Waste heat recovery research – a systematic bibliometric analysis (1991 to 2020)

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Abstract

Human usage of non-renewable energy resources has caused many environmental issues, which include air pollution, global warming, and climate irregularities. To counter these issues, researchers have been seeking after alternative renewable energy sources and ways to manage energy more efficiently. This is where energy recovery technologies such as waste heat recovery (WHR) come into play. WHR is a form of waste to energy conversion. Waste heat can be captured and converted into usable energy instead of dumping it into the environment. In the more recent years, the WHR research field has gained great attention in the scientific community as well as in some energy-intensive industries. This article presents a bibliometric overview of the academic research on WHR over the span of 30 years from 1991 to 2020. A total of 5682 documents from Web of Science (WoS) have been retrieved and analyzed using various bibliometric methods, including performance analysis and network analysis. The analyses were performed on different actors in the field, i.e., funding agencies, journals, authors, organizations, and countries. In addition, several network mappings were done based on co-citation, co-authorship, and co-occurrences of keywords analyses. The research identified the most productive and influential actors in the field, established and emergent research topics, as well as the interrelations and collaboration patterns between different actors. The findings can be a robust roadmap for further research in this field.

Keywords

Bibliometrics · Energy efficiency · Energy recovery · Waste heat recovery · Waste heat utilization · Waste to energy

Introduction

Human civilization is highly dependent on energy. Our non-renewable energy resources, such as fossil fuels, are limited and will be depleted soon. Its high consumption rate has led to many serious environmental issues. Troubling environmental situations in many countries have caused the governments to embrace sustainable development as to avoid compromising the state of future generations (Mendez-Picazo et al. 2021). It has become a major concern for many countries to use energy efficiently and develop in a sustainable way (Dabbous and Tarhini 2021). It is also found that the government’s initiatives and policies are the major driving force for private sectors to implement good environmental practices (Tiago et al. 2021).

Despite the efforts and initiatives, the energy resources are still not utilized efficiently and have many rooms for research and improvements. About thirty percent of total global energy consumption is attributable to the industrial sector, with up to fifty percent of the energy ending up wasted in the form of heat (Omer et al. 2020). As countermeasures, researchers and practitioners have been looking into the use of renewable energy sources as well as methods to manage energy more efficiently. This is the landscape where energy recovery technologies such as waste heat recovery...
recovery (WHR) come into play. Waste heat is the energy that is generated in a certain process and wasted or dumped into the environment instead of being put to practical use (Jouhara et al. 2018). WHR technologies harvest waste heat and convert it into usable energy. Examples of WHR system includes organic Rankine cycle (ORC), steam Rankine cycle (SRC), turbo compound (TC), and thermoelectric generators (TEG).

These technologies have received wide attention due to their importance in reducing environmental impacts and achieving higher energy efficiency of a system. Each of them has been evaluated in various angles on their applications in WHR. For instance, Shu et al. 2014a used a multi-approach evaluation system to evaluate ORC in energy, exergy, and economy viewpoints, while Tian et al. (2015) compared the performance of segmented TEG and traditional TEG for WHR of diesel engine. On the other hand, different WHR systems have been compared against each other in different applications. As an example, Nemati et al. (2017) did a comparison between ORCs and Kalina as a bottoming cycle for waste heat recovery from a cogeneration system. Furthermore, defining the operating conditions or variables of a system that can achieve the highest performance of a system is very important as well. These include the selection of working fluids (Wang et al. 2011a), the operating pressures and temperatures (Pierobon et al. 2013), and other variables.

There are some reviews done on the various WHR technologies and systems. To name a few, H. Chen et al. (2010) reviewed on the various ORC systems in converting waste heat into electrical power, as well as selection criteria of potential working fluids; Lecompte et al. (2015) did an extensive review on different ORC infrastructures; Champier (2017) demonstrated the use of TEG in both industry and domestic uses. More recently, Jouhara et al. (2018) presented a comprehensive summary on the state of the art WHR technologies as well as their applications.

Although the articles mentioned above have presented reviews on some aspects of the WHR technologies, a critical examination of the research dynamics in the WHR research field as a larger subject is still lacking in the scientific literature. Moreover, it is important to classify the publications in a specific field, for instance, WHR, to have a clear view of the field’s research trends and advances (Gaviria-Marin et al. 2019). It is also believed that following rapid scientific research development, a bibliometric analysis which focuses on the quantitative evaluation of publications of different actors in the field can be used to analyze the research dynamics (Wong et al. 2021).

This research aims to fill in such a research gap through examining the global publication landscape of WHR research from 1991 to 2020 based on a bibliometric analysis of 5649 publications extracted from the Web of Science (WoS) database. To the best of the authors’ knowledge, this is the first bibliometric study on WHR research in literature. This paper could provide readers with a complete overview of WHR research over the past thirty years, insights on current research interests, and potential directions for future bibliometric research in WHR as well as other fields.

The remainder of the paper is organized as follows. “Methodology” presents the methodology used in publication search, data extraction, and analysis. “Results and Discussion” displays the general publication and citation trend of WHR publications. Then, performance bibliometric analyses are presented based on various actors, which include funding agencies, journals, authors, organizations, and countries. Next, network analyses have been done based on co-citation, co-authorship, and keyword co-occurrence. Lastly, “Conclusions” summarizes the results, along with some limitations of the research, as well as future research opportunities.

### Methodology

The methodology used in this study was developed based on the works by Gaviria-Marin et al. (2019) and Wong et al. (2021) with modifications. Although there are several databases available, this paper only utilizes the bibliographic records obtained from the Web of Science (WoS) Core Collection. WoS is one of the most elaborate citation indexing services for scientific and scholarly research (Wong et al. 2020). WoS Core Collection contains over 21,100 peer-reviewed, high-quality scholarly journals published worldwide in over 250 disciplines, including engineering, sciences, social sciences, and humanities. The articles listed in WoS are indexed explicitly. This has enabled researchers to observe the flow of ideas and research directions based on time, geographical locations, institutions, and disciplines (Joseph et al. 2018). Thus, WoS has been widely recognized by researchers as the most reliable data source for bibliometric analysis and its high-quality standards (Merigo et al. 2015; Peng et al. 2018).

In June 2021, an advanced search was made in WoS Core Collection using the following search string: TS = (“waste heat recovery” OR “recovery of waste heat” OR “waste heat utilization” OR “utilization of waste heat”), and a time span from 1991 to 2020. Asterisks were used as a wild card to include both the words “utilization” and “utilisation” which are common in publications (Wong et al. 2021). The search string was designed to retrieve publications which can provide insights on

1. publication landscape and citation trend,
2. the top-cited publications,
3. the most productive and influential funding agencies, journals and proceedings, authors, organizations, countries, and
4. the focuses of researchers in the WHR research field.

The search retrieved 5682 documents that fulfilled the search criteria from WoS Core Collection. To refine the search results, only articles, reviews, and conference proceedings were included in the analysis, and these are collectively termed “publications” in this study. Only these publications were considered because they provide original findings on the field’s research (Xing et al. 2019). Consequently, the publications have been narrowed down to 5649 documents. Readers should be noted that the search results might change over time. Full records of all the publications, including the titles, abstracts, authors, keywords, cited references, among other contents, were retrieved and exported from WoS into “.txt” format for further bibliometric analysis.

The data analysis procedure in this study is divided into two stages, which are bibliometric performance analysis and network analysis. First, a general publication and citation trend are established based on the number of publications and citations of each year. Then, the most influential publications have been identified using the total citation as the indicator. A timeline network map was created using CitNetExplorer software to show the citation relationships. Next, bibliometric performance analyses have been done on different actors in the field, including funding agencies, journals and proceedings, authors, organizations, and countries. These analyses were done using a wide range of indicators, including the number of publications and citations, citation ratio (citations/publication), and h-index. The h-index is used as the main indicator to rank the different actors because it is gauging both the productivity and influence levels of a subject. It combines the number of publications and number of citations into a single indicator. For a subject that has an h-index equal to N, it has N publications which received at least N citations (Hirsch 2005). In addition, the dimension of temporality has been included to illustrate the evolution of WHR research over time. The 30 years were broken down into 6 quinquenniums (i.e., Q1: 1991–1995, Q2: 1996–2000, Q3: 2001–2005, Q4: 2006–2010, Q5: 2011–2015, Q6: 2016–2020).

In the next stage, network analyses have been done to demonstrate how different entities in WHR research are related to one another. The objective of this procedure is to show the structural and dynamic aspects of scientific research (Cobo et al. 2012). Co-citation analysis is to study the relationship structure in WHR research using pairs of documents that are commonly cited together. Co-authorship analysis is to study the collaboration relationships among the subjects. Lastly, keyword co-occurrence analysis is used to illustrate the trends and focuses of the research field over time. In this research, co-citation analyses have been done on publication, journal, and author levels, co-authorship analyses have been performed on organization and country levels, whereas analyses of keyword co-occurrences have been performed on different time frames (i.e., 1991–2020, 1991–2000, 2001–2010, and 2011–2020).

The advancement of computer software has allowed network analysis to be perfected in evaluating and visualizing the structures and networks of a field of research. There are various academic software tools available for the purpose of network analysis, including SciMAT (Cobo et al. 2012), VOSviewer (van Eck and Waltman 2010), CiteSpace II (Chen 2006), and IN-SPIRE (Wise 1999). VOSviewer has been chosen to generate the network mappings.

Results and discussions

In this section, first, the general publication and citation trends of the WHR research field are presented. Then, it is followed by bibliometric performance analyses of the different actors, including publications, funding agencies, journals and proceedings, authors, organizations, and countries. Lastly, it will be the co-citation, co-authorship, and keyword co-occurrence analyses. Note that the abbreviations used in the tables are defined in Appendix 1.

General publication and citation trends

The first documented WHR concept in the WoS database was published in the 1970s. A few pioneering works in the field include “Lead Technology as a New Means of Waste Heat Recovery” (Vollhard 1970), “Perspectives for Waste Heat Recovery by Means of Organic Fluid Cycles” (Angelino and Moroni 1973), and “Waste-Heat Utilization” (Nichols 1973). Initially, the WHR topic did not receive much attention from researchers; this can be seen from the relatively low number of publications (1 to 13 each year) from 1970 to 1990. There was a total of 120 publications over the 21 years, an average of 5.7 publications per year.

It should be noted that only documents published between 1991 and 2020 were considered in this study. Figure 1 shows the evolution of publications related to the WHR field over the past 30 years. In this figure, the blue bars indicate the overall number of publications per year in the WoS. The green bars show the evolution of research articles. The yellow bars show the evolution of proceeding papers. Finally, the red bars represent the evolution of review papers. Over the 30-year period, the most published type of document is the research article (4198), followed by proceedings paper (1502) and review (220).
According to Fig. 1, a slow but steady trend has been observed for the first 15 years, from 14 publications in 1991 to 25 publications in 2005. In the last 15 years, however, the WHR topic has received notable attention from researchers and has grown significantly. This is clearly shown by the rise in the annual publications, from 35 in 2006 to 831 in 2020. While the actual driving force behind the dramatic increase in publications such as in 2017 is not known, in the researchers’ opinion, there are several potential reasons for the growth of WHR publications. First, in developed countries, there are these upward trends in environmental protection and tendencies toward sustainable development (Ziółkowski et al. 2017). One of the ways to attain those goals is by converting industrial waste heat into electricity (Hung et al. 1997). Second, an increasing number of researchers worldwide have been highlighting the importance of WHR as an enormous opportunity to reduce industrial energy costs, increase energy efficiency of various industry sectors, and reduce emissions and waste of primary sources and its associated environmental impacts (Jiménez-Arreola et al. 2018; Woolley et al. 2018). Third, an increasing number of journals related to the research topic have emerged, including but not limited to Energy, Energy Conversion and Management, Applied Thermal Engineering, and Applied Energy. Lastly, the spike in annual publications is also driven by policies at the country level as well as the availability of research funding for the field of research. These will be further discussed in the subsequent subsections.

An interesting observation from Fig. 1 is the obvious decrease in the number of proceedings in 2020. This is likely to be caused by the Covid-19 outbreak in the year 2020, resulting in lesser participants in conferences. However, the total number of articles published is unaffected by the pandemic and continued to grow.

Next, to show the temporal evolution of WHR research, the 30-year period is broken down into 6 quinquenniums (i.e., Q1: 1991–1995, Q2: 1996–2000, Q3: 2001–2005, Q4: 2006–2010, Q5: 2011–2015, Q6: 2016–2020). The publication data are organized based on the quinquennium and are presented in Table 1. Throughout Q1 to Q6, the most published type of document is consistently the research article, followed by proceedings paper and review. In addition,

### Table 1  WHR publications based on quinquenniums

| Q   | TP (%)        | Increment compared with the previous quinquennium | NoP based on document types |
|-----|---------------|--------------------------------------------------|----------------------------|
|     |               |                                                  | Article | Proceeding | Review |
| Q1  | 46 (0.81%)    | -                                                | 41      | 9          | 1      |
| Q2  | 93 (1.65%)    | 102%                                             | 60      | 42         | 1      |
| Q3  | 133 (2.35%)   | 43%                                              | 85      | 59         | 2      |
| Q4  | 326 (5.77%)   | 145%                                             | 194     | 159        | 9      |
| Q5  | 1422 (25.17%) | 336%                                             | 953     | 469        | 52     |
| Q6  | 3629 (64.24%) | 155%                                             | 2865    | 764        | 155    |

Q, quinquennium; TP(%), total publication in the quinquennium (percentage in total publication); NoP, number of publications
Table 1 also shows the increment of the total publications in a period compared with its previous quinquennium. The greatest leap lies in between Q4 and Q5, where there is a 336% increment.

Furthermore, to highlight the importance and influence of the WHR research field, the sum of citations per year is shown in Fig. 2. It should be noted that the number of citations (11,909) in 2021 is only until June 2021. The analyzed publications have been cited 110,411 times up to June 2021, with an average of 19.55 citations per publication. The citations consist of 30,530 (27.65%) self-citations and 79,881 (72.35%) without self-citations. The h-index as per calculated by WoS for the analyzed publications is 120. It means that in these publications, there are 120 publications that have each been cited at least 120 times. There are a total of 46,996 citing articles that have cited one or more of the items in this report. The increment in the yearly number of citations indicates the increasing interest from the scientific community.

Next, the citation received by publications in the WHR field can be evaluated by looking at the general citation structure. Table 2 presents the general citation structure of all the analyzed publications. These investigations are classified based on several thresholds related to the number of citations. Accordingly, Table 2 shows that only 11 publications (0.19%) have received at least 500 citations, 122 publications (2.16%) have received at least 120 citations, 4669 publications (82.65%) have been cited at least once, and there are 980 publications (17.35%) received 0 citations.

### Bibliometric performance analyses of WHR research

#### The most influential publications

Over the 30 years, many influential publications have been published. The most straightforward method to identify them is by the number of citations received (Merigo et al. 2015). It reflects the influence, popularity, and attention received by the scientific community (Gaviria-Marin et al. 2019). The 50 most-cited WHR publications are shown in Table 3. The data was extracted from the WoS database. It should be noted that the list only includes articles, reviews, and proceedings from the database and might exclude some works that are highly cited. According to Table 3, the 3 most-cited and influential publications are Pei et al. (2011a), (2012), and Quoilin et al. (2013).

As the top WHR publication, Pei et al. (2011a) demonstrated that by tuning the doping and composition, the convergence of many valleys can be directed in bulk material and resulting in a high Seebeck coefficient and high electrical conductivity. Next, in “Band Engineering of Thermoelectric Materials, Pei et al. (2012) focus on the strategies to manipulate the electronic and atomic structural features of a thermoelectric material to improve its thermoelectric quality. On the other hand, Quoilin et al. (2013) are one of the earlier reviewers on ORC systems, their applications, costs, and technological constraints.

At first glance, some publications in Table 3 might not seem to be related to WHR research. Take the publication “Modeling of simple hybrid solid oxide fuel cell and gas turbine power plant” as an example. Even though a fuel cell
| No. | Title (authors, year)                                                                                     | Journal                                           | TC   |
|-----|-----------------------------------------------------------------------------------------------------------|---------------------------------------------------|------|
| 1   | Convergence of electronic bands for high performance bulk thermoelectrics (Pei et al. 2011b)              | Nature                                            | 2187 |
| 2   | Band Engineering of Thermoelectric Materials (Pei et al. 2012)                                          | Advanced Materials                                | 816  |
| 3   | Techno-economic survey of Organic Rankine Cycle (ORC) systems (Sylvain Quoilin et al. 2013)              | Renewable & Sustainable Energy Reviews            | 769  |
| 4   | A review of working fluid and expander selections for organic Rankine cycle (Bao and Zhao 2013)        | Renewable & Sustainable Energy Reviews            | 737  |
| 5   | Low-grade heat conversion into power using organic Rankine cycles - A review of various applications     | Renewable & Sustainable Energy Reviews            | 667  |
| 6   | Enhancement of Thermoelectric Figure-of-Merit by a Bulk Nanostructuring Approach (Lan et al. 2010)      | Advanced Functional Materials                     | 626  |
| 7   | Preparation and thermoelectric properties of semiconducting Zn4Sb3 (Caillat et al. 1997)               | Journal of Physics and Chemistry of Solids        | 547  |
| 8   | Effect of working fluids on organic Rankine cycle for waste heat recovery (Liu et al. 2004)            | Energy                                            | 539  |
| 9   | Organic Thermoelectric Materials: Emerging Green Energy Materials Converting Heat to Electricity          | Advanced Materials                                | 528  |
| 10  | Parametric optimization and comparative study of organic Rankine cycle (ORC) for low grade waste heat    | Energy Conversion and Management                   | 513  |
| 11  | Fluid selection for a low-temperature solar organic Rankine cycle (Tchanche et al. 2009)                | Applied Thermal Engineering                       | 511  |
| 12  | Heat transfer characteristics of thermal energy storage system using PCM capsules: A review              | Renewable & Sustainable Energy Reviews            | 499  |
| 13  | Achieving better energy-efficient air conditioning - A review of technologies and strategies             | Applied Energy                                    | 445  |
| 14  | Thermo-economic optimization of waste heat recovery Organic Rankine Cycles                              | Applied Thermal Engineering                       | 443  |
| 15  | Study of working fluid selection of organic Rankine cycle (ORC) for engine waste heat recovery          | Energy                                            | 423  |
| 16  | Thermoelectric materials for space and automotive power generation (Yang and Caillat 2006)            | MRS Bulletin                                      | 403  |
| 17  | Latent heat storage materials and systems: A review (Sharma and Sagara 2005)                           | International Journal of Green Energy            | 394  |
| 18  | High thermoelectric performance by resonant dopant indium in nanostructured SnTe (Zhang et al. 2013a)    | Proceedings of the National Academy of Sciences   | 392  |
| 19  | Thermoelectric generators: A review of applications (Champier 2017)                                    | Energy Conversion and Management                   | 391  |
| 20  | Waste heat recovery of organic Rankine cycle using dry fluids (Hung 2001)                              | Energy Conversion and Management                   | 388  |
| 21  | High Thermoelectric Performance in PbTe Due to Large Nanoscale Ag-2 Te Precipitates and La Doping       | Advanced Functional Materials                     | 378  |
| 22  | Broad temperature plateau for thermoelectric figure of merit ZT > 2 in phase-separated PbTe0.75S0.3     | Nature Communications                             | 374  |
| 23  | An examination of regenerative organic Rankine cycles using dry fluids (Mago et al. 2008)              | Applied Thermal Engineering                       | 372  |
| 24  | Performance analysis and optimization of organic Rankine cycle (ORC) for waste heat recovery            | Energy Conversion and Management                   | 372  |
| 25  | Nanostructured Bulk Silicon as an Effective Thermoelectric Material (Bux et al. 2009)                  | Advanced Functional Materials                     | 367  |
| 26  | Experimental study and modeling of an Organic Rankine Cycle using scroll expander                        | Applied Energy                                    | 352  |
| 27  | Review of organic Rankine cycle (ORC) architectures for waste heat recovery                            | Renewable & Sustainable Energy Reviews            | 331  |
| 28  | Energetic and economic investigation of Organic Rankine Cycle applications (Schuster et al. 2009)      | Applied Thermal Engineering                       | 324  |
| 29  | Oxide Thermoelectric Materials: A Nanostructuring Approach (Koumoto et al. 2010)                      | Annual Review of Materials Research               | 312  |
| 30  | Lead telluride alloy thermoelectrics (La Londe et al. 2011)                                          | Materials Today                                   | 303  |
is not a WHR technology, the steam needed in the reforming process can be obtained by using the waste heat from the fuel cell stack to vaporize the feedwater (Chan et al. 2002). Therefore, the publication is indeed related to WHR research and has been cited by many other WHR research articles.

Next, to visualize the relationships between the most-cited publications, a timeline network map of them is created using CitNetExplorer. This is shown in Fig. 3. The vertical dimension represents time. The publications are placed in the vertical dimension based on their publishing year. On the other hand, the horizontal dimension is utilized to provide an indication of the relatedness of publications. Based on their citation relations, publications are positioned close to each other in the horizontal dimension if they are strongly related to each other. A citing publication is always located below the layer of the corresponding cited publication, and they are connected by a line. To make the timeline map clearer, a citation link between two publications is not shown if the publications are also connected through citation links via intermediate publications.

The citation relationships of the 50 most influential publications can be observed in Fig. 3. There are a few pioneering publications which have been cited by many publications along the years. Among them include Caillat et al. (1997), Rowe and Min (1998), Hung (2001), Liu et al. (2004), Chen et al. (2006), Wei et al. (2007), Dai et al. (2009), and Pei et al. (2011b).

### Table 3 (continued)

| No. | Title (authors, year)                                                                                                                                  | Journal                                    | TC  |
|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------|-----|
| 31  | Evaluation of thermoelectric modules for power generation (Rowe and Min 1998)                                                                        | Journal Of Power Sources                   | 303 |
| 32  | Modeling, experimental study and optimization on low-temperature waste heat thermoelectric generator system (Gou et al. 2010)                    | Applied Energy                             | 302 |
| 33  | "Nanoparticle-in-Alloy" Approach to Efficient Thermoelectrics: Silicides in SiGe (Mingo et al. 2009)                                                    | Nano Letters                               | 296 |
| 34  | Enhanced Thermoelectric Figure of Merit of p-Type Half-Heuslers (Yan et al. 2011)                                                                   | Nano Letters                               | 290 |
| 35  | Dynamic modeling and optimal control strategy of waste heat recovery Organic Rankine Cycles (Quoilin et al. 2011a)                                | Applied Energy                             | 289 |
| 36  | Review of organic Rankine cycles for internal combustion engine exhaust waste heat recovery (Sprouse and Depcik 2013)                              | Applied Thermal Engineering                | 288 |
| 37  | High Performance Thermoelectric Materials: Progress and Their Applications (L. Yang et al. 2018)                                                       | Advanced Energy Materials                  | 270 |
| 38  | Analysis and optimization of the low-temperature solar organic Rankine cycle (ORC) (Delgado-Torres and Garcia-Rodriguez 2010)                         | Energy Conversion and Management           | 265 |
| 39  | On the systematic design and selection of optimal working fluids for Organic Rankine Cycles (Papadopoulos et al. 2010)                              | Applied Thermal Engineering                | 264 |
| 40  | A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities (Ebrahimi et al. 2014) | Renewable & Sustainable Energy Reviews    | 263 |
| 41  | Thermoelectric plastics: from design to synthesis, processing and structure-property relationships (Kroon et al. 2016)                             | Chemical Society Reviews                   | 260 |
| 42  | A comparative study of the carbon dioxide transcritical power cycle compared with an organic rankine cycle with R123 as working fluid in waste heat recovery (Y. Chen et al. 2006) | Applied Thermal Engineering                | 247 |
| 43  | Spin caloritronics (Boona et al. 2014)                                                                                                               | Energy & Environmental Science            | 246 |
| 44  | Material and manufacturing cost considerations for thermoelectrics (Le Blanc et al. 2014)                                                          | Renewable & Sustainable Energy Reviews     | 243 |
| 45  | Renewable and sustainable approaches for desalination (Gude et al. 2010)                                                                            | Renewable & Sustainable Energy Reviews     | 240 |
| 46  | Experimental study on low-temperature waste heat thermoelectric generator (Niu et al. 2009)                                                         | Journal of Power Sources                   | 239 |
| 47  | Modelling of simple hybrid solid oxide fuel cell and gas turbine power plant (S. H. Chan et al. 2002)                                                  | Journal of Power Sources                   | 239 |
| 48  | Technologies to recover exhaust heat from internal combustion engines (Saidur et al. 2012)                                                          | Renewable & Sustainable Energy Reviews     | 235 |
| 49  | A review of thermoelectrics research - Recent developments and potentials for sustainable and renewable energy applications (Zheng et al. 2014)     | Renewable & Sustainable Energy Reviews     | 230 |
| 50  | A mathematic model of thermoelectric module with applications on waste heat recovery from automobile engine (Hsiao et al. 2010)                     | Energy                                     | 227 |

TC, total number of citations received
The publications are assigned into 2 main clusters based on their citation relations. Being in the same cluster means they tend to be closely connected to each other in the citation network. The first cluster from the left, in green color, revolves around the thermoelectric research related to WHR. The second cluster, in blue color, focuses on waste heat recovery technologies and systems. The organic Rankine cycle (ORC) systems being the most studied in the cluster. Note that there are 8 publications on the right side that do not belong to these 2 clusters. They belong to other clusters if all 5649 publications are included in the mapping.

Next, based on the idea of k-cores by Seidman (1983), the core publications in the 5649 publications are identified using the software. The minimum number of citation links parameter is set to be 15 (publications which have at least 15 citation relations with other core publications). This has resulted in a total of 528 core publications. For interested readers, the list of the 528 core publications can be found at this link: https://bit.ly/3hMifs3. However, it should be noted that this is not a definite list of all important WHR publications due to the setting on a minimum number of citation links parameter will affect the total number of core publications. For example, if it has been set as 10, then 1255 core publications would have been identified.

The most productive and influential funding agencies

Adequate funding plays a significant role in sustaining research efforts. There have been a total of 2561 agencies which have funded 3180 publications (56.29% of all publications) from 1991 to 2020. Table 4 shows the top ten most productive funding agencies based on their h-index. H-index is used because it considers both productivity and influence. In the event of a tie, the number of publications is considered. In addition, other information such as total number of citations received, average number of citations per publication, and number of publications throughout the 6 quinquenniums are included in the table as well.

As shown in Table 4, the National Natural Science Foundation of China (NSFC), one of the major funding agencies in China, is identified as the most important funding source for WHR research. Its h-index (56), total citations (16,354), and number of publications (905) are the highest among the agencies. It alone contributed to 16.02% of all publications from 1991 to 2020, which far exceeds the publications funded by the other major agencies.

According to the data obtained from WoS, all the publications in Q1 and Q2 received no funding support. In Q3, NSFC being the only funding agency and there was only 1 publication which received funding. The lack of funding...
can be one of the major reasons for the lower number of publications in 1991–2005.

Following the awareness of the urgencies and benefits of WHR technologies, more and more funding agencies invested in this research field. In Q4, a total of 97 agencies have allocated their funds into WHR research. In this period, the agencies funded 66 publications in total, of which 27 of them were funded by the top ten agencies. As can be seen from Table 1, 326 publications were produced in Q4. Therefore, 20% of the total publications in Q4 are funded by at least 1 agency.

In Q5, out of the 1422 total publications, 706 (49.65%) of them were funded by a total of 650 agencies. The top ten agencies have funded 430 publications (30.24%) themselves. Availability of research funding is an important factor for the extraordinary leap in the total publications in between Q4 and Q5.

Lastly, in Q6, the funding agencies have further increased to a number in 2010. They have funded 2407 publications (66.38%), whereas the top ten agencies have funded 1561 publications (43.05%) out of the 3626 total publications.

In addition, Table 4 also shows the number of publications funded by the top ten agencies collectively through the 6 quinquenniums. Overall, the top ten funding sources contributed to 2019 publications (35.74%). Lastly, the three most-cited publications funded by each of the top ten agencies are listed in Table 5.

### The most productive and influential journals and proceedings

WHR research has been published in a wide range of journals and proceedings. The 5649 analyzed publications were published by a total of 1532 journals and proceedings. Table 6 presents the field’s 10 most productive and influential journals and proceedings. The journals are ranked according to their h-index, which gauges both their productivity and influence. In the event of a tie, the total number of publications is considered. Furthermore, other information such as total number of citations received, average number of citations per publication, impact factor (IF), 5-year impact factor (5Y-IF), and publication trend of each journal are included in the table as well. Both the IF and 5Y-IF are extracted from the Journal Citation Reports published by Clarivate Analytics. These indicators are the average number of times articles from the journal published have been cited in the past two years and past five years, respectively. Generally, a higher impact factor would indicate a journal is of better quality.

According to Table 6, Energy is unarguably the most productive and influential journal in the WHR research field. Energy is a journal in energy engineering and research, with a strong focus on energy analysis, energy modeling and prediction, integrated energy systems, energy planning, and energy management. Its IF score is 7.147, and its 5Y-IF score is 6.845. Within the WHR research field, this journal

### Table 4 Worldwide funding agencies in WHR research

| No. | Funding agencies | h   | TC     | AC   | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | TP (%) |
|-----|------------------|-----|--------|------|----|----|----|----|----|----|--------|
| 1   | NSFC             | 56  | 11,354 | 18.07| 0  | 0  | 1  | 6  | 149| 749| 905 (16.02%) |
| 2   | NBRP             | 50  | 7863   | 36.92| 0  | 0  | 0  | 0  | 116| 97 | 213 (3.77%)  |
| 3   | DOE              | 39  | 5856   | 53.72| 0  | 0  | 0  | 7  | 55 | 47 | 109 (1.93%)  |
| 4   | UKRI             | 30  | 2874   | 21.13| 0  | 0  | 0  | 4  | 17 | 115| 136 (2.41%)  |
| 5   | EPSRC            | 28  | 2499   | 21.36| 0  | 0  | 0  | 4  | 15 | 98 | 117 (2.07%)  |
| 6   | NSF              | 28  | 3889   | 47.43| 0  | 0  | 0  | 4  | 30 | 48 | 82 (1.45%)   |
| 7   | FRFCU            | 27  | 2428   | 15.77| 0  | 0  | 0  | 0  | 22 | 132| 154 (2.73%)  |
| 8   | EC               | 27  | 2750   | 23.91| 0  | 0  | 0  | 2  | 18 | 95 | 115 (2.04%)  |
| 9   | NKRDP            | 17  | 968    | 9.22 | 0  | 0  | 0  | 0  | 0  | 105| 105 (1.86%)  |
| 10  | CPSF             | 17  | 1262   | 15.2 | 0  | 0  | 0  | 0  | 8  | 75 | 83 (1.47%)   |

These acronyms are created for ease of presentation. They might not be the official acronyms of the agencies.

AC, averaged citations; NSFC, National Natural Science Foundation of China (China); NBRP, National Basic Research Program of China (China); DOE, United States Department of Energy (United States); UKRI, UK Research Innovation (United Kingdom); EPSRC, Engineering Physical Sciences Research Council (United Kingdom); NSF, National Science Foundation (United States); FRFCU, Fundamental Research Funds for The Central Universities (China); EC, European Commission (Europe); NKRDP, National Key R&D Programmes (China); CPSF, China Postdoctoral Science Foundation (China)
has the highest h-index (68) and productivity (590 publications). Its productivity contributes to 10.44% of all publications over the 30 years. On the influence side, its WHR publications received 18,205 citations, and the average citation per publication is 30.86.

Ranked at the second place, Energy Conversion and Management (IF = 9.709, 5Y-IF = 8.954) has an h-index of 57. This journal covers research on energy generation, utilization, conversion, storage, transmission, conservation, management, and sustainability. The productivity of this journal is outstanding as well, with 522 publications in WHR research. This is 9.24% of all publications from 1991 to 2020. On the other hand, each of the publications

Table 5 Top-cited publications funded by top ten agencies

| Funding agencies | Title of publications (authors, year) | TC |
|------------------|--------------------------------------|----|
| NSFC             | A review of working fluid and expander selections for organic Rankine cycle (Bao and Zhao 2013) | 737 |
|                  | Modeling, experimental study and optimization on low-temperature waste heat thermoelectric generator system (Gou et al. 2010) | 302 |
|                  | A review of research on the Kalina cycle (Zhang et al. 2012) | 211 |
| NBRP             | Study of working fluid selection of organic Rankine cycle (ORC) for engine waste heat recovery (Wang et al. 2011b) | 422 |
|                  | A review of research on the Kalina cycle (Zhang et al. 2012) | 211 |
|                  | The optimal evaporation temperature and working fluids for subcritical organic Rankine cycle (He et al. 2012) | 204 |
| DOE              | Enhancement of Thermoelectric Figure-of-Merit by a Bulk Nanostructuring Approach (Lan et al. 2010) | 623 |
|                  | High thermoelectric performance by resonant dopant indium in nanostructured SnTe (Zhang et al. 2013b) | 391 |
|                  | High Thermoelectric Performance in PbTe Due to Large Nanoscale Ag-2 Te Precipitates and La Doping (Pei et al. 2011a) | 376 |
| UKRI             | Waste heat recovery technologies and applications (Jouhara et al. 2018) | 174 |
|                  | A review of chemical heat pumps, thermodynamic cycles and thermal energy storage technologies for low grade heat utilization (Chan et al. 2013) | 125 |
|                  | Condensing boiler applications in the process industry (Chen et al. 2012) | 95 |
| EPSRC            | Waste heat recovery technologies and applications (Jouhara et al. 2018) | 174 |
|                  | A review of chemical heat pumps, thermodynamic cycles and thermal energy storage technologies for low grade heat utilization (Chan et al. 2013) | 125 |
|                  | Condensing boiler applications in the process industry (Chen et al. 2012) | 95 |
| NSF              | Enhancement of Thermoelectric Figure-of-Merit by a Bulk Nanostructuring Approach (Lan et al. 2010) | 623 |
|                  | Nanostructured Bulk Silicon as an Effective Thermoelectric Material (Bux et al. 2009) | 363 |
|                  | A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities (Ebrahimi et al. 2014) | 262 |
| FRFCU            | The optimal evaporation temperature and working fluids for subcritical organic Rankine cycle (He et al. 2012) | 204 |
|                  | Application of a low pressure economizer for waste heat recovery from the exhaust flue gas in a 600 MW power plant (Wang et al. 2012a) | 117 |
|                  | A dynamic model for thermoelectric generator applied in waste heat recovery (Gou et al. 2013) | 91 |
| EC               | Analysis and optimization of the low-temperature solar organic Rankine cycle (ORC) (Delgado-Torres and Garcia-Rodriguez 2010) | 265 |
|                  | Thermal energy storage (TES) for industrial waste heat (IWH) recovery: A review (Miro et al. 2016) | 204 |
|                  | Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies (Bruckner et al. 2015) | 191 |
| NKRDP            | Perspectives for low-temperature waste heat recovery (Xu et al. 2019) | 53 |
|                  | Evaluation of surfactant on stability and thermal performance of Al2O3-ethylene glycol (EG) nanofluids (Zhai et al. 2019) | 38 |
|                  | Aiming strategy optimization for uniform flux distribution in the receiver of a linear Fresnel solar reflector using a multi-objective genetic algorithm (Qiu et al. 2017) | 36 |
| CPSF             | ASPEN Plus simulation of coal integrated gasification combined blast furnace slag waste heat recovery system (Duan et al. 2015) | 72 |
|                  | Anisotropic thermoelectric properties of layered compounds in SnX2 (X = S, Se): a promising thermoelectric material (Sun et al. 2015) | 71 |

Acronyms of funding agencies can be found in Table 4.
received 27.43 citations on average, and collectively, they have received a total of 14,316 citations.

On the influential aspect of the journals, four journals stand out with more than 10,000 citations. These journals are Energy, Energy Conversion and Management, Applied Energy, and Applied Thermal Engineering. They are also the top four journals in Table 6. The large number of citations is due to these journals include several highly cited publications. For instances, Energy has 35 publications with at least 100 citations, whereas Energy Conversion and Management has 16, Applied Energy has 22, and Applied Thermal Engineering has 19 of such publications.

Another criterion to analyze is the average citation per publication. A journal that stands out in this is Renewable Sustainable Energy Reviews which is ranked at the fifth place with an h-index of 39. Despite having lower productivity of only 75 publications, its WHR publications received 95.79 citations on average. This indicates that these publications are receiving high attention from other researchers. The IF (14.982) and 5Y-IF (14.916) of the journal also reflect the quality of the journal.

The only proceeding in Table 6 is Energy Procedia, with an h-index of 17. It is an Open Access collection of high-quality conference proceedings published between 2009 and 2019 (it has been discontinued as of 2019), spanning the field of energy science, technology, and engineering. It is a collection of proceedings from several conferences, such as International Seminar on Organic Rankine Cycle Power Systems, International Renewable Energy Storage Conference, International Conference on Advances in Energy Engineering, and International Conference on Sustainable Energy and Resource Use in Food Chains. A total of 215 publications are collected in this proceeding and yield 1517 citations in total.

Next, it would be interesting to look at the evolution of journal publications over the 6 quinquenniums. Energy Conversion and Management and International Journal of Energy Research are the two journals that have been publishing WHR publications since Q1. Two more journals emerged in Q2; they are Applied Energy and Applied Thermal Engineering. Although Energy has the highest rank, its WHR publications only began to appear in Q3. Almost all journals have an incremental publishing trend, except for International Journal of Energy Research which its productivity dropped in Q2 and Q3. Nonetheless, it is important to point out that Energy Conversion and Management is one of the leading journals which has been publishing incrementally along the timeline since Q1 and it is still having the highest productivity in Q6.

Lastly, Table 6 also shows the collective number of publications by all the top ten journals and proceedings through the 6 quinquenniums. Their publications have increased drastically from 5 publications in Q1 to 1865 publications in Q6. As a single entity, their h-index is 104, published 2589 WHR publications, and these publications received a total of 72,023 citations.

### The most productive and influential authors

Since its inception, many researchers have participated and contributed to the WHR field. In total, 11,523 authors have published their research findings throughout 1991–2020. The number of publications of each author can be used to evaluate the productivity of an author. However, this has several limitations, including the length of each publication, quality of the journal, and number of authors per publication (Merigó et al. 2015). Recall that the h-index is a composite indicator that combines both productivity and influence, Table 7 presents the 29 most productive and influential authors based on this indicator. In the event of a tie, the number of publications followed by total citations is considered. Only authors with more than 20 publications

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**Table 6** Top ten journals and proceedings in WHR research

| No. | Journals and proceedings | NoP | h | TC | AC | IF | 5Y-IF | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | TP (%) |
|-----|--------------------------|-----|---|----|----|----|-------|----|----|----|----|----|----|-------|
| 1   | Energy                   | 68  | 18,205 | 30.86 | 7.147 | 6.845 | 0 | 0 | 5 | 15 | 181 | 389 | 590 (10.44%) |
| 2   | Energy Conversion and Management | 57  | 14,316 | 27.43 | 9.709 | 8.954 | 1 | 3 | 7 | 9 | 82 | 420 | 522 (9.24%) |
| 3   | Applied Energy           | 56  | 12,003 | 40.55 | 9.746 | 9.953 | 0 | 2 | 2 | 8 | 69 | 215 | 296 (5.24%) |
| 4   | Applied Thermal Engineering | 52  | 12,580 | 29.19 | 5.295 | 5.175 | 0 | 8 | 14 | 23 | 111 | 275 | 431 (7.63%) |
| 5   | Renewable Sustainable Energy Reviews | 39  | 7184 | 95.79 | 14.982 | 14.916 | 0 | 0 | 0 | 5 | 22 | 48 | 75 (1.33%) |
| 6   | Journal of Electronic Materials | 25  | 2120 | 20.38 | 1.938 | 1.746 | 0 | 0 | 0 | 14 | 48 | 42 | 104 (1.84%) |
| 7   | Energies                 | 23  | 1953 | 9.43 | 3.004 | 3.085 | 0 | 0 | 0 | 0 | 25 | 182 | 207 (3.66%) |
| 8   | Journal of Cleaner Production | 23  | 1545 | 20.33 | 9.297 | 9.444 | 0 | 0 | 0 | 3 | 5 | 68 | 76 (1.35%) |
| 9   | Energy Procedia          | 17  | 1517 | 7.06 | - | - | 0 | 0 | 0 | 1 | 39 | 175 | 215 (3.81%) |
| 10  | International Journal of Energy Research | 13  | 598 | 8.19 | 5.164 | 4.913 | 4 | 3 | 1 | 3 | 11 | 51 | 73 (1.29%) |
|     | Overall                  | 104 | 72,023 | 27.82 | - | - | 5 | 16 | 29 | 81 | 593 | 1865 | 2589 (45.83%) |
and an h-index of more than 10 are included in Table 7. It should be noted that some known authors may not appear in Table 7 because of the predetermined parameters of this research as well as the year of indexing the journals in the WoS (Gaviria-Marin et al. 2019).

On a side note, a problem has been discovered in the current WoS analytics. To illustrate with an example, WoS would take these 6 authors – “Li, Jun” (12 publications), “Li, Jian” (16 publications), “Li, Jing” (6 publications), “Li, Juan” (2 publications), “Li, Jie” (3 publications), and “Li, John” (6 publications) – all as “Li, J.” Consequently, WoS is perceiving “Li, J” a single author who has an h-index of 14 with 43 publications and is among the top ten authors in WoS analysis. As a countermeasure, this analysis is done by manually searching in WoS database using the authors’ full names.

According to Table 7, the author with the best combination of productivity and influence in WHR research is Shu Gequn, with an outstanding h-index of 32. Her topics of research revolve around the analysis and optimization of ORC system applications in the internal combustion engine’s heat recovery system (Shu et al. 2014b, c; Tian et al. 2012; Yu et al. 2013). Shu is also the top producer with 105 publications, contributing to 1.86% of all the WHR publications in 30 years. Total citation received by Shu is the highest as well – 3036 citations to date. Ranked in second place is Tian Hua, who has an h-index of 29. Her productivity (101 publications) and influence (2789 citations) are closely matching Shu’s. As a matter of fact, these top two authors have worked closely together. They have co-authored 98 publications, and this number far exceeds other authors.

Table 7  Most productive and influential authors in WHR research

| NoP | Author (country)          | h   | TC     | AC | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | TP (%)
|-----|--------------------------|-----|--------|----|----|----|----|----|----|----|--------|
| 1   | Shu, Gequn (China)       | 32  | 3036   | 28.9 | 0  | 0  | 0  | 0  | 27 | 80 | 105 (1.86%) |
| 2   | Tian, Hua (China)        | 29  | 2789   | 27.61 | 0  | 0  | 0  | 0  | 20 | 81 | 101 (1.79%) |
| 3   | Yari, Mortaza/Morteza (Iran) | 21 | 1165   | 43.15 | 0  | 0  | 0  | 4  | 10 | 13 | 27 (0.48%) |
| 4   | Zhang, Hongguang (China) | 20  | 1148   | 22.96 | 0  | 0  | 0  | 1  | 19 | 30 | 50 (0.89%) |
| 5   | Haglind, Fredrik (Denmark) | 17 | 971    | 23.68 | 0  | 0  | 0  | 0  | 17 | 24 | 41 (0.73%) |
| 6   | Yang, Fubin (China)      | 17  | 956    | 29.88 | 0  | 0  | 0  | 0  | 10 | 22 | 32 (0.57%) |
| 7   | Dai, Yiping (China)      | 17  | 1773   | 57.19 | 0  | 0  | 0  | 5  | 11 | 15 | 31 (0.55%) |
| 8   | He, Ya-Ling (China)      | 17  | 865    | 27.9  | 0  | 0  | 0  | 0  | 7  | 24 | 31 (0.55%) |
| 9   | Lemort, Vincent (Belgium)| 15  | 2632   | 97.48 | 0  | 0  | 0  | 2  | 10 | 15 | 27 (0.48%) |
| 10  | Wang, Ruzhu (China)      | 14  | 478    | 15.42 | 0  | 0  | 3  | 3  | 1  | 24 | 31 (0.55%) |
| 11  | Li, Xiaoya (China)       | 14  | 510    | 18.21 | 0  | 0  | 0  | 0  | 0  | 28 | 28 (0.50%) |
| 12  | Markides, Christos (England) | 14 | 514    | 19.77 | 0  | 0  | 0  | 0  | 0  | 26 | 26 (0.46%) |
| 13  | Bianchi, Giuseppe (England) | 14 | 401    | 16.04 | 0  | 0  | 0  | 0  | 4  | 21 | 25 (0.44%) |
| 14  | Wang, Enhua (China)      | 14  | 1431   | 59.63 | 0  | 0  | 0  | 1  | 18 | 5  | 24 (0.42%) |
| 15  | Van Den Broek, Martijn (Belgium) | 14 | 1714   | 77.91 | 0  | 0  | 0  | 0  | 8  | 14 | 22 (0.39%) |
| 16  | Yang, Yongping (China)   | 14  | 557    | 25.32 | 0  | 0  | 0  | 0  | 9  | 13 | 22 (0.39%) |
| 17  | Romagnoli Alessandro (Singapore) | 13 | 413    | 12.52 | 0  | 0  | 0  | 0  | 1  | 32 | 33 (0.58%) |
| 18  | Wang, Xuan (China)       | 13  | 425    | 13.71 | 0  | 0  | 0  | 0  | 3  | 28 | 31 (0.55%) |
| 19  | Liu, Chao (China)        | 12  | 721    | 21.85 | 0  | 0  | 0  | 0  | 13 | 20 | 33 (0.58%) |
| 20  | Cipollone, Roberto (Italy) | 12 | 426    | 13.74 | 0  | 0  | 0  | 0  | 6  | 25 | 31 (0.55%) |
| 21  | De Paepe, Michel (Belgium) | 12 | 854    | 38.82 | 0  | 0  | 0  | 0  | 7  | 15 | 22 (0.39%) |
| 22  | Wang, Jiangfeng (China)  | 12  | 1416   | 67.43 | 0  | 0  | 0  | 5  | 9  | 7  | 21 (0.37%) |
| 23  | Yu, Qingsbo (China)      | 11  | 472    | 16.28 | 0  | 0  | 0  | 0  | 6  | 23 | 29 (0.51%) |
| 24  | Zhuge, Weilin (China)    | 11  | 340    | 11.72 | 0  | 0  | 0  | 1  | 7  | 21 | 29 (0.51%) |
| 25  | Zhang, Yangjun (China)   | 11  | 324    | 12     | 0  | 0  | 0  | 1  | 7  | 19 | 27 (0.48%) |
| 26  | Shi, Lingfeng (China)    | 11  | 442    | 17.68 | 0  | 0  | 0  | 0  | 0  | 25 | 25 (0.44%) |
| 27  | Xu, Jinliang (China)     | 11  | 603    | 25.13 | 0  | 0  | 0  | 0  | 11 | 13 | 24 (0.42%) |
| 28  | Liu, Peng (China)        | 11  | 354    | 15.39 | 0  | 0  | 0  | 0  | 2  | 21 | 23 (0.41%) |
| 29  | Pierobon, Leonardo (Denmark) | 11 | 570    | 25.91 | 0  | 0  | 0  | 0  | 13 | 9  | 22 (0.39%) |
| Overall |                      | 65  | 18,549 | 28.54 | 0  | 0  | 3  | 17 | 187 | 443 | 650 (11.51%) |
On the influential aspect, nine authors stand out with more than 1000 citations. They are Shu Gequn, Tian Hua, Yari Mortaza/Morteza, Zhang Hongguang, Dai Yiping, Lemort Vincent, Wang Enhua, Van Den Broek Martijn, and Wang Jiangfeng. Another aspect of analyzing is the average citation per publication. The author with the highest number is Lemort Vincent, with an average of 97.48 citations per publication. This indicates that these publications are receiving high attention from other researchers. Despite only having 27 WHR publications, 5 of them are among the 50 most-cited publications, as recorded in Table 3. Other authors who stand out in this aspect include Van Den Broek Martijn and Wang Jiangfeng, with an average of 77.91 and 67.43 citations per publication, respectively.

In addition, Table 7 also presents the authors’ productivities over the quinquenniums. None of the 29 authors have any publication from 1991 to 2000. Wang Ruzhu is the most veteran author among themselves. He has 3 publications in Q3, and to date, he has produced 31 WHR publications in total. In Q4, 8 new authors started publishing in this research area, among which Dai Yiping and Wang Jiangfeng stand out with 5 publications they co-authored. The following quinquenniums (Q5 and Q6) show a great leap in the number of new authors as well as the number of publications.

The last row of Table 7 summarizes the collective productivity and influence of the 29 authors. Their h-index as a group is 65. Collectively, they have produced 650 publications, which contribute to 11.51% of all the WHR publications. Their publications began in Q3 with only 3 publications and have drastically increased from Q4 to Q6. Their publications have received a total of 18,549 citations, and that is 28.54 citations per publication on average.

The most productive and influential organizations

One of the responsibilities of organizations is promoting the development of a certain research field. Over the past 30 years, the WHR field has slowly become an attractive field of study in many organizations. This section presents the analysis of WHR research performed in different organizations. Top organizations with 50 publications or more are listed in Table 8. They are ranked based on their h-index in this field of research. In the event of a tie in the h-index, the number of publications is considered.

According to Table 8, the most productive and influential organization is the Xi An Jiaotong University, with an h-index of 39. In the second and third places are the Tianjin University and Tsinghua University, with h-indexes of 36 and 35, respectively. Fourth and fifth places are occupied by Chinese Academy of Sciences and Shanghai Jiao Tong University, both with an h-index of 25.

In terms of productivity, Tianjin University has the highest number of publications, 219, contributing to 3.88% of all WHR publications from 1991 to 2020. The second most productive organization is Xi An Jiaotong University, with 210 publications. In the third and fourth places are Tsinghua University and North China Electric Power University, with 163 and 104 publications, respectively.

In terms of influence, there are four organizations with more than 3000 citations. The organization with the highest total citations received is Tianjin University, with 5325 citations. Following closely in the second place is Xi An Jiaotong University, with 5285 citations. The other 2 organizations with more than 3000 citations are the Chinese Academy of Sciences and Tsinghua University, with 4951 and 3549 citations, respectively.

Another interesting aspect of analyzing is the average citations per publication. A high number indicate that the

| No. | Organizations (country)                  | h   | TC    | AC   | Q1  | Q2  | Q3  | Q4  | Q5  | Q6  | TP (%) |
|-----|----------------------------------------|-----|-------|------|-----|-----|-----|-----|-----|-----|--------|
| 1   | Xi An Jiaotong University (China)       | 39  | 5285  | 25.17| 0   | 0   | 0   | 12  | 48  | 150 | 210 (3.72%) |
| 2   | Tianjin University (China)              | 36  | 5325  | 24.32| 0   | 0   | 0   | 1   | 51  | 167 | 219 (3.88%) |
| 3   | Tsinghua University (China)             | 35  | 3549  | 21.77| 0   | 0   | 0   | 8   | 45  | 110 | 163 (2.89%) |
| 4   | Chinese Academy of Sciences (China)     | 25  | 4951  | 51.57| 0   | 0   | 0   | 2   | 24  | 70  | 96 (1.7%)   |
| 5   | Shanghai Jiao Tong University (China)   | 25  | 1992  | 24.00| 0   | 0   | 0   | 4   | 12  | 59  | 83 (1.47%)  |
| 6   | Beijing University of Technology (China)| 24  | 2370  | 29.63| 0   | 0   | 0   | 1   | 33  | 46  | 80 (1.42%)  |
| 7   | North China Electric Power University (China)| 23  | 1491  | 14.34| 0   | 0   | 0   | 1   | 30  | 73  | 104 (1.84%) |
| 8   | Chongqing University (China)            | 21  | 1904  | 27.20| 0   | 0   | 0   | 2   | 22  | 46  | 70 (1.24%)  |
| 9   | Technical University of Denmark (Denmark)| 20  | 1368  | 24.87| 0   | 0   | 0   | 0   | 19  | 36  | 55 (0.97%)  |
| 10  | Northeastern University China (China)    | 17  | 884   | 12.45| 0   | 0   | 0   | 3   | 16  | 52  | 71 (1.26%)  |
| 11  | Nanyang Technological University (Singapore)| 17  | 1192  | 22.49| 0   | 0   | 3   | 1   | 5   | 44  | 53 (0.94%)  |
|     | Overall                                 | 72  | 28,746| 25.13| 0   | 0   | 7   | 37  | 292 | 808 | 1144 (20.25%) |
publications from an organization are receiving high attention from other researchers. In the first place, despite having only 96 publications, the Chinese Academy of Sciences has an average of 51.57 citations per publication. A closer inspection of its publications shows that there are 7 publications with more than 100 citations, and 3 of them are among the 50 most-cited publications listed in Table 3. Moreover, the most-cited paper by the China Academy of Sciences, “Convergence of electronic bands for high performance bulk thermoelectrics” (Pei, Shi, et al., 2011), is also the most-cited paper in 30 years. It alone has received over 2000 citations. These are the few reasons for its high average citations per publication. Other organizations which stand out in this aspect despite lower productivity include Beijing University of Technology and Technical University of Denmark, with an average of 29.63 and 24.87 citations per publication, respectively.

Furthermore, it would be interesting to look at the organizations’ productivities over the 6 quinquenniums. As shown in Table 8, none of the top organizations have any publication in Q1 and Q2. In Q3, Shanghai Jiao Tong University and Nanyang Technological University started publishing in this field of research. In Q4, all the organizations, except for the Technical University of Denmark, have published in the area. Notably, being one of the newly emerged organizations at that period, Xi An Jiaotong University is the highest producer, with 12 publications. During the last two quinquenniums, all the organizations have recorded a great leap in their productivity.

Lastly, Table 8 shows the overall productivity and influence of the 11 organizations. As a single entity, they have an h-index of 72. Together they have produced 1144 publications, which contribute to more than 20% of all the publications. They started publishing in the WHR field in Q3 with only 7 publications and have subsequently increased to 808 publications in Q6. Their publications have received a total of 28,746 citations, and that is an average of 25.13 citations per publication.

### The most productive and influential countries

Policies by governments increasingly recognize the benefits of supporting research and development investment, and the effects of such investment on a country’s economic growth are well documented in the literature (Becker 2015). Researchers often travel and work in different countries. In this sense, an author may have publications in more than 1 country. Therefore, it might be interesting to analyze WHR publications geographically. Over the 3 decades, 98 countries have contributed to the field of research. Table 9 presents the countries with more than 80 publications. They are

| No. | Countries | h   | TC   | AC   | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | TP  | (%   )  |
|-----|-----------|-----|------|------|----|----|----|----|----|----|-----|-------|
| 1   | China     | 77  | 37,167 | 19.68 | 0  | 5  | 17 | 70 | 460 | 1337 | 1889 | 33.44% |
| 2   | USA       | 71  | 21,926 | 30.93 | 11 | 12 | 22 | 71 | 255 | 338  | 709  | 12.55% |
| 3   | England   | 39  | 6068  | 17.59 | 3  | 3  | 1  | 11 | 64  | 263  | 345  | 6.11%  |
| 4   | Iran      | 39  | 5318  | 22.73 | 0  | 2  | 4  | 6  | 37  | 185  | 234  | 4.14%  |
| 5   | Japan     | 35  | 4552  | 23.22 | 4  | 11 | 21 | 40 | 47  | 73   | 196  | 3.47%  |
| 6   | South Korea | 34 | 3574  | 19.22 | 0  | 4  | 5  | 6  | 54  | 117  | 186  | 3.29%  |
| 7   | Germany   | 33  | 4622  | 17.85 | 6  | 10 | 5  | 13 | 68  | 157  | 259  | 4.58%  |
| 8   | Italy     | 31  | 4032  | 14.5  | 0  | 0  | 4  | 6  | 0   | 210  | 278  | 4.92%  |
| 9   | Spain     | 31  | 3501  | 24.65 | 1  | 2  | 3  | 3  | 32  | 101  | 142  | 2.51%  |
| 10  | India     | 29  | 3501  | 13.06 | 1  | 3  | 6  | 12 | 51  | 195  | 268  | 4.74%  |
| 11  | Taiwan    | 29  | 3388  | 28.96 | 0  | 2  | 4  | 10 | 44  | 57   | 117  | 2.07%  |
| 12  | Canada    | 27  | 2657  | 19.12 | 2  | 3  | 2  | 14 | 43  | 75   | 139  | 2.46%  |
| 13  | France    | 27  | 2894  | 22.43 | 0  | 1  | 1  | 10 | 32  | 85   | 129  | 2.28%  |
| 14  | Australia | 27  | 2623  | 28.51 | 1  | 3  | 3  | 0  | 31  | 54   | 92   | 1.63%  |
| 15  | Turkey    | 25  | 1725  | 13.07 | 0  | 2  | 6  | 8  | 24  | 92   | 132  | 2.34%  |
| 16  | Denmark   | 25  | 2019  | 22.94 | 1  | 0  | 0  | 2  | 25  | 60   | 88   | 1.56%  |
| 17  | Singapore | 24  | 2181  | 25.96 | 1  | 0  | 4  | 1  | 16  | 62   | 84   | 1.49%  |
| 18  | Malaysia  | 23  | 1615  | 16.82 | 0  | 0  | 5  | 24 | 67  | 96   | 1.70%  |
| 19  | Belgium   | 23  | 3875  | 47.26 | 0  | 0  | 1  | 3  | 27  | 51   | 82   | 1.45%  |
| 20  | Sweden    | 22  | 2242  | 23.85 | 1  | 1  | 1  | 4  | 28  | 59   | 94   | 1.66%  |
| 21  | Poland    | 18  | 1052  | 8.35  | 0  | 1  | 3  | 5  | 19  | 98   | 126  | 2.23%  |
| Overall | 118 | 102,056 | 21.13 | 32 | 63 | 105 | 276 | 1280 | 3075 | 4831 | 85.52% |

Table 9 Most productive and influential Countries in WHR research
ranked based on the h-index. In the event of a tie, the number of publications is considered.

By far, China is the most productive and influential country in WHR research, with the highest h-index of 77. China’s productivity has far exceeded that of other countries. It has produced 1889 publications, which accounts for 33.44% of all publications. In terms of its influence, it has received 37,167 citations, which is well above the others as well. The size of the country, the number of researchers, and its investment in this research area are some of the reasons that can explain this ranking. Referring to Table 7, out of the 29 most productive and influential authors, 19 of them are researchers from China. Also, as can be seen in Table 4 and 5 out of 10 most productive funding agencies are from China. In addition, there are many highly cited papers that originated from the country; 11 out of the 50 most-cited publications in Table 3 were originated from China. Therefore, it is not a surprise that China is ranked in the first place.

The USA is in second place, with an h-index of 71. It has 709 publications, contributing to 12.55% of all publications. In terms of its influence, it has received a total of 21,926 citations. Although the USA’s productivity and citations received are lower than China, it has higher average citations per publication of 30.93, whereas China only has 19.68 citations per publication. A higher average citation per publication indicates that the publications from a country are receiving more attention than a country with a lower number. Belgium is the country with the highest average, which is 47.26 citations per publication. Other countries with high average citations include Australia, Taiwan, and Singapore. Next, Table 9 also presents the countries’ productivities over time. The countries which have published since as early as Q1 can be considered as the pioneering countries in WHR research. They are the USA, the UK, Japan, Germany, Spain, India, Canada, Australia, Denmark, Singapore, and Sweden. In Q2, 7 more countries emerged in the field, including China, Iran, South Korea, Taiwan, France, Turkey, and Poland. In Q3, Italy and Belgium started publishing in WHR research. The last country that emerged in Table 9 is Malaysia in Q4.

The USA has been the leading country for the first 4 quinquenniums until it was overtaken by China in Q5. Overall, most countries have increasing productivity over time, except for a few countries that had a decrement in between Q2 and Q4. The countries that had a temporary production decrement include the UK, Germany, Canada, Australia, Denmark, and Singapore. Progressing from Q4 to Q6, all countries have expanded their participation in the field and have seen a substantial increment in their productivity.

Lastly, the last row of Table 9 summarizes the collective productivity and influence of the 21 countries. Their h-index as a group is 118. Altogether, they have produced 4831 publications, which is 85.52% of all the WHR publications. Their publications began as early as Q1 with 32 publications and have increased progressively from Q1 to Q4. Then they have huge productivity increments in both Q5 and Q6. Their publications have received a total of 102,056 citations, and that is 21.13 citations per publication on average.

### Network analyses of WHR research

A comprehensive performance analysis of WHR research has been presented in the previous section. This section aims to show the publication structure and dynamic aspect of the research field by visualizing bibliographic connections between different actors. Through various network analyses, the main documents and the most representative structures and connections between the elements will be identified (Blanco-Mesa et al. 2017; Merigo et al. 2018; Wang et al. 2018). In this research, VOSviewer software is utilized to analyze the publications and generate graphical network maps using co-citation analysis, co-authorship analysis, and keyword co-occurrence analysis. The network mappings are represented by a network of nodes and lines. The nodes represent the subjects, and the size of a node represents its total link strength (as calculated using VOSviewer). On the other hand, the lines connecting the nodes represent the relationships between them. A thicker line represents a stronger relationship.

### Co-citation analyses

First, the co-citation of publications in WHR is analyzed. Two publications are co-cited when they are cited by a third publication (Marshakova 1973; Small 1973). In addition, when two publications are co-cited by more publications, the co-citation relation between the two publications is stronger. Table 10 presents the co-citation of the most-cited references in the WHR field. Note that TC in this table is the total citations received by a particular publication within the WHR field only. The cited references are ranked based on their total link strengths (TLS) as calculated in VOSviewer, and TC acts as the tiebreaker.

According to Table 10, the publication with the highest TLS is “Working fluids for low-temperature organic Rankine cycles” by Saleh et al. (2007). It is also the most-cited reference within the WHR research field. Saleh et al. (2007) analyzed the characteristics of 31 different working fluids in view of their selection in an ORC application. It is one of the earliest studies on different working fluids for ORC and has been cited in many subsequent WHR publications.

Note that there are a total of 18 publications in Table 10 which are also in Table 3, such as Quoilin et al. (2013), (Bao and Zhao 2013), and Tchanche et al. (2011). They are marked with a “1” in Table 10. These publications have received high attention not only among the WHR
| No. | Cited reference                                                                 | TC  | TLS  |
|-----|----------------------------------------------------------------------------------|-----|------|
| 1   | Working fluids for low-temperature organic Rankine cycles (Saleh et al. 2007)    | 293 | 2225 |
| 2   | A review of thermodynamic cycles and working fluids for the conversion of low-grade heat (H. Chen et al. 2010) | 293 | 1920 |
| 3   | A review of working fluid and expander selections for organic Rankine cycle (Bao and Zhao 2013) | 323 | 1907 |
| 4   | Effect of working fluids on Organic Rankine cycle for waste heat recovery (Liu et al. 2004) | 248 | 1899 |
| 5   | A review of organic rankine cycles (ORCs) for the recovery of low-grade waste heat (T. C. Hung et al. 1997) | 277 | 1860 |
| 6   | Study of working fluid selection of Organic Rankine cycle (ORC) for engine waste heat recovery (Wang et al. 2011a) | 251 | 1811 |
| 7   | Parametric optimization and comparative study of organic Rankine cycle (ORC) for low grade waste heat recovery (Dai et al. 2009) | 230 | 1709 |
| 8   | Thermo-economic optimization of waste heat recovery Organic Rankine Cycles (Quoilin et al. 2011b) | 241 | 1619 |
| 9   | Techno-economic survey of Organic Rankine Cycle (ORC) systems (Quoilin et al. 2013) | 296 | 1549 |
| 10  | Low-grade heat conversion into power using organic Rankine cycles – A review of various applications (Tchanche et al. 2011) | 252 | 1526 |
| 11  | Waste heat recovery of organic Rankine cycle using dry fluids (T.-C. Hung 2001) | 197 | 1490 |
| 12  | An examination of regenerative organic Rankine cycles using dry fluids (Mago et al. 2008) | 182 | 1421 |
| 13  | Fluid selection for a low-temperature solar organic Rankine cycle (Tchanche et al. 2009) | 168 | 1391 |
| 14  | Fluid selection for the Organic Rankine Cycle (ORC) in biomass power and heat plants (Drescher and Brüggemann 2007) | 186 | 1336 |
| 15  | Optimum design criteria for an Organic Rankine cycle using low-temperature geothermal heat sources (Madhawa Hettiarachchi et al. 2007) | 151 | 1299 |
| 16  | Performance analysis and optimization of organic Rankine cycle (ORC) for waste heat recovery (Wei et al. 2007) | 178 | 1251 |
| 17  | Internal Combustion Engine (ICE) bottoming with Organic Rankine Cycles (ORCs) (Vaja and Gambarotta 2010) | 188 | 1238 |
| 18  | Performance comparison and parametric optimization of subcritical Organic Rankine Cycle (ORC) and transcritical power cycle system for low-temperature geothermal power generation (Shengjun et al. 2011) | 153 | 1187 |
| 19  | A study of organic working fluids on system efficiency of an ORC using low-grade energy sources (T. C. Hung et al. 2010) | 117 | 1101 |
| 20  | Design and testing of the Organic Rankine Cycle (Yamamoto et al. 2001) | 135 | 1053 |
| 21  | Review of organic Rankine cycles for internal combustion engine exhaust waste heat recovery (Sprouse and Depcik 2013) | 195 | 1009 |
| 22  | Experimental study and modeling of an Organic Rankine Cycle using scroll expander (Quoilin et al. 2010) | 137 | 966 |
| 23  | Efficiency optimization potential in supercritical Organic Rankine Cycles (Schuster et al. 2010) | 125 | 933 |
| 24  | Process integration of organic Rankine cycle (Desai and Bandyopadhyay 2009) | 112 | 920 |
| 25  | Analysis of exhaust waste heat recovery from a dual fuel low temperature combustion engine using an Organic Rankine Cycle (Srinivasan et al. 2010) | 127 | 875 |
| 26  | Parametric optimization and performance analysis of a waste heat recovery system using Organic Rankine Cycle (Roy et al. 2010) | 108 | 875 |
| 27  | On the systematic design and selection of optimal working fluids for Organic Rankine Cycles (Papadopoulos et al. 2010) | 99 | 856 |
| 28  | Dynamic modeling and optimal control strategy of waste heat recovery Organic Rankine Cycles (Quoilin et al. 2011a) | 173 | 848 |
| 29  | Simulation and thermodynamic analysis of a bottoming Organic Rankine Cycle (ORC) of diesel engine (DE) (Yu et al. 2013) | 134 | 848 |
| 30  | A procedure to select working fluids for Solar Organic Rankine Cycles (ORCs) (Rayegan and Tao 2011) | 102 | 848 |
| 31  | Working fluids for high-temperature organic Rankine cycles (Lai et al. 2011) | 105 | 845 |
| 32  | Testing and modeling a scroll expander integrated into an Organic Rankine Cycle (Lemort et al. 2009) | 125 | 834 |
| 33  | Review of organic Rankine cycle (ORC) architectures for waste heat recovery (Lecompte et al. 2015) | 173 | 809 |
| 34  | A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation (Vélez et al. 2012) | 127 | 809 |
| 35  | Design and experimental study of ORC (organic Rankine cycle) and radial turbine using R245fa working fluid (Kang 2012) | 111 | 794 |
| 36  | A review of researches on thermal exhaust heat recovery with Rankine cycle (Wang et al. 2011b) | 134 | 764 |
| 37  | Fluids and parameters optimization for the organic Rankine cycles (ORCs) used in exhaust heat recovery of Internal Combustion Engine (ICE) (Tian et al. 2012) | 122 | 764 |
| 38  | The optimal evaporation temperature and working fluids for subcritical organic Rankine cycle (He et al. 2012) | 92 | 737 |
| 39  | Energetic and economic investigation of Organic Rankine Cycle applications (Schuster et al. 2009) | 103 | 725 |
| 40  | Zeotropic mixtures as working fluids in Organic Rankine Cycles for low-enthalpy geothermal resources (Heberle et al. 2012) | 102 | 709 |
| 41  | A performance analysis of a novel system of a dual loop bottoming organic Rankine cycle (ORC) with a light-duty diesel engine (Zhang et al. 2013a) | 101 | 702 |
| 42  | Dynamic modeling and simulation of an Organic Rankine Cycle (ORC) system for waste heat recovery (Wei et al. 2008) | 110 | 701 |
publications but also among publications from the other research fields.

Next, the co-citation structure of journals in the WHR field is another interesting unit to be analyzed. This analysis could show those journals which have received a great number of citations and how they are connected within this field. Figure 4 presents the mapping of journal co-citation structure with a threshold of 50 citations. In the visualization, each node represents a journal. The TLS of a journal is represented by its node size, and the distances between the nodes indicate the relatedness of the journals. Journals that are closer to each other indicate that they have a stronger co-citation relation. To have a clearer presentation, Fig. 4 displays only 100 journals with the greatest TLS and 250 most representable connections.

As shown in Fig. 4, there are three clusters of journals with distinctive colors. The biggest cluster is colored in blue and consists of most of the journals with the highest TLS. A high degree of overlapping can be observed in between the blue and the red clusters. It shows that the journals in the 2 clusters are highly related. The green cluster, on the other hand, is further away on the right-hand side. The journals in the green cluster are less often to be co-cited with the journals in the other clusters.

The biggest node in Fig. 4 is Energy. It is the leading journal in the WHR field with the highest TLS of over 520,000. This makes sense given that Energy has the largest number of total citations received and, consequently, with a wider network of connections. This is followed by Applied Thermal Engineering, Energy Conversion and Management, Applied Energy, and Renewable Sustainable Energy
Reviews. This result is consistent with the results presented in Table 6, where the top 5 influential journals are the 5 with the highest TLS. The other journals in Table 6 exist in Fig. 4 as well.

Another interesting topic to analyze is the co-citation of authors. Assuming that the relationship between two authors is closer if they are cited together more, this analysis aims to show the structure and connections of authors (White and Griffith 1981). Figure 5 presents the results of this analysis. It is developed with a threshold of 50 citations, and only the 100 authors with the highest TLS are shown. Furthermore, only 250 most representable connections are shown to have a clearer visualization. In the figure, each node represents an author, and its size indicates an author’s TLS. The relatedness of the authors is represented by the distances between them. Authors that are closer in the distance indicate that they have a stronger co-citation relation.

There are three clusters of authors with distinctive colors in Fig. 5. The biggest cluster is red in color. Sylvain Quoilin, Tzu-Chen Hung, and Bertrand Fankam Tchanche are among the authors with the highest TLS in this cluster. The second cluster, green in color, is overlapping with the first. Gequn Shu, En-Hua Wang, and Jian Song are the authors with the highest TLS in this cluster. As can be seen by the distances and the links, the authors in these 2 clusters have strong co-citation relations in between themselves. The smallest cluster is blue in color. Its authors have lower TLS and have weaker relations with the other journals in red and green clusters.

Figure 5 authenticates the important role of Gequn Shu in the field of research. Remember that in Table 7, she is the most influential and productive author in the field. Many other authors in Table 7 appear in Fig. 5 as well. More importantly, this analysis has revealed other relevant and strongly connected researchers who have not been recorded in Table 7 due to their lower h-index, such as Sylvain Quoilin, Bertrand Fankam Tchanche, Tzu-Chen Hung, Huijuan Chen, and Steven Lecompte, among others.

**Co-authorship analyses**

Advancement in communication technologies enables more interorganizational and international research collaborations. Co-authorship analyses have been carried out in VOSviewer to illustrate these collaborations. First, the collaborations among the organizations have been analyzed. The result is presented in Fig. 6, which is based on thresholds of 20 publications and 100 citations. Only 33 organizations meet the thresholds, and all of them have been included in this figure. Each organization is represented by a node, the size of
each node indicates its TLS, and the thickness of connecting lines signifies the strength of the relationship between the organizations.

Chinese Academy of Sciences is found to be the most connected organization in the WHR field. It has the highest TLS of 68. This is followed by Tsinghua University, University of the Chinese Academy of Sciences, Beijing University of Technology, Xi An Jiaotong University, and other organizations. Note that all the top productive and influential organizations in Table 8 exist in Fig. 6 as well.

As can be seen in Fig. 6, the strongest interorganizational collaboration exists in between the Chinese Academy of Sciences and the University of the Chinese Academy of Sciences. Other notable collaborations include but are not limited to the collaborations in between Beijing University of Technology and Collaborative Innovation Center of Electric Vehicles in Beijing, Tsinghua University and Beijing University of Technology, as well as Xi An Jiaotong University and China University of Petroleum. This analysis also reveals other strongly connected organizations that have not been recorded in Table 8 due to their lower h-index, such as Imperial College London, Ghent University, and Guangxi University.

Next, the collaborations among the countries based on co-authorship are presented in Fig. 7. It is developed with thresholds of 20 publications and 100 citations. Only 46 countries meet the thresholds, and all of them are included in the figure. In this figure, each node represents a country, node size indicates the TLS of a country, and the thickness of connecting lines signifies the strength of the relationship between the countries.

Through the co-authorship analysis, it is found that China is the most connected country in the WHR field, with the highest TLS of 367. This is followed by the USA, England, and other countries. The 3 countries with the highest TLS are also the most productive and influential countries, as recorded in Table 9. Cross-examination with Table 9 indicates that international collaborations might play an important role in WHR research productivity as the strongly connected countries are also the top producers and influencers in the field.

As can be observed in Fig. 7, the strongest international collaboration exists in between China and the USA. The second strongest link is formed in between China and England. In addition, China also exhibits strong connections with several other countries such as Australia, Taiwan, Japan, Singapore, and Scotland. Lastly, this analysis reveals other strongly connected countries which are not included in Table 9 due to lower h-index. These countries include but are not limited to Saudi Arabia, Scotland, Egypt, and Vietnam.

**Keyword co-occurrence analyses**

A keyword analysis is an important part of the bibliometric analysis because it reveals the focus of researchers on a particular research topic (Wong et al. 2021) as well as the conceptual structure of a research field (Callon et al. 1983). Through preliminary analysis, it was found that one of the main keywords is “waste heat recovery”; however, it was written differently in several forms, including “waste-heat recovery” and “waste heat-recovery.” To analyze the
keywords more accurately, “waste-heat recovery” and “waste heat-recovery” were replaced by “waste heat recovery” in the bibliographic database files. Another main keyword which had a similar issue, “organic rankine cycle,” is also termed as “organic rankine-cycle” and “ORC.” They have been changed to “organic rankine cycle.” Lastly, “utilisation” has been changed into “utilization” for the same reason. The 50 most frequent keywords over 30 years are identified and summarized in Table 11. There are 4 keywords which occur more than 1000 times in the publications; they are “waste heat recovery,” “organic rankine cycle,” “optimization,” and “performance.”

To further analyze the keywords, a keyword co-occurrence network map for the entire period of 1991–2020 is created in VOSviewer and presented in Fig. 8. The minimum number of occurrences of a keyword is set to be 5, and only 50 most frequent keywords are included. Only the 125 most representative connections are shown to have a clearer mapping.

Three clusters were identified in Fig. 8 and are represented by three different colors. The keyword “waste heat recovery” is the main theme, and it is positioned at the center of the map. Along with 22 other keywords, they are grouped in the red cluster. The cluster focuses on the WHR systems’ design, performance, optimization, and efficiency. On the other hand, the main keyword in the green cluster is “organic rankine cycle.” This cluster consists of 15 keywords, and it mainly revolves around ORC system applications, performance analysis, and working fluids selection. The last cluster (in blue) contains 12 keywords and focuses on thermodynamic, energy, and exergy analyses in the WHR research field.

In addition, to observe how the keywords have evolved over time, the keyword co-occurrence mappings for the following time periods, 1991–2000, 2001–2010, and 2011–2020, are done as well. These are presented in Figs. 9, 10, and 11, respectively. The minimum number of occurrences of a keyword is set to be 2 for Fig. 9, whereas for Figs. 10 and 11, it is set to be 5. A maximum of 50 keywords with the greatest link strength are included in the mappings, and only 125 most representative connections are displayed.

As shown in Fig. 9, there are only 31 keywords with 2 or more occurrences in the first decade. The main keywords include “waste heat recovery,” “heat recovery,” “waste heat,” and “waste heat utilization.” In the second decade, there are 56 keywords with 5 or more occurrences but only 50 are included in Fig. 10. “Waste heat recovery” has become the dominant keyword, which is placed at the center of the

Table 11 The 50 most frequent keywords in WHR research

| No. | Keywords             | Frequency | No. | Keywords             | Frequency |
|-----|----------------------|-----------|-----|----------------------|-----------|
| 1   | waste heat recovery  | 2710      | 26  | working fluid        | 194       |
| 2   | organic rankine cycle| 1558      | 27  | multiobjective optimization| 180      |
| 3   | optimization         | 1142      | 28  | engine               | 165       |
| 4   | performance          | 1045      | 29  | low-grade heat       | 163       |
| 5   | design               | 765       | 30  | parametric optimization| 153      |
| 6   | system               | 764       | 31  | generation           | 150       |
| 7   | energy               | 685       | 32  | diesel-engine        | 148       |
| 8   | thermodynamic analysis| 506     | 33  | flow                 | 147       |
| 9   | working fluids       | 465       | 34  | waste heat utilization| 139      |
| 10  | waste heat           | 412       | 35  | zeotropic mixtures   | 137       |
| 11  | power                | 390       | 36  | conversion           | 133       |
| 12  | performance analysis | 377       | 37  | energy recovery      | 132       |
| 13  | efficiency           | 357       | 38  | cogeneration         | 129       |
| 14  | recovery             | 347       | 39  | exchanger            | 125       |
| 15  | simulation           | 311       | 40  | water                | 125       |
| 16  | exergy analysis      | 294       | 41  | cycle                | 124       |
| 17  | temperature          | 293       | 42  | gas                  | 118       |
| 18  | model                | 264       | 43  | exhaust              | 116       |
| 19  | systems              | 261       | 44  | plant                | 107       |
| 20  | thermoelectric generator| 246   | 45  | gas-turbine          | 98        |
| 21  | exergy               | 243       | 46  | driven               | 97        |
| 22  | power-generation     | 242       | 47  | exergoeconomic analysis| 92         |
| 23  | heat recovery        | 219       | 48  | thermo-economic analysis| 92         |
| 24  | energy efficiency    | 204       | 49  | working fluid selection| 91         |
| 25  | selection            | 196       | 50  | thermo-economic optimization| 89   |
map and connected to other keywords. “Performance” and “optimization” are the second and third keywords with the highest occurrences. Note that “organic rankine cycle” has emerged as the main keyword in this decade and has formed the blue cluster together with 6 other keywords.

In the last decade, the keywords which meet the threshold of minimum 5 occurrences have drastically increased to 1223 keywords. Figure 11 presents the network mapping of the 50 strongest keywords in the last decade. “Waste heat recovery” remains to be the most dominant keyword and forms the largest cluster (in red) of 24 keywords. Next to it, “organic rankine cycle” has become the second strongest keyword in terms of both occurrences and link strength. It belongs to the green cluster, which consists of 14 keywords.

It is interesting to notice that Fig. 11 is highly resembling Fig. 8. This makes sense because almost 90% of WHR publications were published during the last decade. Therefore, the strongest keywords of the last decade are very likely to be the strongest keywords over the 30 years as well.

**Conclusions**

This research presents the publication landscape of the WHR research field based on 5649 publications extracted from the WoS core collection. Two main bibliometric methods have been used, namely, bibliometric performance analysis and network analysis. Overall, this research field has grown
spectacularly over the 30 years in both the number of publications and the number of citations received, especially during the last decade.

One of the major driving forces behind the drastic growth is the availability of research funds. The most important funding agency is the National Natural Science Foundation of China (NSFC), with an h-index of 56. It has funded 905 publications, and they have received over 16,000 citations.

WHR is a multidisciplinary research field. Its publications have been published in 1532 journals and proceedings. The top publication outlet for WHR research is Energy, with an h-index of 68. Energy has published 590 WHR publications, and these publications have received over 18,000 citations.

Regarding individual researcher, the author with the best combination of productivity and influence in WHR research is Shu Gequn, with an h-index of 32. She has produced a
total of 105 WHR publications, which have received over 3000 citations collectively. In addition, this research also identified highly cited publications. The top one being Pei, Shi, et al. (2011), which has gained a high level of attention among researchers and received 2187 citations to date.

Next, the research analyzes organizations’ productivity and influence as they play an important role in promoting the advancement of a research field. It is found that the most productive and influential organizations are from China. Xi An Jiaotong University, with an h-index of 39, has been identified to be the top performer in the field. It has produced 210 publications which have received 5285 citations in total.

Focusing on the country level, China is the top performer in this field. The result is not surprising as the country has dominated on other levels as well, i.e., top publications, top authors, top funding agencies, and top organizations. China has an h-index of 77, produced 1889 publications, and obtained 37,167 citations. As indicated by the co-authorship analysis, China is also found to be the most connected country in the WHR field.

On the other hand, network analyses have been done to complement the performance analyses using co-citation, co-authorship, and keyword co-occurrence techniques. Keyword co-occurrence analysis was done in different decades to reveal how the keywords have evolved over the years. “Waste heat recovery” has been the main keyword over the decades, whereas “organic rankine cycle” and related keywords have gained more attention ever since the second decade.

Finally, there are some limitations of this research which need to be considered. First, the analyses performed were exclusively based on the data extracted from the WoS core collection. The results would have been different if other databases were used. Hence, it is recommended to replicate the research using other databases such as Scopus, Dimensions, Semantic Scholar, and Google Scholar. It is also important to note that the information extracted from WoS may change over time as new documents are added to the database. In addition, the types of documents which are included in this research are articles, reviews, and conference proceedings only. This could have potentially omitted other documents that may be equally important. Thus, all other document types could be included in future research. Next, some research collaborations start few years before the dissemination of research findings in publications, whereas the data in WoS only represent completed collaborations. Therefore, those collaborations which are currently running could not be captured in the network mappings. Future bibliometric research can propose methods to capture and include those current collaborations in the network mappings. Lastly, a limitation must be noted related to the main indicator, the h-index, which is used to rank the different actors. It does not benefit highly cited actors with moderate productivity. Thus, readers should interpret the results of this paper with caution and take other indicators presented into account as well. Further studies can include or propose other indicators which are unbiased toward highly cited actors with moderate productivity.

With these limitations in mind, the information presented in this study offers readers an overview of the state of the field. For those seeking to do research in this area, the core articles which have been identified may be a good starting point. It also provides general guidance on the most productive and influential actors. Moreover, this research also provides critical information in identifying potential researchers and organizations to start collaborating with. In addition, being aware of the top authors is important as they may set the stage for future developments in the field. Ambitious researchers who aim to expand the research frontier could monitor the top authors’ recent works to identify the most recent research opportunities. Finally, this research has identified a problem in WoS analytics when dealing with author names. It would take author names such as “Li, Jing,” “Li, Juan,” and “Li, Jie” as a single author “Li, J.” Future bibliometric studies should take note of this problem.

Abbreviations

TP (%): total publications of a subject (the percentage out of the grand total publications of 5649); TC: total citations received; AC: average citations per publication; h: h-index; NoP: number of publications; IF: impact factor (extracted from the 2020 edition of Clarivate’s Journal Citation Reports); 5Y-IF: 5-year impact factor (extracted from the 2020 edition of Clarivate’s Journal Citation Reports); Q: quinquennium; Q1: quinquennium 1: year 1991–1995; Q2: quinquennium 2: year 1996–2000; Q3: quinquennium 3: year 2001–2005; Q4: quinquennium 4: year 2006–2010; Q5: quinquennium 5: year 2011–2015; Q6: quinquennium 6: year 2016–2020; TLS: total link strength.

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Author contribution

CTK developed the methodology of the paper, contributed to writing, revising, and improving the manuscript. QYK contributed to writing, revising, and improving the manuscript. SR managed and coordinated the research activities, contributed to writing, revising, and improving the manuscript. KYW conceptualized the idea of the paper, coordinated the research activities, contributed to writing, revising, and improving the manuscript. The authors contributed equally to this work.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.
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