KnE Social Sciences

The 1st International Conference on Creative Design, Business and Society (1st ICCDBS) 2023

KNE Publishing

Research Article

Measuring Energy Efficiency of Power Plants Using Data Envelopment Analysis: A Bibliometric Study

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Abstract.
Electricity resources have emerged as a global necessity, with increased demand coinciding with the issue of global warming and the resulting surge in greenhouse gas emissions. Improving power generation efficiency is crucial to addressing this critical problem. This article compiles and analyzes published research focused on efficiency measurement using Data Envelopment Analysis (DEA) in power plants, drawing data from two major journal databases: Web of Science and Scopus. A comprehensive screening process yielded a dataset comprising 162 articles within the realm of DEA in power plant analysis. A bibliometric analysis reveals interesting findings: the most prolific journal in this domain is "Energy Economy," while "Energy Policy" holds the utmost influence. Notable contributors include China, Iran, and the United States, and an in-depth examination of the ten most impactful articles is also provided. Further scrutiny of citation networks and bibliographic coupling unveils various clusters with distinct thematic areas.

Keywords: Data Envelopment Analysis (DEA), power generation, bibliometric

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Published: 19 November 2024

Publishing services provided by Knowledge E

Selection and Peer-review under the responsibility of the 1st ICCDBS Conference Committee.

1. Introduction

Electricity resources have become a fundamental necessity for individuals worldwide in the era of globalization. They play a pivotal role in propelling the global economy and are indispensable across nearly every sector. According to the latest electricity market report released by the International Energy Agency (IEA), there has been a consistent upward trend in global electricity demand over the past few decades. The report projects a 2.4% increase in 2022, following a remarkable 6% surge in the previous year [1]. The growth of electricity is the fastest-growing source of final energy demand, and over the next 25 years, its expansion is projected to outpace the overall growth of energy consumption [2]. In the process of generating electricity, power plants inevitably produce undesirable outputs, such as air pollution that harms the environment. It is

essential to ensure that the total weight of inputs, including non-economic factors like oxygen, matches the weight of the resulting outputs. Any material inputs introduced into the production process that cannot be transformed into desirable outputs should be considered undesirable.

The most effective approach to simultaneously ensure a consistent electricity generation capacity while minimizing undesirable emissions is to comprehensively analyze the overall performance of power plants, with the aim of enhancing energy efficiency. Evaluating energy efficiency holds significant importance for both the industry and government decision-makers, as it offers invaluable insights for future planning and sustainable development.

In the power generation industry, there has been a growing focus on measuring energy efficiency. Measuring energy efficiency typically involves evaluating the power generated per unit of energy input. The efficiency measurement in power plants poses challenges due to the various factors influencing inputs and outputs. Overcoming many of these challenges has been achieved through the adoption of Data Envelopment Analysis (DEA) as an efficiency measurement tool. There has been a rapid increase in the applications of DEA to assess the efficiency of power plants in various countries and economic conditions, and to account for environmental factors and generate accurate efficiency estimates. However, these studies are currently dispersed, and it is crucial to examine their specific areas of concentration, identify promising research directions, and prioritize essential areas for further investigation.

This article presents a bibliometric analysis to streamline research efforts in the realm of power plant performance measurement using the DEA method. This research marks the first effort of a comprehensive analysis of the DEA applications in the context of power plants, with a specific focus on research objects, conducted through bibliometric analysis. The article is structured as follows.

2. Methodology Research

This section outlines the primary stages and procedures for conducting the bibliometric study, as portrayed in Figure 1. Three primary databases are frequently used to extract abstract information and citations: Google Scholar, Scopus, and Web of Science [3]. This analysis, however, is based on two of the world's leading research databases that carefully follow to content selection and maintenance standards - Scopus (managed

by Elsevier) and Web of Science (WoS) - which strictly comply to content selection and maintenance criteria (operated by Clarivate). While Google Scholar is sometimes considered because it is the largest database, its approach has been a subject of debate within the scientific community due to limited information regarding content coverage and the results being influenced by the time of the user's visit, rather than taking into account other quality indices for publications [4].

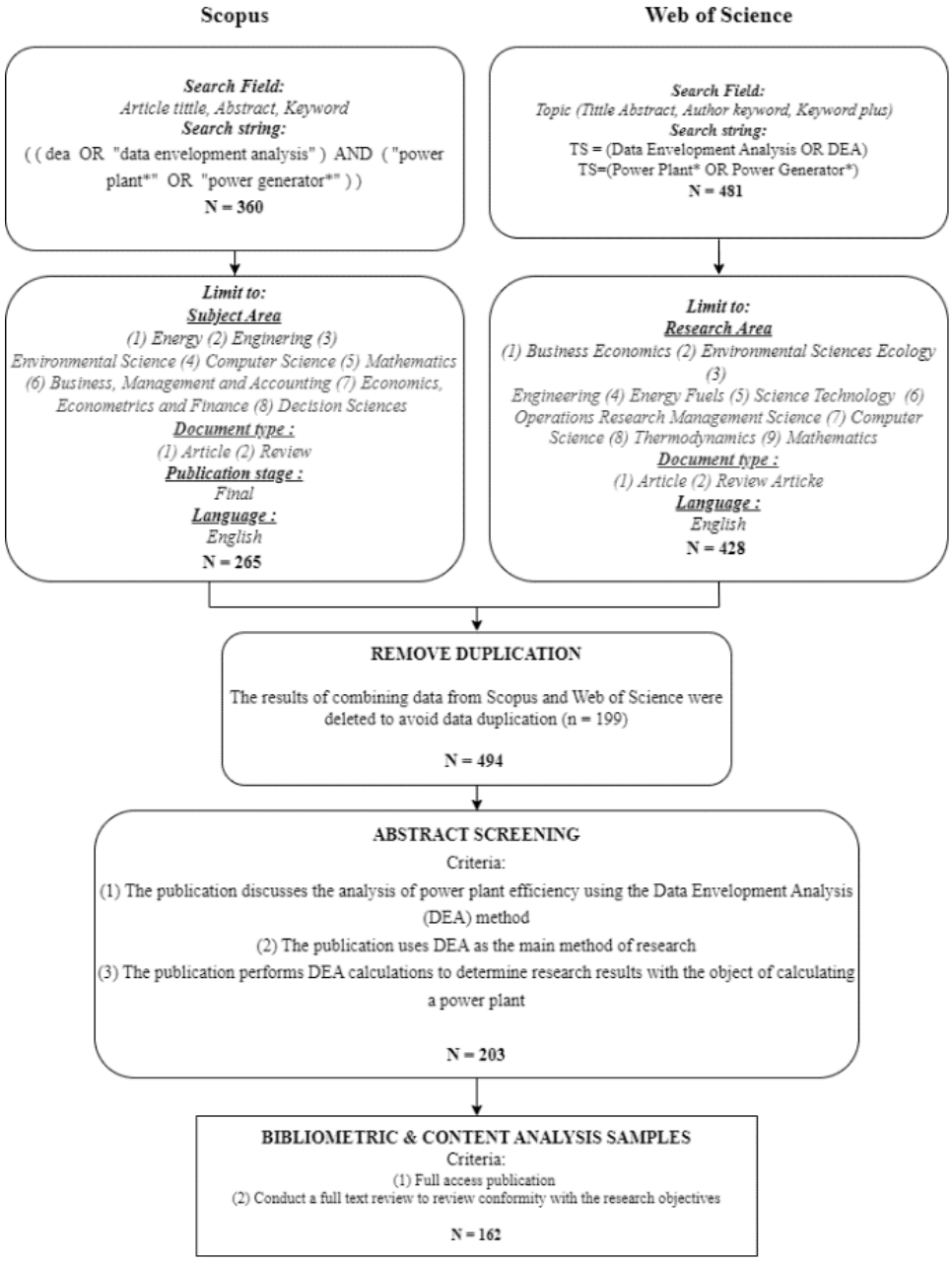

Figure 1: The Methodology of The Study.

Figure 1 illustrates the systematic methodology in conducting the study. First, in order to extract all relevant articles from two databases, we define a set of keywords used

to create more complex and comprehensive searches: ((’Data Envelopment Analysis’ OR ’DEA’) AND (’Power Plant*’ OR ’Power Generator*’)). Second, we narrow down the research subject areas, document types, and languages. This procedure yielded 265 articles from Scopus and 428 articles from WoS. In the third step, we address data duplication from both databases, resulting in 494 articles that proceed to the subsequent phase.

The fourth stage involves a manual screening process, where we carefully review the abstract of each remaining article to assess its relevance. Given the diverse nature of articles retrieved from the databases, our focus is on conducting a comprehensive study of those that satisfy the following criteria: (a) The abstract must explicitly mention power plant efficiency assessed through Data Envelopment Analysis (DEA) as the primary objective; (b) The abstract must highlight the use of DEA as the primary research method; (c) The abstract should provide information about the input-output variables and the outcomes of DEA calculations related to the measurement of energy efficiency in power plants. Following this rigorous screening process, a total of 203 articles progress to the final stage of our study.

The final step in the article screening process involves a comprehensive review of all 203 articles to evaluate their relevance to the research objectives. This final stage leads to the selection of 162 publications for further analysis, which is conducted using bibliometric analysis using VOS viewer. The VOS viewer is powerful in processing and displaying co-citation maps based on data from 5,000 major scientific journals. Additionally, it allows for the creation of multidimensional scaling maps using statistical packages such as SAS, SPSS, R, and other less commonly used techniques [5].

3. Results and Discussion

3.1. Publication Trends

The distribution of publications per year from a sample of 168 articles spanning the years 1996 to 2022 is depicted in Figure 2, providing insight into the annual developments within the field of DEA research in power plants. The initial publication on this subject emerged in 1996, authored by John Zeitsch and Denis Lawrence, wherein they explore the development and application of performance metrics in the electricity industry, emphasizing economic efficiency through the utilization of multilateral total factor productivity and DEA [6]. In 1999, subsequent research surfaces, examining DEA

scenarios for power plants [7]. Post-1999, research in this domain exhibits consistent growth and broadens its scope of inquiry. Since 2010, there has been a substantial rise in the annual volume of publications. This growth can be attributed to the increasing attention on the power plant efficiency by the scientific community.

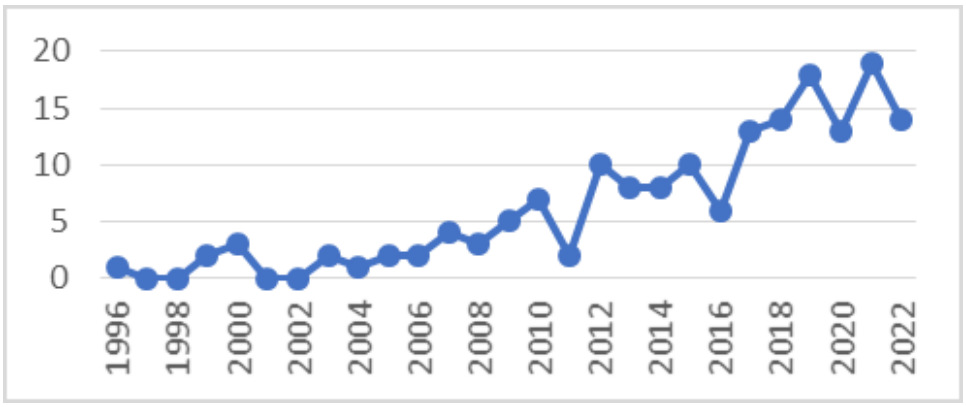

Figure 2: Number of publications from 1996 to 2022.

Figure 3 illustrates the progression of leading scholarly publications within the DEA domain as applied to power plants. The graphic provides an overview of academic journals that disseminate scholarly works pertaining to DEA in power plants, shedding light on their efficiency and impact. Among the 162 publications included in the research sample, the Energy Economics journal stands out with the highest productivity, contributing more than 10% of the sample in this study, comprising a total of 20 articles. This graphical representation, in turn, presents valuable insights into their scholarly output and influence.

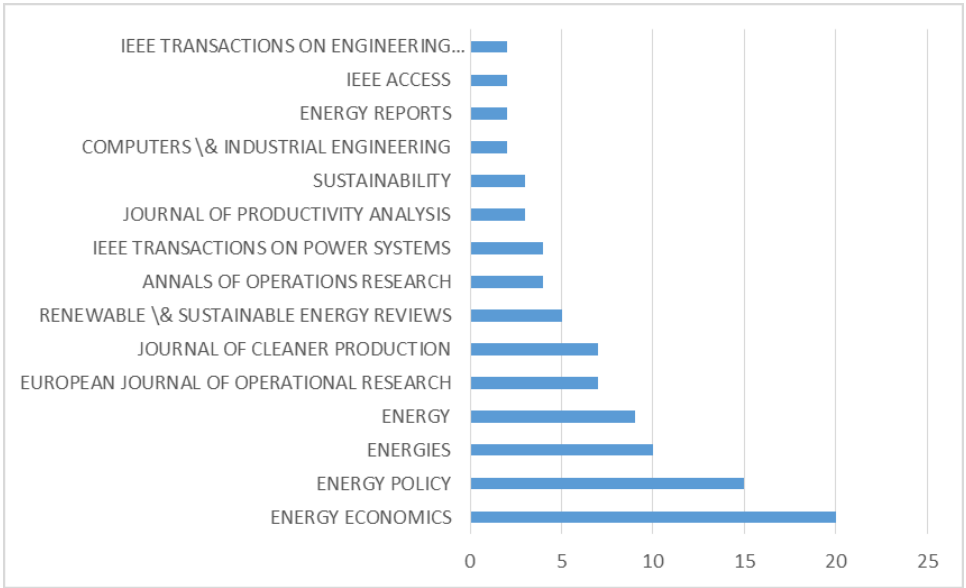

Figure 3: Most influential journals.

Among the 162 publications included in the research sample, it is noteworthy that the Energy Economics journal stands out with the highest productivity, contributing more than 10% of the sample in this study, comprising a total of 20 articles.

3.2. Author's Country of Affiliation

Regional evolution is a key component of bibliometric analysis concerning the development and assessment of a country's policies within a specific research field. In Figure 4, we observe the total publications over time for the top 18 author-affiliated countries. China leads the list with the highest number of publications, followed by Iran, the United States, India, and Japan. When examining the regional contributions of Germany, the United Kingdom, Italy, and Finland, it becomes evident that the European Union has made substantial efforts.

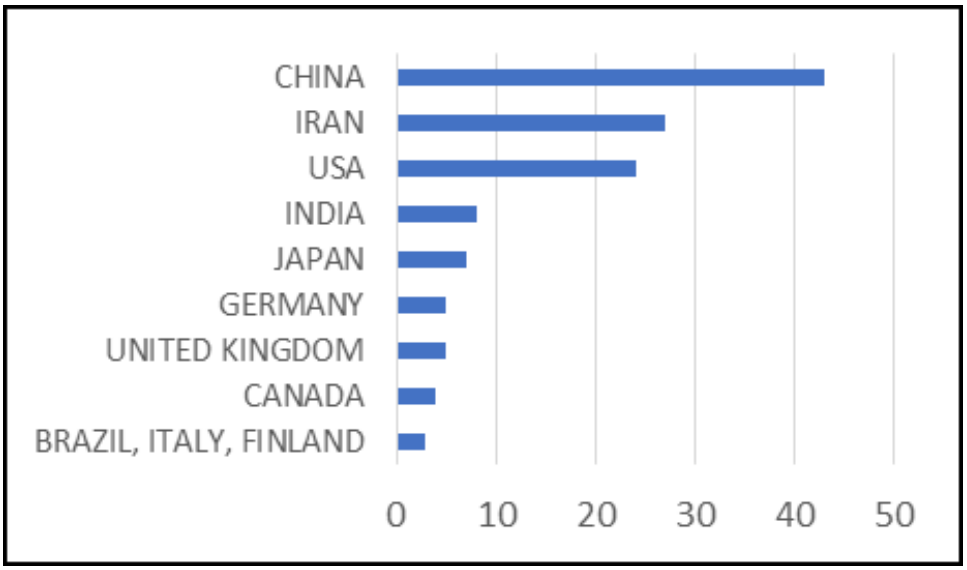

Figure 4: Author's country of affiliation.

Electrical energy consumption is a major contributor to global warming and is intrinsically linked to China's economic development. The magnitude of China's future electricity demand and the challenges associated with decarbonizing the power supply explain why, for the first time in 2016, global investments in electricity surpassed those in oil and gas, necessitating a robust policy escalation [1].

In second place is Iran, which currently heavily relies on fossil fuels for electricity generation. Given the government's commitment to reducing the use of conventional energy sources and the global focus on environmental concerns, Iran must reconsider its energy mix policy within the electricity sector and transition towards a more diversified

energy portfolio. Numerous studies in Iran have sought to evaluate the efficiency of power generation and have proposed a comprehensive decision-making framework for assessing alternative energy sources for electricity production in Iran. The objective is to determine the most suitable energy mix, considering various aspects of sustainable development.

The European Union is among the regions that prioritize enhancing the efficiency of power plants, particularly in the realm of renewable energy. This emphasis is closely related to the goals outlined in the Paris Climate Agreement, which aims to limit the global average temperature increase to below 2°C [8]. Achieving these objectives necessitates action at all levels and across all sectors.

Figure 5 displays countries that have frequently cooperated, with the thickness of the red lines indicating increasing levels of cooperation between the two countries. The United States, Japan, China, Vietnam, Iran, and Canada are among the countries that have collaborated the most. The frequency of cooperation among these six countries and several others is summarized in Table 1. The collaboration data reveals that these cooperative efforts span diverse regions, including those in Asia, America, and Europe. Most countries with strong collaborative relationships also tend to have high publication rates, with the exception of India. This highlights that, despite India having a significant number of publications, its collaborations are predominantly with other countries.

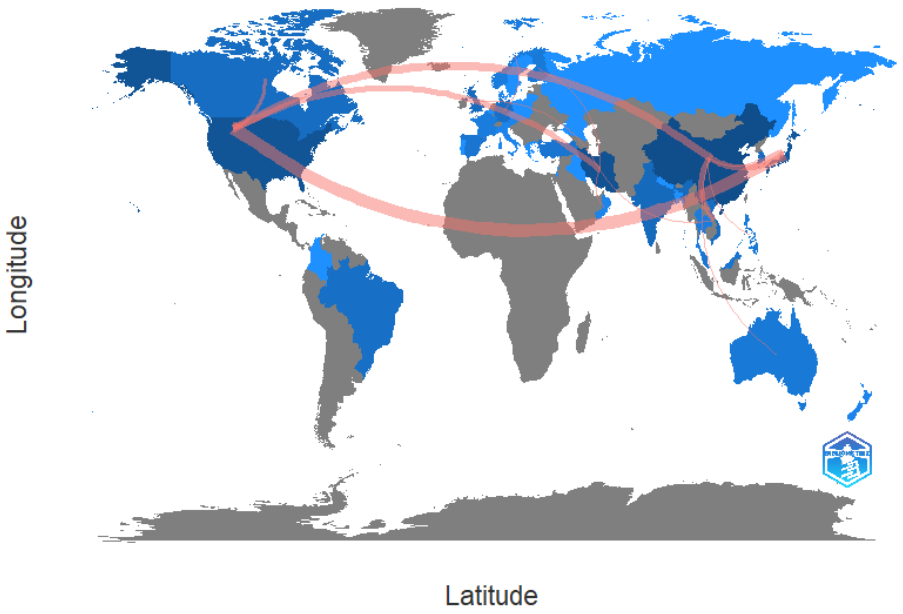

Figure 5: Interstate Collaboration.

Table 1: Inter-Country Collaboration Frequency.

USA	JAPAN	16
CHINA	USA	8
CHINA	VIETNAMESE	6
CHINA	JAPAN	5
IRAN	USA	5
USA	CANADA	3
CHINA	AUSTRALIA	2
CHINA	KOREA	2
CHINA	PHILIPPINES	2
GERMANY	NORWAY	2
IRAN	FINLAND	2
IRAN	OMAN	2
IRAN	UNITED KINGDOM	2
IRAN	VIETNAMESE	2

3.3. Authorship Bibliometrics

Authorship bibliometrics is a subfield of bibliometrics that studies and quantifies many elements of authorship in academic publications. It provides insights into the patterns and characteristics of authors' contributions to scientific and academic literature.

Table 2 displays the cumulative profiles of the top ten authors with the most publications from 1996 to 2022, accounting for group articles available in the Scopus and WoS collection databases. These profiles provide insights into the key contributions to research on power plant efficiency over the years.

Toshiyuki Sueyoshi, Department of Management, New Mexico Institute of Mining & Technology, emerges as the major contributor to this subject, with 21 publications. Sueyoshi's study has taken him to three countries: the United States, China, and Japan. Mika Goto is close behind in second place, with 19 publications. Ali Azadeh and Xiaohong Liu tie for third place, both having contributed six publications.

It's worth noting that academics frequently use the H-index as a metric to assess scholars' output. Based on publications and citations, this index has evolved into a fundamental standard for assessing the productivity and impact of researchers, scientists, institutions, departments. The H-index within this sample aligns with the productivity of the authors.

Table 2: Authors With the Most Publications.

Authors	Articles	H-index
SUEYOSHI T	19	16
GOTO M	18	14
AZADEH A	6	4
LIU X	6	5
MOSTAFEAIPOUR A	5	4
WANG C	5	4
ZHANG N	5	4
COOK W	4	4
HAMPF B	4	4
LEE C	4	4

3.4. Citation Analysis

Citation analysis involves the examination of how often a particular work has been cited by others, as well as the patterns and context of those citations. It can provide valuable insights into various aspects of the scholarly communication process and the research landscape.

Table 3 shows the ten articles using the DEA method in power plants, with the most citations seen from local citations (LC) and global citations (GC). The number of citations an article obtained from other articles in the exact search performed in the study is referred to as LC, whilst the total number of citations obtained by an article from all publications indexed in the database used in the study is referred as GC [9,10].

The publications with the most citations are dominated by articles published in 2000-2012. The article with the most LC and GC is [11]. This article discusses environmental policies, the notion of eco-efficiency, and the difficulty of measuring overall company performance due to the absence of market prices for non-productive outputs, so data envelopment analysis (DEA) is used to measure efficiency [11].

3.5. Co-citation Analysis

Co-citation analysis is a technique used to identify publications or references that are frequently mentioned in the same article (referred to as cited references). Figure 6 portrays the network of co-citation mapping of this study.

TABLE 3: Authors With the Most Citations.

Authors	Title	Local Citations	Global Citations
KORHONEN PJ, 2004, EUR J OPER RES	Eco-efficiency analysis of power plants: An extension of data envelopment analysis	26	433
SARICA K, 2007, ENERGY	Efficiency assessment of Turkish power plants using data envelopment analysis	21	132
MUNISAMY S, 2015, J CLEAN PROD	Eco-efficiency change in power plants: using a slacks-based measure for the meta-frontier Malmquist–Luenberger productivity index	11	78
PARK SU, 2000, INT J PROD ECON	The efficiency of conventional fuel power plants in South Korea: A comparison of parametric and nonparametric approaches	10	59
LINS ME, 2012, RENEW SUST ENERG REV	Performance assessment of alternative energy resources in the Brazilian power sector using data envelopment analysis	9	44
HAMPF B, 2014, J PROD ANAL	Separating environmental efficiency into production and abatement efficiency: a nonparametric model with application to US power plants	6	45

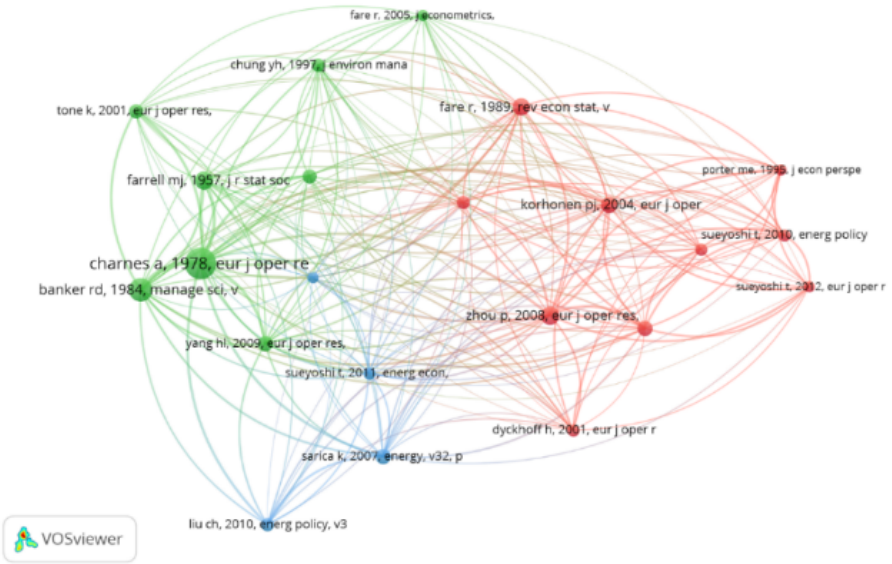

Figure 6: Co-citation Mapping.

Cluster 1 consists of 10 articles indicated by red nodes with interconnected network nodes. The underlying theme of this cluster is the use of DEA in measuring power generation efficiency, for instance: Measuring the ecological efficiency by comparing environmental performance indicators [12], multilateral accounting of unwanted production outputs, e.g pollutants [13], measuring market prices for reducing the pollutants produced [11], distinguishing the disposable features among unwanted outputs in the production process [14].

Cluster 2, indicated by a green node, consists of conceptual publications focusing on the development of the DEA models with illustrative examples on energy efficiency measurement in power plants. DEA mathematical programming to obtain an ex post facto evaluation of the relative efficiency of management achievements by estimating technical and scale inefficiencies [15], the slacks-based measure of efficiency in DEA [16], the use of DEA to evaluate a program [17], and the six DEA-based performance models for production processes that produce desired and unwanted outputs [18,19].

Cluster 3, indicated by a blue node, presents the use of DEA in power plants. This cluster is the closest to the research topic being carried out. Stability tests are conducted to verify the stability of the DEA model [20], the comparison use of DEA-VRS and DEA-CRS [21], an integrated efficiency: operational and environmental for measuring the efficiency of fossil fuel power plants [22,23], and the DEA applications in energy and the environment in the last four decades, including the concept and methodology of DEA's environmental assessment [24].

3.6. Thematic Evolution

The thematic evolution of this field is divided into two periods. The first period spans from 1996 to 2011, and the next the subsequent one extends from 2012 to 2022. This period division is prompted due to a substantial increase in 2011, which is assumed to mark a pivotal turning point in the discussion of the DEA within the context of power plants.

In the following section, there is a strategy diagram featuring four quadrants based on Callon's centrality and Callon's density. The X axis represents Callon's centrality which measures the level of interaction between clusters, while the Y axis is Callon's density which measures the strength of the relationship between words within a cluster.

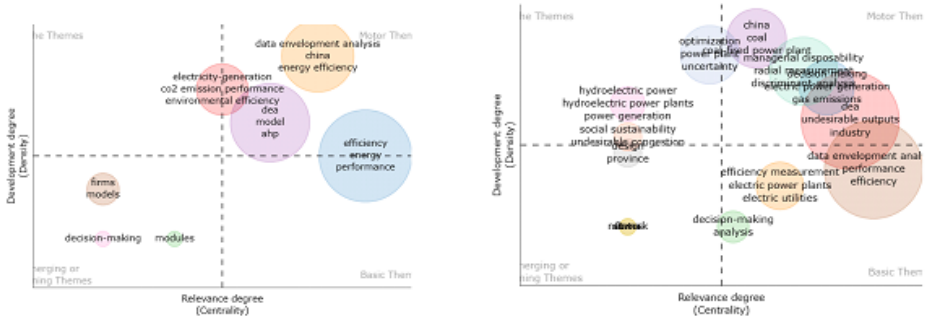

Figure 7: Thematic Map Period I – 1996-2011(left) & Period II – 2012-2022 (right).

Figure 7 depicts the thematic patterns in publications within two periods: 1996-2011 and 2012-2022. In Period I, the majority of articles are centered around the motor theme, signifying the significance and thorough development of these particular topics. For instance, research has extensively delved into the application of DEA for measuring energy efficiency in China, the integration of DEA with Analytical Hierarchy Process (AHP), and the examination of environmental efficiency for reducing CO2 emissions. Some themes can be classified as emerging, indicating that while the field of literature has initiated the exploration of DEA methods in power plants, it has yet to extend its discourse to encompass newer and emerging subjects.

Figure 7 also shows a significant increase in the number of thematic patterns during Period II (2012-2022), with more than double the number observed in Period I. Some topics that are considered emerging themes in Period I have gained prominence and received more attention during Period II. The primary topic of discussion during this second period is related to emissions and undesirable outputs. In the niche themes quadrant, several new themes have emerged, including hydroelectricity and social sustainability, suggesting that these topics are now receiving more attention.

4. Conclusion

This article has undertaken a comprehensive review of research efforts that employ Data Envelopment Analysis (DEA) to measure efficiency in power plants, utilizing data from two prominent journal databases, Web of Science and Scopus.

Through an extensive screening process, a dataset of 162 articles in the realm of DEA in power plant analysis was assembled. A bibliometric analysis has shed light on several intriguing insights. “Energy Economy” emerged as the most prolific journal in this field, while “Energy Policy” exerted the greatest influence. Notable contributors to

this body of research include China, Iran, and the United States, underscoring the global relevance of the topic. Furthermore, we have delved into the ten most impactful articles, providing a deeper understanding of the key developments in this area.

The exploration of citation networks and bibliographic coupling has revealed various clusters, each representing distinct thematic areas within the broader context of power plant efficiency. This analysis not only highlights the breadth and depth of research in this domain but also underscores the diverse avenues of inquiry and the importance of global collaboration in addressing the imperative challenge of enhancing power generation efficiency.

Future research should aim to expand the data collection process by considering additional databases, such as specialized energy and sustainability journals, to ensure a more comprehensive view of the field. To track the evolution of research trends and their impact, a longitudinal study that includes a wider time range would be valuable. This could reveal shifts in focus and emerging topics.

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