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Article

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Research Trends of Waste Heat Recovery Technologies: A Bibliometric Analysis from 2010 to 2020

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ABSTRACT

Waste heat recovery (WHR) technologies have become vital to promote efficient operation in energy systems. The present investigation presents a bibliometric analysis of the research trends in the WHR field in the last decade (2010-2020). The study implements advanced methodologies to gather relevant information for interested readers on this topic. Results indicated that WHR technologies have registered more than 14,000 articles in the selected timeline with an increasing tendency. Moreover, the number of citations escalated to more than 25% in 2020, using 2010 as the baseline. Three primary research clusters stated that power cycles are the most cited topic in the WHR field. The journal "Energy" featured the highest citation margin, whereas the most relevant author from the database was Bejan et al. Lastly, China is leading the progress in the number of articles and subsequently the citation score, which is primary promoted by the "Chinese Academy of Science." The study identified that the reduction of citations of WHR topics in the last 5 years might be primarily attributed to a transition in a more complex concept of multigeneration. In conclusion, the area of WHR technologies has maintained an increased interest in academia in the last 10 years while contributing to the exploitation of power cycle proposals, turbomachinery, heat exchangers, among others. Also, WHR plays a central role in the development of the next generation of multigeneration units.

Keywords: Bibliometrics, Waste Heat Recovery, Energy, Multigeneration
JEL Classification: Q42

1. INTRODUCTION

Global energy is increasingly engaging advanced technologies to promote sustainable development while reducing the alarming rate of greenhouse emissions (Valencia et al., 2020; Herrera et al., 2018; Duarte et al., 2014; Ramirez et al., 2019). The unprecedented growth of the world population and convectional energy practices triggers a tremendous concern about environmental pollution and future energy sources (Jamel et al., 2013; Muk and He., 2007; Demirbas, A., 2008; Valencia et al., 2020; Gutierrez et al., 2020). The energy market has been primarily governed by fossil fuels, which remains as the primary mover of the global economy (Bae and Kim, 2017). Specifically, internal combustion engines governed electricity generation in non-interconnected areas, which possess significant challenges towards the implementation of alternative power generation systems. Therefore, there is an increasing necessity to integrate alternative technologies from small to large power plants that improve the overall conversion efficiency.

Power cycles have emerged as a concrete facilitator of the utilization of waste heat at large scales. In this sense, the operational functionality is described as bottoming cycle that uses the energetic contribution of flue gases as the thermal source to promote energy conversion. Several power cycles such as Rankine, Kalina, Organic Rankine (ORC), and Brayton have been proposed in the literature to conceptualize a waste heat recovery system from a primary energy source (Valencia et al., 2020). Moreover, thermodynamic modeling emerges as an essential tool to unravel the feasibility of energy systems from a techno-economic perspective since it identifies the operational parameters that increase energy efficiency, maximize net power output, and reducing exergy destruction (Orozco et al., 2019; Duarte et al., 2017; Mouaky and Rachek, 2020).

One of the important aspects of the operation of power cycles is the appropriate selection of the working fluid. For example, the working fluid variety in ORC applications is extensive but they commonly represent an environmental hazard and the adverse feasibility in high energy sources is a concrete limitation (Alibaba et al., 2020). In contrast, Carbon Dioxide (CO_2) has demonstrated enormous advantages while implemented in Brayton cycles such as low toxicity index and inflammability, low capital cost, and most importantly the adaptability to operate with supercritical conditions (32°C at 3.4 kPa) compared to other fluid such like water (374°C at 22MPa) (Pacheco et al., 2018). The last pattern enables to design of components with less complexity and size which reflects on improving compatibility (Orozco et al., 2019; Chu et al., 2019).

Precisely, Supercritical CO_2 Brayton Cycles (SCBC) has been implemented in several applications demonstrating its versatility with a wide range of energy sources. Vasquez et al, (2015) found that the SCBC cycle maintains high energetic efficiencies (>50%) for concentrated solar power applications which demonstrates the efficacy of this energy conversion system. The authors used Python as the computational modeling environment and the optimization was based on the Sequential Least SQuares Programming (SLSQP). On the other hand, exergy analysis is an important mechanism to compare the quality of energy of every component of the system while characterizing key design aspects to improve the overall conversion efficiency (Diaz et al., 2017). Marchionni et al. (2019) implemented a complete analysis of different SCBC configurations for WHR applications based on energy, exergy, and economic perspectives. In this study, Matlab® software was implemented as the modeling tool due to the simplicity and robustness within the calculations and optimization tasks.

Overall, based on the literature review there is concrete progress towards the implementation and optimization of power cycles that contribute to WHR systems. However, the amount of published research condensing the research trends of WHR systems is significantly reduced. A few examples can be found in the literature. Yu et al. (2021) examined the main characteristics of supercritical Brayton cycles according to the emerging trends and developments in this topic. The study concluded that the U.S lead the investigation in Brayton cycles, followed by China, whereas the main contributions of published articles centered on new configuration proposals and integration in power plants such as solar and nuclear applications. Moreover, the authors revealed that the average citation margin in this field is 13.45. However, the main drawback of this investigation is the low spectrum of the analysis as it only analyzed a database of 774 articles. Similarly, Sultan et al. (2021) performed a recent survey on CO_2 power technologies while relating scientific research mappings. The main contribution of this study was the identification of the increased attention of the design of heat exchangers and the implementation of optimization methodologies. In general, most of the studies dealing with research trends in WHR technology center on a specific topic such as Brayton cycles or ORC cycles. Therefore, there is a pressing need to close the knowledge gap immersed in the current state of WHR technologies from a global perspective.

The main contribution of the investigation is to describe the main trends immersed in WHR technologies in the last decade. The study implements a complete bibliometric characterization to accurately measure research impact indications that serve as a robust tool to create a comprehensive framework in the investigation field. The incorporation of technical aspects about the energy potential of a great variety of energy sources emerges as a novel aspect from former research. Therefore, this investigation contributes to close the knowledge gap associated with the role of WHR technologies. This paper is structured as follows: Section 2 describes the main parameters of the bibliometric analysis and research impact metrics. Section 3 displays the core findings of the investigation and critically discusses the results. Finally, Section 4 provides the conclusive remarks, limitations, and oncoming perspectives in this field.

2. METHODOLOGY

The section describes the main characteristic of the bibliometric analysis performed in WHR trends in the timeline of 2010-2020. Accordingly, the database was extracted from the SCI-Expanded online version of Thomson Reuters Web of Science, where the filter by title was used to search the following keywords: "Bottoming cycle OR waste heat recovery OR Energy Recovery OR Cogeneration OR Poligeneration OR Trigeneration OR combined heat and power OR energy conversion system OR Waste heat to Power OR power cycles OR Power Generation." The software used to process the WoS files (Web of Science) was HistCite TM as it provides historical maps of bibliographic collections resulting from searches of subjects, authors, institutional journals, or sources in the ISI Web of Science. The software generates chronological historiographies that highlight the most cited works in the recovered collection; other listings include classifications by authors, journals, institutions, countries, cited documents, and keywords (Yonoff et al., 2019). Moreover, the database processing and analysis of scientific results, subject categories, journals, authors, countries, and institutes were processed via Microsoft Excel 2020 and Grapher® (Figure 1).

3. RESULTS AND DISCUSSION

3.1. Research Output

According to Figure 2, the number of articles related to WHR technologies presented a sharp and constant rise since 2010. In contrast, the number of citations in this area is reducing significantly in the last 5 years. Remarkably, the highest number

Figure 1: Methodology flowchart

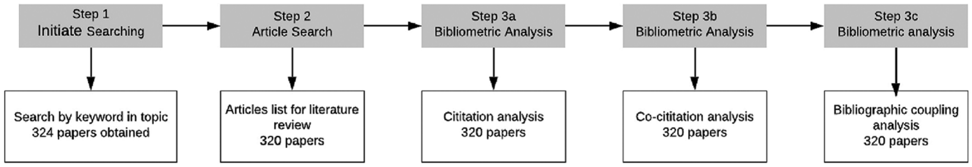
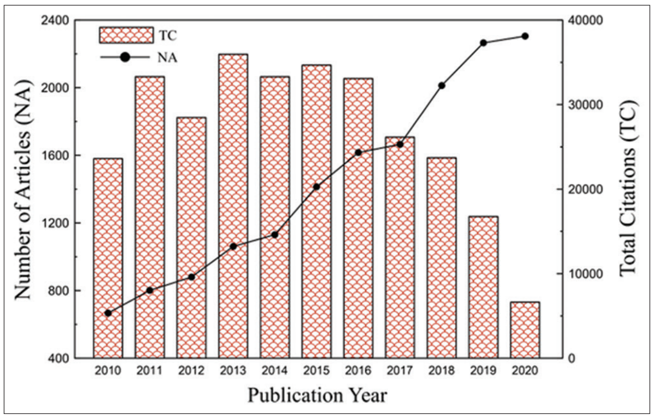


Figure 2: Distribution of bibliometric records



of citations occurred in 2013 with nearly 2200, whereas in 2020 this amount did not exceed 800.

This trend could be associated with a transitional state of this field to a more complex characterization of multigeneration systems that comprise cogeneration (WHR), trigeneration, and multigeneration units. Therefore, one might assume that WHR technology has been immersed in a wider research cluster that still deals with WHR systems, which is in line with the magnification of articles that contain this topic. Table 1 summarizes the bibliometric distribution.

The characterization of the type of document from the database becomes essential to understand the trends immersed in the publication of this field, as well as the interest of readers and publishers. Accordingly, Table 2 displays the distribution of the publication in the database according to the document type. Notice a new parameter is introduced in the description section (TC/NA) that represents the publication density.

Based on the results, the original article submissions represent nearly 86% of the total submissions in the database, followed by review papers. Accordingly, in the last decade, more than 14,000 articles remain available online, representing the largest citation mark from the batch with around 245,000 citations in total. Review papers overcome more than 660 documents that are 21 times less than original articles. Notably, the citation density of review articles (54.82) is at least 30% higher than original article submissions. The latter demonstrates that the review articles feature high-citation marks per unit, which can be associated with the wide content characteristics that are driven to condense relevant information in the topic, thus fostering increased attention of occasional readers and researchers. Moreover, proceeding papers represent the third place in document production and present higher citation density than articles, which demonstrates the relevance of such conferences to create connections within research units and academics.

Table 1: Bibliometric distribution metrics

Year	NA	TC
2010	667	23606
2011	801	33306
2012	880	28468
2013	1061	35955
2014	1131	33300
2015	1414	34668
2016	1616	33079
2017	1665	26147
2018	2013	23706
2019	2265	16762
2020	2305	6635

Table 2: Bibliometric distribution

Document Type	Documents	Percent	TC	TC/NA
Article	14567	86.4	245448	16,85
Proceedings Paper	750	4.4	12964	17,29
Review paper	669	4.0	36676	54,82
Editorial Material	185	1.1	387	2,09
Article; Early Access	184	1.1	77	0,42
Correction	94	0.6	207	2,20
Letter	13	0.1	14	1,08
Review; Book Chapter	9	0.1	223	24,78
Book Chapter	2	0.0	20	10,00

Table 3: Top 10 journals in the WHR technology from 2010-2020

No.	Journal	NA	%	TC	TC/year
1	Energy	1151	6.8	31937	4810.58
2	Energy Conversion and Management	964	3.9	22178	4256.50
3	Applied Energy	662	5.7	23801	3793.20
4	Energies	586	1.7	4403	955.07
5	Applied Thermal Engineering	583	3.5	13812	2160.61
6	Renewable Energy	344	2.0	7749	1319.46
7	Renewable & Sustainable Energy Reviews	295	0.7	16363	2287.53
8	Journal of Cleaner Production	284	0.7	4131	1051.99
9	International Journal of Hydrogen Energy	257	1.0	4391	718.00
10	International Journal of Energy Research	184	0.3	1642	273.29

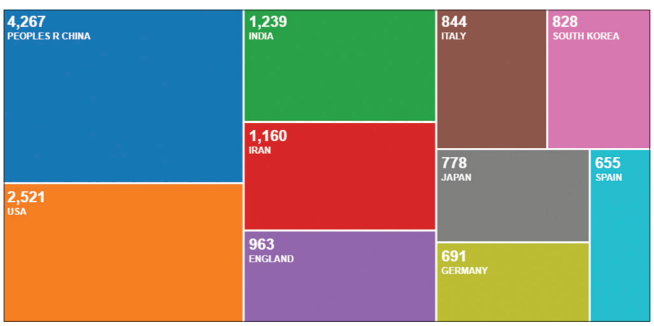
Consequently, it is important to examine the performance metrics of the different journals in terms of bibliometric distribution, as shown in Table 3.

Based on the results of Table 3, the journal “Energy” features both the highest number of articles (1151) and citation margin (4810 TC/year). The second contributor to the number of articles correspond to “Energy Conversion and Management” with more than 900 publications, however, the citation index of the journal “Applied Energy” is 2.2% higher. The latter demonstrates the impact factor of this journal in this research field that reaches 5.7% of the database analyzed. Interesting a journal that specialized in hydrogen technologies is placed in the ninth position, which elucidates the links of both WHR and hydrogen fields. In fact, future predictions point that this trend will increase since the next generation of polygonation units (which included WHR technologies) is increasingly perusing the incorporation of hydrogen production within the useful commodities. Once again, a journal that focuses on review papers (seventh position) features a higher citation index than other journals that incorporates more publications. This behavior supports the importance of review papers for the continuous development and state-of-the-art characterization in a research field (Table 4).

Table 4: Top 10 author publications in the WHR technology from 2010-2020

No.	Main author/Year/Journal	CT	%
1	Bejan et al., 1996, Thermal Design Optimization	5400	2.6
2	Chen et al., 2010, Renewable Sustainable Energy Reviews	1495	1.3
3	Quoilin et al., 2013, Renewable Sustainable Energy Reviews	1340	1.2
4	Saleh et al., 2007, Energy	1401	1.2
5	Logan et al., 2006, Environmental Science and Technology	5520	1.1
6	Bao et al., 2013, Renewable Sustainable Energy Reviews	1207	1.1
7	Tchanche et al., 2011, Renewable Sustainable Energy Reviews	1192	1.1
8	Hung et al., 1997, Energy	1155	1.0
9	Dai et al., 2009, Energy Conversion and Management	874	1.0
10	Wang et al., 2011, Energy	695	0.9

Figure 3: Top ten countries in WHR technologies



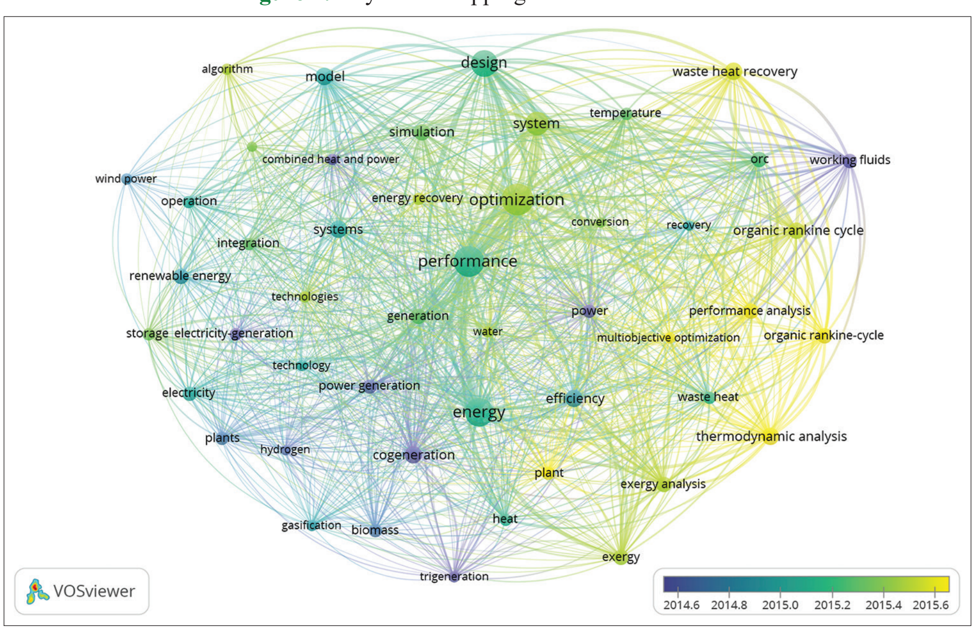
Based on the results, the most relevant document corresponds to thermal design optimization which states the basics of thermoeconomics modeling while involving a vast variety of WHR systems. Notice that in the top 10 distribution the journal Renew Sustainable Energy Reviews contains four documents, which demonstrates the relevance of review papers for interested readers. Subsequently, Figure 3 displays the main countries that support research involving WHR technologies.

Based on the distribution map presented in Figure 4, China is significantly leading the research clusters around WHR progress with more than 4,000 documents in the database. The near competitor in terms of presence in the field is the U.S with more than 2,500 which represents 59% of the presence of China. England represents the most significant contributor in this field in Europe with 963 publications in the database.

On the other hand, Figure 4 assists in evaluating the association of keywords within the database analyzed. Notice that the colors are related to the association strength within the list of keywords.

According to the results, it can be highlighted that the keyword "waste heat recovery" presents intensive correlation (2015.6) to "organic ranking cycle," "thermodynamic analysis," "algorithm," and "plant." The aforementioned can be associated with the numerous applications in power plants that integrated WHR systems using ORC and therefore the thermodynamic modeling via advanced algorithms has paved the consolidation of techno-economic characterization. In contrast, a less correlation strength

Figure 4: Keywords mapping of the WHR database



can be seen for keywords such as "hydrogen," "trigeneration," "biomass," "gasification" and "electricity generation" which is in agreement with the evolution of WHR (cogeneration) field into a more complex concept of multigeneration units that promote the diversification of the useful products of an energy system.

4. CONCLUSIONS

This investigation reports the bibliometric analysis of the WHR field between 2010 and 2020. The study implements advanced methodologies to gather a wide database while identifying the main trends and research perspectives on the topic.

In general, it can be concluded that the WHR topic has been extensively studied in the last decade with more than 14,000 articles with a citation margin of more than 16.2 per year. Interested readers should stress on available information on the journals "Energy" and "Energy Conversion and Management," which represents wide acceptance in the audience. Also, the study identified that review papers overcome the most cited documents per unit, despite not being the most published type of document (Research article). The latter can be associated with the pressing need for new researches to obtain condensed information on a specific topic.

On the other hand, China is leading the global citations and publication in this field, followed by the U.S. Moreover, the keyword association demonstrated that ORC and Brayton technologies overcome the vast majority of publications of the database. Also, it was identified that keywords like hydrogen, trigeneration, and energy storage features increased attention in the WHR field. The latter demonstrates that the WHR field is experiencing a transitional state to multigeneration units that combine cogeneration (WHR) and other useful commodities. This pattern is in agreement with the reduction of citation of WHR topic in the last 5 years.

In conclusion, WHR technologies have contributed to close the knowledge gap regarding power cycle proposals, turbomachinery, heat exchangers, among others. However, the demanding necessity of efficient energy management has accelerated the consolidation of advanced multigeneration units.

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