that the interest and impact of EE-EI had been extended to other disciplines, such as energy fuels, ecology, material science, urban studies, and public policy, among others.

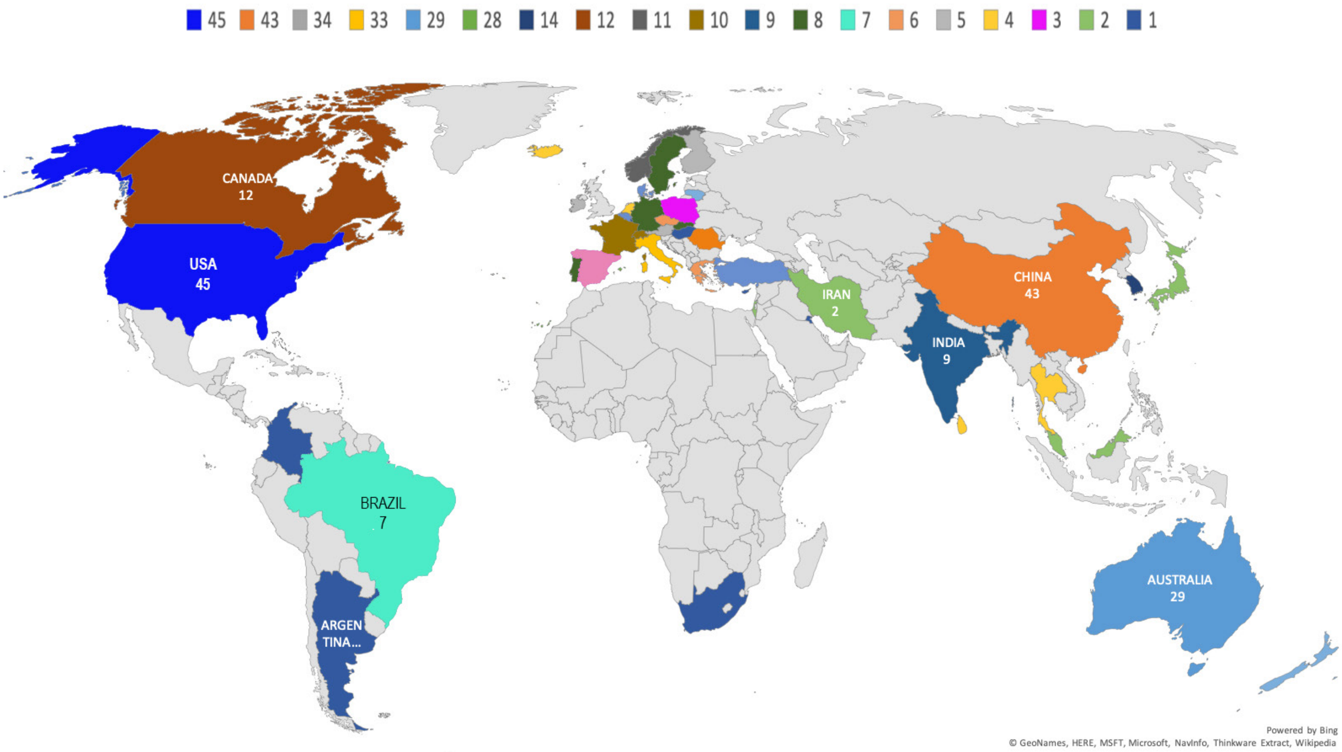


Figure 3. The number of publications distributed by country and region (based on the publications found in WoS).

In the early years, from 1996 to 2014, the research hot topics revolved around environmental problems caused by energy-inefficient building designs, as findings confirmed that operating energy contributed the most to environmental degradation. After this issue was identified, associated mitigation strategies were proposed. The addition of insulation to the building envelope was one of the most effective strategies, with immediate improvement in energy conservation and an environmental impact reduction. Starting in 2015, an environmental impact reduction, particularly in carbon emissions, became the priority focus agreed on by researchers from all fields. This focus prompted researchers and practitioners to reexamine the balance between operating energy and embodied energy and to study mitigation strategies from a more holistic life cycle perspective. Besides operating energy, the energy embodied in the construction process, transportation, and demolition is included, with the whole embodied energy spectrum having become the focus area. Moving forward, since 2017, other factors outside of the building construction and environmental field have been gradually introduced to account for uncertainties that buildings could encounter during their long life span. Globally, as operating energy efficiency continues to improve, the importance of embodied energy will increase. Consequently, many research efforts have concentrated on finding alternative materials to replace certain traditionally energy-intensive heavy building materials, such as concrete, that contribute to the environmental impact.

The second characteristic of EE-EI research is the socioeconomic influence: the differences between developing and developed countries. EE-EI research is a global trend, and in the last decades, developing and developed countries have contributed almost equally to this research topic. The global research activities and collaborations have not been influenced by the economic development status of the regions, since all countries face similar risks and threats related to the environmental impact from the building industry. However, there are distinctions in perspectives and aims. Developing countries appear to focus more on the method, procedure, and accuracy of embodied energy counting, since the top five cited publications in research clusters one and two were all from developed countries.

The differences may be due to developing countries facing challenges from both environmental degradation and energy poverty. In developing countries, the overall energy consumption will increase regardless of improvement in the energy efficiency of buildings. It is predicted that in 2050, China's total energy consumption in the building sector will be 15 times higher than that in 1970. Additionally, Brazil and India will consume almost 11 to 12 times more energy by 2050 than in 1970 [21]. These changes are related to population growth and increases in living standards. In 2016, 18% of the population in India and 27% of the population in other developing Asian countries did not have access to electricity [22]. This situation must improve in order for developing countries to

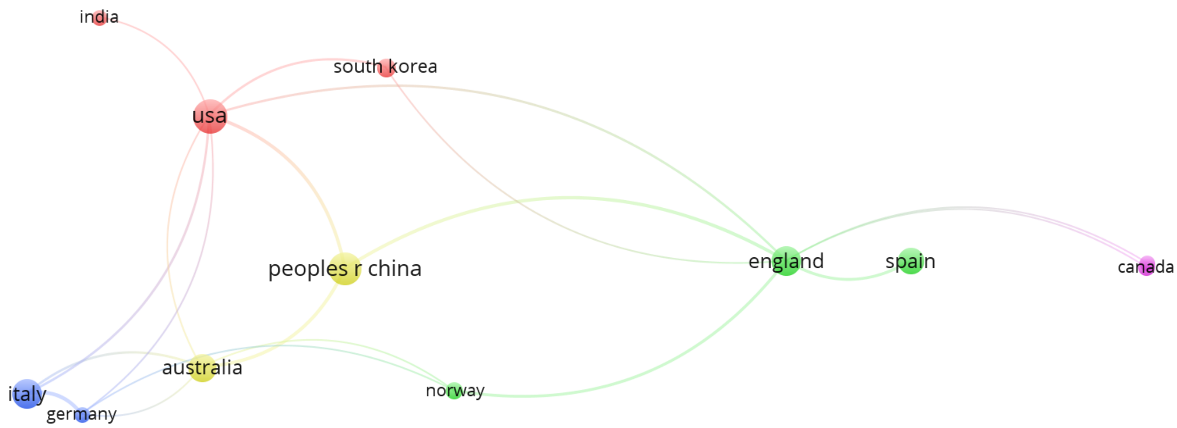


Figure 4. Illustrates worldwide distribution of the contributing countries and regions.

catch up with the developed world. With both a projected high population growth and energy consumption increase as living standards rise, the predicted environmental impact will become another major issue that developing countries will cope with in the coming decades.

With this knowledge, developing countries are keen on finding or adopting a low-energy and low-impact development path which leads to energy conservation and environmental impact reduction simultaneously. Conversely, developed countries face a unique challenge different from most developing countries, which is an aging building stock and infrastructure. In the European Union, 75% of buildings were built before 1990, meaning they are not energy efficient and require upgrades [23]. Consequently, the retrofitting of building stocks is a priority for both Europe and developed countries [24]. Renovation and energy retrofits could conserve embodied energy that is already imbedded in the existing building structure; therefore, determining an accurate method to measure embodied energy and its related contribution to a carbon emissions reduction have been prioritized. The first step to forming an accurate embodied energy assessment is to have a robust embodied energy inventory. Accordingly, in the past couple decades, several inventory databases have been created in developed countries.

In this systematic review, an evaluation of the global research in EE-EI publications from 1996–2019 was provided. The topic of EE and EI studies has experienced rapid growth since 2015, and its publication output is characterized by a multidisciplinary and multi-regional approach. However, there have been limited reviews on the connection between the two topics. In response, this study provides a holistic and detailed understanding of the research activities to date. From the present literature review and the clusters obtained from the co-citations of 320 documents in the database, the author concluded that EE-EI research is characterized by a wide variety of research themes and a multidisciplinary approach. Moreover, connections exist among the three identified research clusters: (1) embodied energy components and mitigation strategies, (2) embodied energy analysis and significance across regions, and (3) the balance between energy efficiency and environmental impact.

This study has two limitations. The first limitation is due to the database used in this review. Although Web of Science is one of the largest global databases for academic research publications and is the most widely accepted and frequently used database [24], other databases, such as Scopus, may contain publications that have not been included in Web of Science. Secondly, this review largely relied on a quantitative approach. There is a certain correlation between quantity and quality; for example, a high citation count indicates a higher influence, hence higher quality. However, the content and exact quality of publications cannot be simply interpreted by numbers. For instance, quite a few literature review papers are among the top cited publications, but this does not mean a paper with fewer citations on experimental and empirical research is less valued or influential. The next step, a content analysis, could be conducted to offset these limitations.

## ENDNOTES

1. Chastas, P., Theodosiou, T., Kontoleon, K. J., & Bikas, D. (2018). Normalising and assessing carbon emissions in the building sector: A review on the embodied CO2 emissions of residential buildings. Building and Environment, 130, 212-226.

2. Moncaster, A. M., & Symons, K. E. (2013). A method and tool for 'cradle to grave'embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. Energy and Buildings, 66, 514-523.

3. European Committee for Standardization. "Sustainability of construction works". Accessed on December 29,2019. https://standards.cen.eu/dyn/www/f?p=204:7:0::::FSP_ORG_ID:481830&cs=181BD0E0E925FA84EC4B8BCCC284577F8

4. Pomponi, F., & Moncaster, A. (2016). Embodied carbon mitigation and reduction in the built environment–what does the evidence say?. Journal of environmental management, 181, 687-700.

5. Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings—A review of current trends. Energy and Buildings, 66, 232-245.

6. Szalay, A. Z. Z. (2007). What is missing from the concept of the new European Building Directive?. Building and Environment, 42(4), 1761-1769.

7. Kneifel, J., O'Rear, E., Webb, D., & O'Fallon, C. (2018). An exploration of the relationship between improvements in energy efficiency and life-cycle energy and carbon emissions using the BIRDS low-energy residential database. Energy and buildings, 160, 19-33.

8. Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. Energy and buildings, 42(10), 1592-1600.

9. Birgisdottir, H., Moncaster, A., Wiberg, A. H., Chae, C., Yokoyama, K., Balouktsi, M., ... & Malmqvist, T. (2017). IEA EBC annex 57 'evaluation of embodied energy and CO2eq for building construction'. Energy and Buildings, 154, 72-80.

10. Crawford, R. H., & Stephan, A. (2013, January). The significance of embodied energy in certified passive houses. In Proceedings of World Academy of Science, Engineering and Technology (No. 78, p. 453). World Academy of Science, Engineering and Technology (WASET).

11. Pomponi, F., & Moncaster, A. (2016). Embodied carbon mitigation and reduction in the built environment–what does the evidence say?. Journal of environmental management, 181, 687-700.

12. Moncaster, A. (2015). Pathways to low carbon building: reflection on the special issue.

13. Pritchard, A. (1969). Statistical bibliography or bibliometrics. Journal of documentation, 25(4), 348-349.

14. Osareh, F. (1996). Bibliometrics, citation analysis and co-citation analysis: A review of literature I. Libri, 46(3), 149-158.

15. Garfield, E., & Merton, R. K. (1979). Citation indexing: Its theory and application in science, technology, and humanities (Vol. 8). New York: Wiley.

16. Kessler, M. M. (1963). Bibliographic coupling between scientific papers. American documentation, 14(1), 10-25.

17. Smith, D. R. (2007). Historical development of the journal impact factor and its relevance for occupational health. Industrial health, 45(6), 730-742

18. Ugolini, D., Bonassi, S., Cristaudo, A., Leoncini, G., Ratto, G. B., & Neri, M. (2015). Temporal trend, geographic distribution, and publication quality.

19. Zheng, T., Wang, J., Wang, Q., Nie, C., Shi, Z., Wang, X., & Gao, Z. (2016). A bibliometric analysis of micro/nano-bubble related research: current trends, present application, and future prospects. Scientometrics, 109(1), 53-71.

20. van Nunen, K., Li, J., Reniers, G., & Ponnet, K. (2018). Bibliometric analysis of safety culture research. Safety science, 108, 248-258.

21. World Bank, 2014. Energy Use. Accessed December 30, 2019. http://data.worldbank.org/indicator/EG.USE. COMM.KT.OE.

22. Outlook, E. A. (2017). From Poverty to Prosperity, 2017. Paris: International Energy Agency.

23. Buildings Performance Institute Europe. "State of the building stock." Access on December 29,2019. http://bpie.eu/wp-content/uploads/2017/10/State-of-the-building-stock-briefing_26Ott_v1.pdf

24. Pombo, O., Rivela, B., & Neila, J. (2016). The challenge of sustainable building renovation: assessment of current criteria and future outlook. Journal of Cleaner production, 123, 88-100.

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