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REVIEW

# Knowledge Mapping of Hybrid Solar PV and Wind Energy Standalone Systems: A Bibliometric Analysis

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**ABSTRACT**

Renewable energy is becoming more attractive as traditional fossil fuels are rapidly depleted and expensive, and their use would release pollutants. Power systems that use both wind and solar energy are more reliable and efficient than those that utilize only one energy. Hybrid renewable energy systems (HRES) are viable for remote areas operating in standalone mode. This paper aims to present the state-of-the-art research on off-grid solar-wind hybrid energy systems over the last two decades. More than 1500 published articles extracted from the Web of Science are analyzed by bibliometric methods and processed by CiteSpace to present the results with figures and tables. Productive countries and highly cited authors are identified, and hot topics with hotspot articles are shown in landscape and timeline views. Emerging trends and new developments related to techno-economic analysis and microgrids, as well as the application of HOMER software, are predicted based on the analysis of citation bursts. Furthermore, the opportunities of hybrid energy systems for sustainable development are discussed, and challenges and possible solutions are proposed. The study of this paper provides researchers with a comprehensive understanding and intuitive representation of standalone solar-wind hybrid energy systems.

**KEYWORDS**

Wind energy; solar PV; standalone; citation bursts; emerging trends

## 1 Introduction

Limited fossil fuels are rapidly consumed to meet the increasing energy demand which is an inevitable result of economic development [1,2]. Nowadays renewable energy resources have become more and more attractive all over the world due to the characteristics of being sustainable and easily accessible, such as wind energy and solar energy [3,4]. Renewable energy resources are environmentally friendly while utilization of conventional energy resources would discharge pollutants including greenhouse gases. Renewable energies are regarded as promising power supply sources rather than conventional energy particularly considering the global warming phenomena and the rising cost of fossil fuels. In addition to generating electricity, the renewable power system can also provide eco-friendly products such as hydrogen, fresh water, and hot water, which are helpful for the sustainable development of human beings [5–7].

However, power-generating systems that rely on single renewable resources are not applicable because of the fluctuant nature of weather conditions. Two or more renewable energies are set as primary sources for HRES that could realize zero carbon emission, which means that HRES are more environmentally friendly compared to traditional energy systems that use fossil fuels. By combining two or more technologies that often have a complementary relationship in terms of availability, HRES can offer a more consistent energy supply and reduce storage needs than singular renewable energy systems. Thus, HRES are more popular than those using a single source due to the performance of reliability and high efficiency [8,9]. Among these hybrid systems, solar energy and wind energy are very common since they are omnipresent and freely available. According to the working modes, hybrid solar PV and wind energy systems can be classified into two types: one is connected to a power network which is called on-grid or gird connected type and the other is not connected to a power network, which is usually called off-grid or standalone type. Owing to the expensive cost of extending the network of the power grid, the hybrid solar PV and wind energy standalone system (HPWESS) is a viable choice to offer power for remote regions including rural communities and remote islands that are far away from the power network. A comprehensive analysis was conducted to examine the techno-economic parameters of hybrid solar/wind/diesel systems in Iran, specifically for a non-residential electricity consumer. It was found that off-grid systems exhibited an electricity cost ranging from 9.3 to 12.6 C/kWh, along with a renewable fraction varying from 0% to 43.9%. Moreover, the study highlighted a significant reduction in $CO_2$ emissions, with a maximum decrease of 791,560 kg per year [8]. As a part of an ongoing project, a feasibility study on off-grid solar and wind power systems was conducted for non-electrified villages in Ethiopia. The study revealed that the levelized cost of electricity varies between 0.1/kWh and 0.121/kWh, which falls within the lower range of global electricity tariffs. The research will continue to cover the remaining sites, to supply modern electricity generated from renewable energy sources to the 10,500 families residing in the area [9]. The application of HPWESS has satisfied the energy demand in remote areas, protected the surrounding environment and improved living conditions for people who live there, which attracted the attention of scientists and engineers to carry out abundant studies on this special field for sustainable development [10,11].

It is not a simple job for researchers to get a comprehensive understanding of HRES or know about newly rising technologies due to the quick development of relevant studies as well as consequently a substantial amount of literature that focuses on the field. In addition, review articles in one field usually display the main content in the text without graphs or with few graphs, resulting in a less rich presentation and less intuitive experience for readers. On account of the reasons mentioned earlier, this paper aims to review the up-to-date research status of HPWESS based on published journal articles indexed by the database of WOS and try to find the future developing trend in the application of HRES. Analysis results are displayed with plentiful graphs which give an intuitive sense for researchers who want to study HRES. First of all, the most relevant articles are obtained by setting up a well-designed search formula on WOS. Then, the information in the literature is imported and analyzed in the CiteSpace software. More than 1,500 papers have been taken into consideration to draw pictures that represent the research status in search scope and representative papers in terms of different topics are discussed to provide in-depth understanding. The future developing trend is predicted based on the bursts analysis of keywords and articles. The study of this paper will present a comprehensive understanding of the latest research status and future development trends on HRES for researchers and policymakers.

## 2 Method

Bibliometrics involves the examination of published materials such as books, journal articles, datasets, and blogs, along with their associated metadata like abstracts, keywords, and citations. This analysis utilizes statistical methods to depict and establish connections between these published works. The underlying premise is that the scholarly output of a particular field is reflected in the published literature. In a more focused context, researchers can utilize bibliometrics to trace the development of a specific topic by observing its dissemination throughout the literature. Additionally, they can identify the attributes of journal articles that are highly downloaded to determine their impact. Since large quantities of bibliometric data can be summarized to present the state of the intellectual structure and emerging trends of a research topic or field, the bibliometric methodology is an effective tool for gaining an overview of numerous kinds of literature that are very difficult to process by manual work. In the paper, the bibliometric methodology is introduced to reveal the research status of HPWESS, and the CiteSpace software based on the method is adopted to process the relevant articles and then the analysis results are shown as graphs and tables. CiteSpace is a Java-based software application designed to analyze and visualize co-citation networks. Its primary objective is to facilitate the examination of emerging trends within a specific field of knowledge. By allowing users to capture a series of snapshots over time and merge them together, CiteSpace enables the exploration of bibliographic information, particularly citation data obtained from the Web of Science, through interactive visualizations. This empowers users to navigate and uncover various patterns and trends within scientific publications, ultimately enhancing their understanding of the scientific literature more efficiently compared to an unguided search. In CiteSpace, the fundamental unit of analysis is a knowledge domain, and scientific publications are deemed relevant if they contribute to a deeper comprehension of the specific knowledge domain under investigation. Consequently, the process of data collection plays a crucial role in utilizing CiteSpace, as the extent of data coverage directly affects the scope of subsequent analyses.

The first task of bibliometrics is to define the study scope including the research area, literature database, and time span. As previously mentioned, HPWESS has been set as the research area. WOS, Google Scholar (GS), and Scopus are the main databases that are used to evaluate the scientific impact of a specific topic by researchers. By comparison of these three citation resources, Adriaanse et al. found that WOS has the most citations, followed by GS and Scopus. WOS retrieved the unique entries and had the best total coverage of the journal sample population, which indicates that WOS has the most popularity in scientific activities [12]. Thus, WOS is adopted as the literature database. A primary query was carried out to identify the reasonable time duration of articles published. The time span is set from 2005 to 2022 since a few articles about the research area were reported before 2005 and most of the relevant papers were published in the set time range, which was found in the primary query. By contacting experts and reading literature, the content of the research area can be classified into three parts, which are listed in Table 1. The search formula below Table 1 is built up to perform formal data retrieval about the research area based on prior classification.

**Table 1:** Search terms

| Categories | Keywords |
|---|---|
| 1. Solar PV | "solar∗" or "PV" or "photovolt∗" |
| 2. Wind Energy | "wind" or "WT" |
| 3. Standalone | "grid independent" or "standalone" or "stand alone" or "off grid" or "grid isolated or "autonomous" |

Note: TS = ((solar OR PV OR photovolt∗) AND (wind OR WT) AND ("grid independent" OR standalone OR "stand alone" OR "off grid" OR "grid isolated" OR "autonomous")).

In order to analyze the search results that are extracted from the database, the CiteSpace software is introduced to process the retrieval data. The main analysis steps include data extraction from the database, data cleaning, data import, data analysis, and visualization [13]. After the first two steps, it was found that 1,573 articles about the research area were published (the publication amount may vary due to different accessibility of WOS for users). The information including title, authors, abstract, and keywords is then imported into the software for processing. At the end of the visualization, figures that reflect the state of the research area are demonstrated, which will be shown in the next part.

## 3 Results and Discussion

### *3.1 Productive Countries and Highly Cited Authors*

Preliminary analysis shows that more than 130 countries have published at least one paper about HPWESS, which reveals a worldwide interest in the utilization of HRES, especially for districts far away from the power grid. It was found that ten countries issued more than 50 papers in the research area. Among them, developing countries and developed countries are fifty-fifty, as depicted in Fig. 1. Moreover, all the top three productive countries are developing countries, i.e., India, China, and Iran, which published 216 papers, 146 papers, and 124 papers, respectively. It is not very common in a research field as developed countries usually lead scientific and technical studies, which may indicate that developing countries pay more attention to taking advantage of HRES in remote areas.

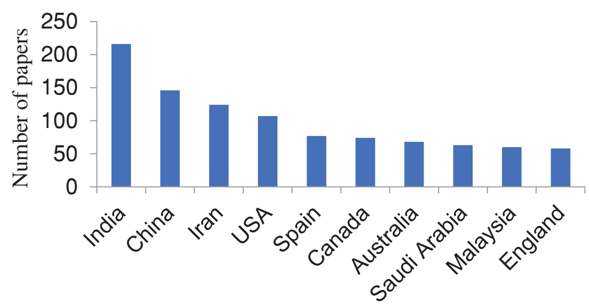


**Figure 1:** Publication amounts of the top ten productive countries

On the other hand, the number of researchers who have been listed as co-authors in articles that studied HPWESS is beyond 4,000, which represents that numerous people paid effort to develop the special energy system. The citation count of each author is taken as the metric to identify the impact of researchers among them. For considering as many authors as possible and reducing the processing time, the total citations of authors who have published equal or more than 5 articles or who have published one article with over 300 citations are set as comparison objectives. After analyzing by CiteSpace and carefully examining by us, it is found that there are only 9 authors who published double-digit articles ranging from 10 to 16, whereas the citation of 50 authors has exceeded 100. The citation leaders in the research area are figured out and the top twenty of them are ranked by the total citation count. All the leaders have been cited over 500, and the top nine leaders even have been cited over 1,000, as shown in Table 2. The top three highly cited authors are Yang HX, Lu L, and Dufo-Lopez R, whose total citations are 1,953, 1,867, and 1,545, respectively. The citation counts of the leaders are very high, which reflects that the research on the special HRES has been widely concerned by scientists and engineers, and the authors listed in Table 2 can be regarded as impact researchers who led the development of HPWESS.

### *3.2 Hot Topics*

HRES is one kind of complicated system that includes many distinct contents for people to explore and develop. Researchers' interests in this special field may only focus on limited aspects of research content. People are often eager to ask such questions: what topics are being studied? Which topics are addressed frequently? How to find the hot topics? In order to figure out the hot topics of our study scope, the data extracted from WOS is processed in CiteSpace software using cluster analysis from which large amounts of data are classified into groups (clusters) based on similarity. Each year, the top 50 most cited articles are picked to create one network of references cited in that year [14]. For the overall search time span, i.e., the year from 2005 to 2022, distinct networks are then synthesized to form graphs that depict the clusters. Members in one cluster are more similar (in some sense) than those in other clusters. At the same time, each cluster is marked by a label generated by the algorithm of cluster analysis while hotspot articles for each cluster are demonstrated. Different clusters composed of group articles with respect to a similar topic are identified by the software and the detail is discussed in Sections 3.2.1 and 3.2.2.

**Table 2:** Total citation leaders in the study scope

| Rank | Name | Citation | Rank | Name | Citation |
|---|---|---|---|---|---|
| 1 | Yang HX | 1953 | 11 | Sanchis P | 742 |
| 2 | Lu L | 1867 | 12 | Fang ZH | 634 |
| 3 | Dufo-Lopez R | 1545 | 13 | Rosen MA | 609 |
| 4 | Bernal-Agustin JL | 1409 | 14 | Chauhan A | 601 |
| 5 | Maleki A | 1202 | 15 | Guerrero JM | 549 |
| 6 | Zhou W | 1170 | 16 | Jurado F | 519 |
| 7 | Saini RP | 1154 | 17 | Dragicevic T | 518 |
| 8 | Wang CS | 1057 | 18 | Deshmukh SS | 513 |
| 9 | Ma T | 1042 | 19 | Deshmukh MK | 506 |
| 10 | Nehrir MH | 816 | 20 | Bajpai P | 505 |

### *3.2.1 Landscape Visualization*

The landscape view for our research area shows that eight clusters marked from #0 to #7 are derived from input data and two hotspot articles for each cluster tagged with the names of the first author followed by the year of publication are pointed out. As illustrated in Fig. 2, each node in the graph represents an article studied on HPWESS and the nodes with the same color belong to the same cluster. The largest cluster #0 has 120 nodes whereas the smallest cluster #7 just has 12 nodes. All the hotspot articles are checked by us and it indicates that the selected articles are highly associated with the cluster label, which proves that cluster analysis of the software is credible to process numerous data for classifying meaningful groups.

Obviously, the eight clusters can be regarded as hot topics since they are constituted by articles with similar subjects including highly cited members. The relevant contents of hotspot articles for each cluster are summarized in Table 3. For cluster #0, researchers usually referred to the comprehensive development of HRES including algorithms, implementation software, unit sizing, components modeling, configuration optimization, and performance estimation for the whole energy system. The research work related to HRES carried out using 19 software at different locations worldwide was summarized, which provides the current status for researchers to adopt the suitable tool for developing hybrid systems [15]. Studies on the state-of-the-art of optimal planning of HRES, which uses the

Hybrid Optimization Model for Electric Renewables (HOMER) software to meet economic, technical and emission constraints were reviewed [16].

**Table 3:** Hotspot articles for clusters shown in Fig. 2

| | Hot topics | Hotspot articles | Relevant content |
|---|---|---|---|
| #0 | Hybrid renewable energy system | Sinha et al. (2014) | The current status and main features of 19 software for developing HRES are reviewed [15]. |
| | | Bahramara et al. (2016) | State-of-the-art utilization of HOMER for optimal designing of HRES is presented [16]. |
| #1 | Techno-economic analysis | Mamaghani et al. (2016) | Techno-economic analysis of a standalone hybrid power generation system in Colombia has been conducted by HOMER software [17]. |
| | | Mandal et al. (2018) | Techno-economic feasibility of different configurations of HRES in Bangladesh is evaluated and optimized by HOMER software [18]. |
| #2 | Feasibility study | Zhou et al. (2010) | The progress of feasibility study for standalone hybrid power systems is reviewed on different meteorological databases [19]. |
| | | Erdinc et al. (2012) | Different optimum sizing methods for widening HRES penetration by improving the system applicability in view of the economy are analyzed [20]. |
| #3 | Power management strategies | Koutroulis et al. (2006) | A methodology for optimal sizing of standalone PV/WG systems subject to zero load rejection is proposed [21]. |
| | | Dufo-Lopez et al. (2007) | A novel strategy for controlling standalone HRES with hydrogen storage is presented [22]. |
| #4 | Case study | Ogunjuyigbe et al. (2016) | Five scenarios of grid-independent HRES for a typical residential house are studied using the Genetic Algorithm [23]. |
| | | Ramli et al. (2018) | Optimal sizing of a PV/wind/diesel/battery system is carried out using a Multi-Objective algorithm and tested using three case studies [24]. |
| #5 | Hydrogen production | Ipsakis et al. (2009) | The operating policies for the hydrogen production of a standalone system are proposed [25]. |
| | | Eroglu et al. (2011) | A hydrogen tank is introduced to store the excess energy of a PV/wind/fuel cell hybrid power system [26]. |
| #6 | Remote island | Ma et al. (2014) | Detailed analysis, description, and expected performance of standalone hybrid wind-solar systems for a remote island are presented [27]. |

(Continued)

**Table 3 (continued)**

| | Hot topics | Hotspot articles | Relevant content |
|---|---|---|---|
| | | Singh et al. (2016) | An artificial bee colony algorithm is adopted to optimize the sizing of components for standalone HRES in islanded microgrids [28]. |
| #7 | Electrification option | Kirubi et al. (2009) | Electrification of community-based micro-grid in rural Kenya which contributes to higher social and economic benefits is demonstrated [29] |
| | | Chaurey et al. (2010) | Techno-economic comparison of the two options for rural electrification is presented [30]. |

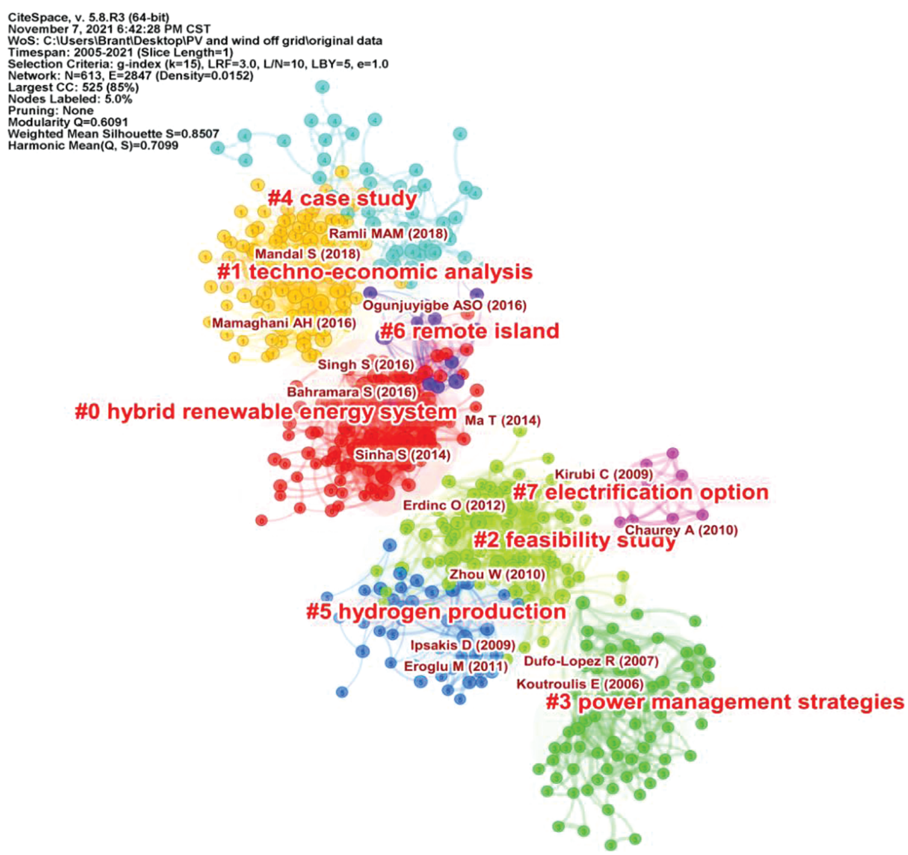


**Figure 2:** Landscape view of major clusters in the research area

Developments of optimization and modeling of HRES including energy resources, power conditioning units, techniques for energy flow management, and backup energy systems for standalone applications were discussed [31]. Performance evaluation of the Wind-PV-Diesel-Battery energy system for a remote area located in Malaysia was conducted to ensure the system's feasibility with regard to net present value and $CO_2$ emission reduction [32]. Sizing methodologies and sixteen methods of optimization for hybrid solar PV/wind energy systems were presented for researchers to deal with complexity and challenges in the application of HRES [33].

For cluster #1, techno-economic studies on standalone hybrid PV and wind energy systems were conducted in many countries such as Bangladesh, Colombia, India, Iran, Malaysia, etc. The economic, technical, and environmental performances of these systems were discussed under different operational scenarios. Techno-economic feasibility of an off-grid hybrid wind turbines, PV panels, and diesel generators power system for rural electrification in three villages located in Colombia was analyzed [17]. Techno-economic feasibility of various system configurations for HRES in Bangladesh were evaluated and optimized by HOMER software with respect to the cost of energy and net present cost [18]. To satisfy the load demand of a non-residential community, techno-economical parameters of a hybrid wind/PV/diesel/battery system in the south of Iran were studied using HOMER software for modeling as well as optimization [34]. A techno-economic feasibility of an off-grid hybrid wind turbines, PV panels, diesel generators, and lead acid battery power system for a remote community in Bangladesh was conducted to meet the electric load requirements using the HOMER software tool [35]. The performance of a hybrid off-grid PV-wind-diesel-battery system for a resort center in Malaysia was evaluated to determine the best-optimized system configuration according to techno-economic analysis [36].

For cluster #2, feasibility evaluations for standalone hybrid solar-wind power systems were carried out in terms of meteorological data, economy, optimization techniques, or sizing model, as well as sensitivity analysis was concerned. Research progress including simulation, optimization, and control technologies for reliably integrating the off-grid hybrid solar-wind power systems was reviewed [19]. A detailed analysis of combining renewable energy sources with backup elements to make up a hybrid system for environment-friendly, more economical, and reliable supply of power in various load requirement conditions was provided [20]. The sizing methodology which ensured that the total expense of the hybrid PV/wind/diesel power system was minimized while guaranteeing the availability of the energy was studied by a deterministic algorithm [37]. The simulation, optimization techniques, and tools for standalone HRES, were revised to determine an optimal configuration for the electricity generation with minimized cost [38]. Multi-objective optimization for a standalone wind-PV-diesel-battery system was described to minimize the life cycle emissions along with the levelized cost of energy by the Strength Pareto Evolutionary Algorithm [39].

For cluster #3, power/energy management strategies or control strategies were applied to micro-grid powered by standalone hybrid wind/PV systems for optimizing the utilization expense and lifetime of the energy system. The optimization problems were evaluated by considering various configurations. A methodology was applied to design a hybrid standalone power system, and the results proved that hybrid WG/PV systems lead to lower system costs compared to cases where either exclusively PV or exclusively WG sources were utilized [21]. A novel strategy to manage standalone hybrid renewable power systems with hydrogen storage was demonstrated to minimize the total cost throughout its lifetime and optimize the use of spare energy [22]. An overall power management strategy was designed for the standalone wind/PV/FC alternative energy system to control power flows among the storage unit and the different energy sources in the system which was verified under various scenarios [40]. An hourly energy management system of a standalone hybrid PV/WT energy system integrated with a hydrogen subsystem was proposed to ensure the optimization of the utilization cost [41]. Various power management strategies of a standalone hybrid PV/WT/FC power system with a battery bank were presented to evaluate the battery energy efficiency [42].

For cluster #4, many optimization methods including particle swarm optimization, Genetic Algorithm, Multi-Objective algorithm, artificial neural networks, and improved bees algorithm were adopted to promote the performance of standalone hybrid PV/wind systems for actual application scenarios. To achieve the goal of minimizing $CO_2$ emissions, Life Cycle Costs, and dump energy, Genetic Algorithm was used to examine five cases of hybrid renewable energy systems for a typical residential [23]. The multi-objective optimization algorithm was adopted to calculate the Cost of Electricity, the Renewable Factor, and the Loss of Power Supply Probability for a hybrid PV/wind/diesel system and was checked in three case studies with different house numbers in the city of Yanbu, Saudi Arabia [24]. A hybrid optimization algorithm was proposed for a standalone hybrid wind and solar power system to improve the accuracy of size optimization and was tested for the load demand of the city of Khorasan, Iran [43]. To minimize the total net present cost of the hybrid WT/PV/FC systems with hydrogen storage in the northwest area of Iran, the optimal design and energy management were presented by using an intelligent flower pollination algorithm [44]. A hybrid genetic algorithm with particle swarm optimization considering all objectives was applied for the optimal sizing of a standalone PV/WT/Battery system to minimize the total present cost by satisfying the load demand for a remote house in Tehran, Iran [45].

For cluster #5, hydrogen tanks were introduced to hybrid wind/PV power systems as an energy storage option, which stores excess energy of the power system and satisfies the load demand of users when the power supply of the system is insufficient. Power management strategies for a standalone PV/WT system that stores excessive energy as hydrogen was developed to satisfy the load requirement through effective utilization of the fuel cell and electrolyzer under variable power generation situations [25]. A hybrid PV/WT/FC power system for standalone applications was presented and shown with a mobile house in which wind and solar energy were adopted as fundamental sources and a fuel cell was adopted as backup power as well as surplus energy was converted to hydrogen [26]. The hybrid system of PV, FC, and ultra-capacitor for power generation was studied to develop the integration of alternate energy sources with appropriate power control strategies for an autonomous system [46]. The renewable energy potential for a pilot area was introduced via HOMER using energy cost analysis and the feasibility of utilizing wind and solar energy with hydrogen storage units to satisfy the load demand as a standalone system for the region was also evaluated [47]. HOMER was adopted to identify the optimum size of a hybrid renewable energy system with a hydrogen storage unit for Bozcaada Island in Turkey by examining the cost of energy and the net present cost [48].

For cluster #6, mathematical models including a genetic algorithm and artificial bee colony algorithm were developed to estimate the performance of hybrid PV/wind energy systems located in remote islands. Different configurations of these systems under various scenarios were examined as well. A techno-economic evaluation and feasibility study for a standalone hybrid PV/wind/battery system in a remote island were carried out to attain an optimal system configuration with respect to the system cost of energy and net present cost [27]. An artificial bee colony algorithm was applied for the optimization of a hybrid PV/wind/biomass power system to meet the electrical requirement of a small area and the results were compared with that obtained from HOMER and particle swarm optimization algorithm [28]. The pumped hydro storage was built to serve the standalone hybrid PV/wind system which was applied to power a remote island and the technical feasibility of the proposed system was then examined [49]. For optimizing a hybrid PV/wind energy system for a remote island, a mathematical model with a genetic algorithm was developed and two systems with various wind turbine sizes were analyzed and compared [50]. Different unions of renewable energies and storage technologies for a standalone power supply system to power a remote island were investigated and compared and four configurations based on two scenarios were considered and analyzed [51].

For cluster #7, standalone hybrid PV/wind energy systems were viable for remote rural areas to satisfy the load demand. Studies on the techno-economic comparison, feasibility examination, and performance evaluation for the electrification option were completed to develop the hybrid system in rural areas. A case study on an electric microgrid in rural Kenya was presented which showed that rural electrification can contribute to critical improvement in efficiency per specialist and a comparing development in pay levels [29]. A techno-economic comparison of off-grid PV power plants with microgrids and mini-grids was presented to offer fundamental types of assistance to rustic families that are not associated with the electric framework in terms of annualized life cycle costs [30]. Four different scenarios that utilize the Integrated Renewable Energy System to satisfy the electrical and cooking needs of unelectrified villages in India were modeled and optimized [52]. The feasibility of a standalone system for supplying a medium-sized hotel's electrical energy demands in Kish Island, Iran was examined. Non-renewable and renewable energy sources were checked in view of their related expense and effectiveness [53]. Techno-economic examinations of a hybrid PV-wind simulation model were developed for small-scale application in an instructive structure in the northeast Indian state of Tripura. The tangible performance of a comparative plant in the commonsense state of the site was also evaluated [54].

It should be noted that just as some nodes are in cross zones of different clusters, the objectives of some articles may relate to more than one hot topic, for instance, Ma et al. presented a techno-economic evaluation and feasibility study for standalone hybrid PV/wind system in a remote island which can be classified as cluster #0, cluster #1, cluster #2, or cluster #6 [27]. To make the description easier to follow, this kind of node is treated as the default classification of the software.

### *3.2.2 Timeline Visualization*

Despite the landscape view presenting a spatial distribution of hot topics concerned by researchers in standalone HRES, the developments of such topics are not clear with time passing. As depicted in Fig. 3, timeline visualization arranges clusters over time which shows an intuitive sense of the development of hot topics along with time. The span of the publication year is listed at the top of the view. Serial numbers of clusters increase from top to bottom. Nodes for each cluster are located on the same horizontal timeline that contains two parts: one is a solid line in which related research is active and the other is a dotted line in which related research is comparatively inactive. The nodes with bigger sizes mean that they are either highly cited members or citation burst members or both. Corresponding references for these particular nodes are displayed below each timeline, and the most cited article is placed at the lowest location. Besides, the curved lines for any two nodes indicate that the two references are co-cited at least once. According to Fig. 3, studies on off-grid HRES started in 2003, which mainly focused on the feasibility and power management of the energy systems. As a hot topic, the feasibility study lasted 13 years (from 2003 to 2015) while power management of HRES continued to be a hot issue for 8 years (from 2003 to 2010). Hydrogen produced by HRES attracted researchers' attention between 2007 and 2014,which broadened the output of HRES and expanded application scenarios for energy systems. The application of HRES in remote islands, which was a hot topic between 2014 and 2018, proved that HRES is a viable electricity option for remote areas far from existing grids to achieve sustainable development. The latest hot spots include techno-economic analysis and case study, which started in 2013 and 2016, respectively, revealed that techno-economic analysis combined with case study may be the emerging trend for the research of HRES. For the sake of a deeper understanding of the timeline view, the largest three clusters and the cluster related to sustainable products, i.e., clusters #0, #1, #2 and #5 will be discussed further in the following part.

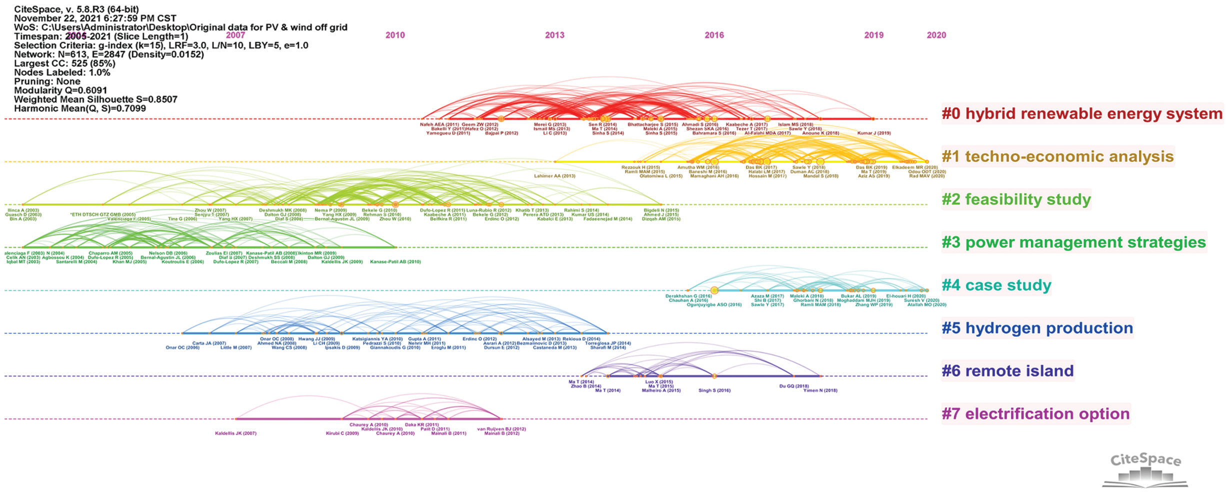


**Figure 3:** Timeline view of major clusters

Cluster #0 labeled with a hybrid renewable energy system is the largest cluster which consists of 120 references across 9 years from 2011 to 2019. In 2012, Bajpai et al. summarized the research on optimization, operation, energy control, and modeling of components for standalone HRES. Developments of systems and units as well as energy flow management techniques were discussed thoroughly [31]. Most of the big nodes for cluster #0 emerged between 2014 and 2016, as shown in Fig. 4. In 2014, Sinha et al. presented 19 software with their main features for HRES. The capabilities, limitations, and availability of different software have also been identified [15]. In 2015, Sinha et al. reviewed different optimization techniques and sizing methodologies for hybrid PV-wind systems. They presented studies on optimization during the last 2.5 decades and 16 optimization methods containing hybrid algorithms [33]. In 2016, Bahramara et al. introduced state-of-the-art of research for optimal planning of HRES by using HOMER software [16].

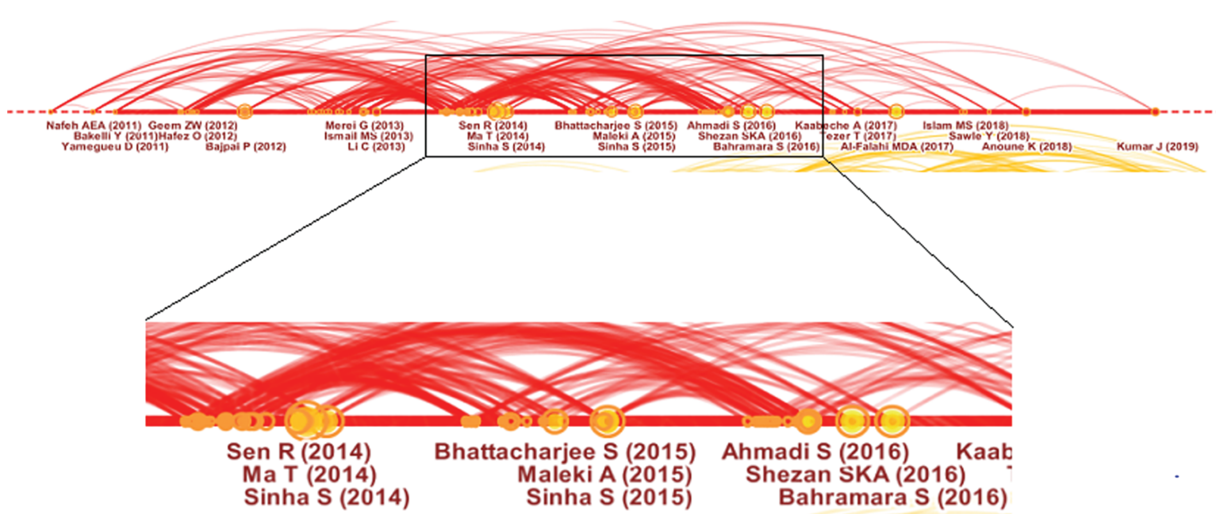


**Figure 4:** Timeline of cluster #0 hybrid renewable energy system

Cluster #1 labeled with techno-economic analysis is the second largest cluster which contains 110 nodes that last an 8-year duration from 2013 to 2020. Members with big size mainly located between 2016 and 2018, as depicted in Fig. 5. Mamaghani et al. presented the application of a standalone hybrid power system for rural electrification in Colombia and performed a techno-economic feasibility of the system by HOMER software in 2016 [17]. Hossain et al. proposed a multi-ideal mix of standalone HRES for a huge hotel centrally located in the South China Sea with a complete performance analysis. The technical and economic analysis of the system in view of net present cost and cost of energy was conducted by HOMER software in 2017 [36]. Mandal et al. investigated the potential application of HRES in the northern area of Bangladesh and evaluated the techno-economic feasibility of various system configurations, estimating an optimized configuration using HOMER software as well in 2018 [18].

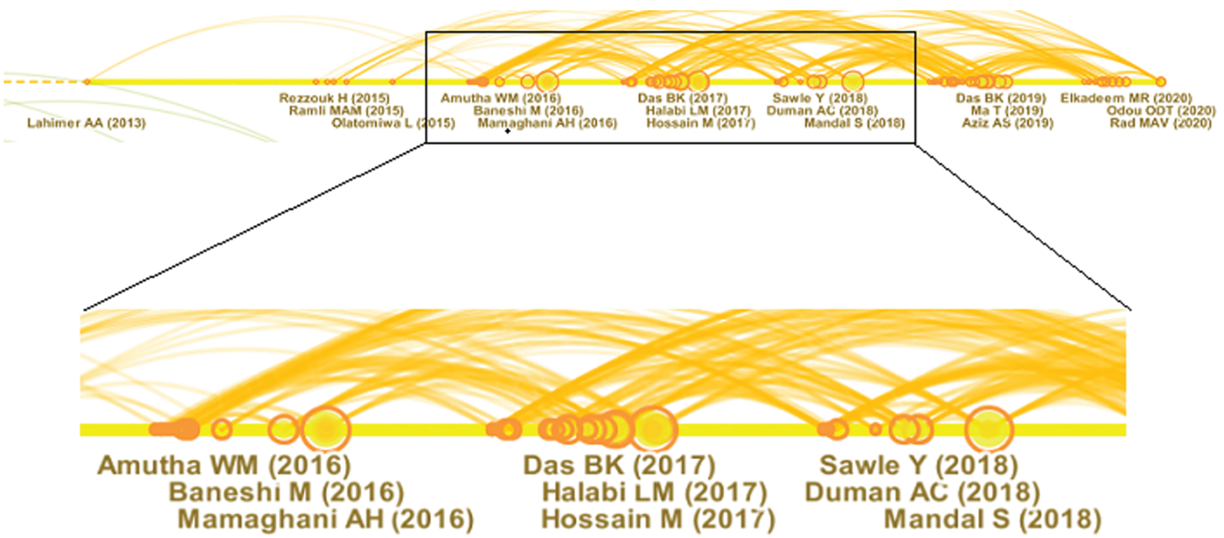


**Figure 5:** Timeline of cluster #1 techno-economic analysis

Cluster #2 marked with a feasibility study is the third largest cluster constructed by 101 members. As illustrated in Fig. 6, the cluster has a longer active period than the previous two clusters, which range an 11-year duration from 2005 to 2015, whereas the size of the big nodes of cluster #2 is smaller than that of cluster #0 and #1. It indicates that the big nodes in cluster #2 have less influence in the research area than that in clusters #0 and #1. Valenciaga et al. in 2005 assessed the performance of an extensive supervisor control for a hybrid wind and PV generation application using a comprehensive nonlinear model [55]. The biggest nodes for cluster #2 appear in the time from 2010 to 2012. Zhou et al. in 2010 reviewed the progress of the component simulations, system optimization, feasibility study, and control technologies for hybrid energy systems. The feasibility study proceeded on both time-series and statistical meteorological databases [19]. Among several commercially available system devices, Belfkira et al. in 2011 suggested the optimal number and type of components for a hybrid wind/PV/diesel power system which is utilized to minimize the total expense of the system while satisfying the load requirement by using a deterministic algorithm [37]. Bekele et al. in 2012 presented a feasibility study of a hybrid Hydro/Wind/PV system in Ethiopia. The National Meteorological Agency of Ethiopia was utilized for the assessment of wind and solar energy potentials while the basic electric needs of the community were estimated [56].

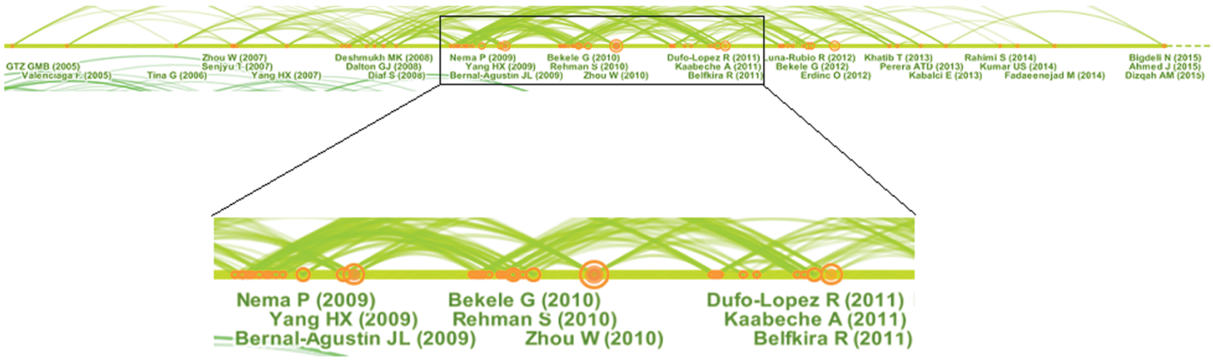


**Figure 6:** Timeline of cluster #2 feasibility study

Cluster #5 marked with hydrogen production is the sixth cluster constructed by 54 members. As shown in Fig. 7, the cluster has a 9-year active period lasting from 2006 to 2014. Unlike the three largest clusters, there are no obvious big members illustrated in the timeline of cluster #5, which indicates that the studies on standalone HRES along with hydrogen production were fascinating but not particularly hot during the 9-year. In 2009, Ipsakis et al. developed efficient power management strategies for a standalone solar-wind system that stores excessive energy as hydrogen for later utilization in a fuel cell. The impact of major operating variables on the strategies was investigated [25]. In 2010, Giannakoudis et al. proposed a systematic design approach that empowers the simultaneous consideration of synergies elevated among numerous sub-systems within a united power system and the uncertainty involved in the system operation [57]. In 2011, Eroglu et al. demonstrated a hybrid PV/wind/fuel cell power system applied in a mobile house, which used renewable energy as the primary source and a fuel cell as backup power for the system [26]. In 2012, Dursun et al. presented a model to evaluate the hydrogen production capacity of a standalone renewable hybrid power system sited in Istanbul, Turkey, and the results were compared with experimental data [58].

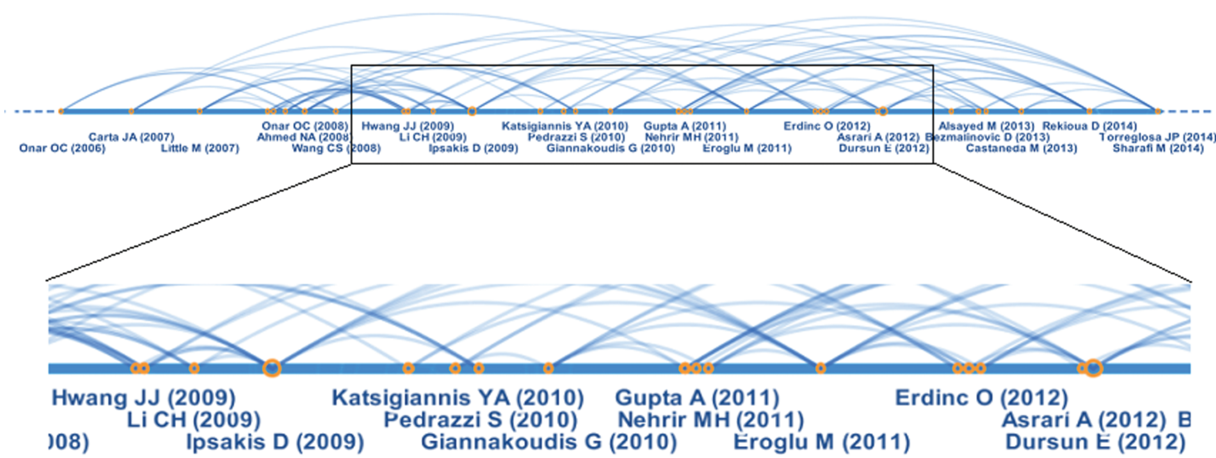


**Figure 7:** Timeline of cluster #5 hydrogen production

### 3.3 *Emerging Trends and New Developments*

The citation count of one term increasing rapidly in a short time indicates that the term is becoming a particular issue drawing widespread attention from the scientific community in the related field. This phenomenon, which is called citation bursts, can be detected using published articles or listed keywords as the objective term. Citation detection in which scientists should be interested may reveal the emerging trends of the research area and provide clues for new developments in such areas. In this section, keywords and references with citation bursts will be discussed based on the analysis of previous search records.

#### *3.3.1 Keywords with Citation Bursts*

Fig. 8 presents the top 20 keywords with the strongest citation bursts in standalone hybrid PV/wind systems. The column of bursts strength is followed by that of the start year, while the rightmost column presents the duration of citation bursts with red blocks. Among these keywords, *simulation* has a strong burst strength of 16.45 and lasts for 11 years, i.e., from 2005 to 2015, which indicates the theoretic analysis of standalone HRES via computer simulation has been conducted frequently in the episode. The keywords *array* associated with PV has the longest duration of citation burst lasts 13 years (2005–2017), whereas the burst strength is almost the lowest in the list, which means scientists pay continuous attention to the PV array but the related study is not very active. The most recent keywords with citation bursts are *homer*, *performance analysis*, and *microgrid*. Citation bursts of the first started in 2018, and that of the other two started in 2019, respectively. Even though they do not have strong bursts strength in comparison with other keywords in Fig. 8, these keywords can be regarded as indicators for emerging trends of standalone hybrid PV/wind energy systems since the citation bursts of these keywords may persist in the future.

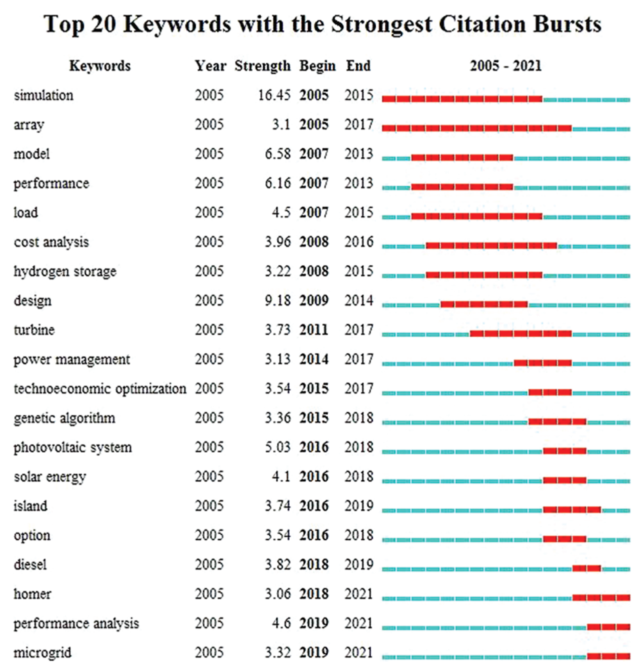


**Figure 8:** Keywords with the strongest citation bursts in the search field

### *3.3.2 Articles with Citation Bursts*

In addition to keywords with citation bursts, references detected in bursts analysis can be identified as other indicators for future work. The top 20 references with the strongest citation bursts are listed in Fig. 9. Just like Fig. 8, the rightmost column in Fig. 9 shows the duration of the bursts with red blocks while the publication year of one reference is denoted by the first dark blue block if the burst did not start in the publication year. References with the same start year of citation bursts are considered as a group. The reference which has the strongest burst strength in each group is chosen as the representative member that will mainly focus on if its burst strength is greater than ten. These representative references marked with stars in Fig. 9 are discussed as follows.

**Top 20 References with the Strongest Citation Bursts**

| References | Year | Strength | Begin | End | 2005 - 2021 |
|---|---|---|---|---|---|
| ★ Yang HX, 2007, SOL ENERGY, V81, P76, DOI 10.1016/j.solener.2006.06.010, DOI | 2007 | 13.04 | **2008** | 2012 | |
| ★ Yang HX, 2009, APPL ENERG, V86, P163, DOI 10.1016/j.apenergy.2008.03.008, DOI | 2009 | 11.95 | **2009** | 2014 | |
| Diaf S, 2008, APPL ENERG, V85, P968, DOI 10.1016/j.apenergy.2008.02.012, DOI | 2008 | 8.92 | **2010** | 2013 | |
| ★ Zhou W, 2010, APPL ENERG, V87, P380, DOI 10.1016/j.apenergy.2009.08.012, DOI | 2010 | 20.77 | **2011** | 2015 | |
| Ipsakis D, 2009, INT J HYDROGEN ENERG, V34, P7081, DOI 10.1016/j.ijhydene.2008.06.051, DOI | 2009 | 13.19 | **2011** | 2014 | |
| ★ Bernal-Agustin JL, 2009, RENEW SUST ENERG REV, V13, P2111, DOI 10.1016/j.rser.2009.01.010, DOI | 2009 | 13.09 | **2012** | 2014 | |
| Belfkira R, 2011, SOL ENERGY, V85, P100, DOI 10.1016/j.solener.2010.10.018, DOI | 2011 | 11.55 | **2012** | 2016 | |
| Rehman S, 2010, ENERGY, V35, P4986, DOI 10.1016/j.energy.2010.08.025, DOI | 2010 | 11.25 | **2012** | 2015 | |
| Bekele G, 2010, APPL ENERG, V87, P487, DOI 10.1016/j.apenergy.2009.06.006, DOI | 2010 | 9.29 | **2012** | 2015 | |
| Dufo-Lopez R, 2011, APPL ENERG, V88, P4033, DOI 10.1016/j.apenergy.2011.04.019, DOI | 2011 | 9.15 | **2012** | 2016 | |
| ★ Bajpai P, 2012, RENEW SUST ENERG REV, V16, P2926, DOI 10.1016/j.rser.2012.02.009, DOI | 2012 | 17.27 | **2013** | 2017 | |
| Erdinc O, 2012, RENEW SUST ENERG REV, V16, P1412, DOI 10.1016/j.rser.2011.11.011, DOI | 2012 | 13.79 | **2013** | 2017 | |
| Kaabeche A, 2011, ENERGY, V36, P1214, DOI 10.1016/j.energy.2010.11.024, DOI | 2011 | 10.99 | **2013** | 2016 | |
| Luna-Rubio R, 2012, SOL ENERGY, V86, P1077, DOI 10.1016/j.solener.2011.10.016, DOI | 2012 | 9.41 | **2014** | 2017 | |
| Bekele G, 2012, APPL ENERG, V97, P5, DOI 10.1016/j.apenergy.2011.11.059, DOI | 2012 | 9 | **2014** | 2017 | |
| ★ Sinha S, 2014, RENEW SUST ENERG REV, V32, P192, DOI 10.1016/j.rser.2014.01.035, DOI | 2014 | 13.64 | **2015** | 2019 | |
| Ma T, 2014, APPL ENERG, V121, P149, DOI 10.1016/j.apenergy.2014.01.090, DOI | 2014 | 12.02 | **2015** | 2019 | |
| Sen R, 2014, RENEW ENERG, V62, P388, DOI 10.1016/j.renene.2013.07.028, DOI | 2014 | 11.98 | **2015** | 2018 | |
| ★ Mamaghani AH, 2016, RENEW ENERG, V97, P293, DOI 10.1016/j.renene.2016.05.086, DOI | 2016 | 8.89 | **2018** | 2021 | |
| ★ Mandal S, 2018, J CLEAN PROD, V200, P12, DOI 10.1016/j.jclepro.2018.07.257, DOI | 2018 | 10.24 | **2019** | 2021 | |

**Figure 9:** References with the strongest citation bursts in the search field

In order to obtain the optimal component sizes of a hybrid PV/wind/battery power system, Yang et al. in 2007 proposed the Hybrid Solar-Wind System Optimization Sizing model [59]. They applied this model to ensure that the power system meets reliability requirements in terms of technique and economics. The citation burst of the reference lasted for 5 years from 2008 to 2012.

In 2009, Yang et al. published an article with a recommendation for an optimal model for designing hybrid PV-wind systems [60]. They used the model to plan a hybrid system to power a telecommunication relay station. The monitoring results of this project showed great integral qualities between wind and solar energy. The burst lasted 6 years from 2009 to 2014.

The utilization of a hybrid solar-wind energy source for an off-grid system will improve the system's efficiency and power reliability. In 2010, Zhou et al. summarized the research state of standalone hybrid PV/wind/battery energy systems including the simulation, optimization, and control technologies [19]. They found that efforts to raise the systems' performance, accurately predict output, and dependably incorporate them with different sources are still needed. The study has the strongest citation burst of 20.77 in the entire list and lasted for 5 years from 2011 to 2015.

Bernal-Agustin et al. introduced the most relevant papers on the design, simulation, optimization, and control of standalone hybrid systems in 2009 [38]. They found that the most popular systems are those consisting of Wind Turbines and/or a PV Generator and/or Diesel Generator, with batteries as energy storage. Besides, the design and simulation tools were briefly described. The citation burst for the article lasted for 3 years from 2012 to 2014.

In 2012, Bajpai et al. published a review of hybrid renewable energy systems [31]. They discussed the research of modeling, unit sizing, optimization, and energy management in detail, which aims to show a comprehensive understanding of the research in this subject. The article is ranked second by its strength of citation burst and has 5 years lasting from 2013 to 2017.

Sinha et al. presented 19 software with their main features and current status for HRES in 2014 [15]. They also reviewed related research work carried out by this software at different locations worldwide. The paper aimed to provide basic insight for researchers to identify and utilize suitable tools to study hybrid systems. The burst of citations of the paper lasted 5 years from 2015 to 2019.

The most recent article in Fig. 8 is announced by Mandal et al. in 2018 [18]. They evaluated the techno-economic feasibility of different hybrid energy system configurations in the northern region of Bangladesh and selected an optimized system by using HOMER software. Moreover, the authors discussed the social and economic benefits of the application of the hybrid system as well as their barriers and challenges. Meanwhile, Mamaghani et al. analyzed hybrid electrification systems for rural areas in Colombia in 2016 [17]. They discussed the techno-economic feasibility of hybrid systems with different climatic characteristics by HOMER software. The burst for the former started in 2019 and that for the latter started in 2018, respectively. The end of their bursts cannot be confirmed at the time of writing. Both of the articles that focused on the research of techno-economic feasibility are the hotspot articles of one hot topic that is generated in cluster analysis, i.e., cluster #1. Moreover, they both conducted the study of the hybrid system using the software of HOMER which is identified as one of the indicator keywords for emerging trends and new developments at the end of Section 3.3.1. Thus, it can be deduced that techno-economic analysis of hybrid wind and solar energy standalone systems using HOMER is one of the emerging trends in the HRES field.

It can be concluded that using HOMER software to conduct performance analysis and to determine optimal configurations are emerging trends and new developments in the research on HRES. HOMER which models micropower systems with single or multiple power sources such as solar energy, wind energy, biomass energy, etc., is designed for simulation and optimization of hybrid energy systems. HOMER efficiently identifies the most economical combination of components to fulfill both electrical and thermal requirements. By conducting extensive simulations on numerous system configurations, HOMER effectively optimizes the overall cost over the system's lifespan. Additionally, it provides valuable insights through sensitivity analyses on the majority of input variables. As a powerful tool for designing hybrid energy systems, HOMER provides a convenient way to present the optimal configurations of HRES for scientists, engineers as well as policymakers. Moreover, the results obtained from HOMER could be adapted by related companies to produce components or systems with high efficiency and reliability, which is beneficial for advancing the development of HRES.

### *3.4 Opportunities and Challenges for HPWESS*

Since substantial fossil fuels are quickly burned to meet power demands as the development of the world, people are suffering the depletion of these unrenewable resources and consequently, high price to pay for energy consumption as well as harmful effects on the environment and human beings resulting from air pollution emission of dust, greenhouse gases, etc., when fossil fuels are used to produce power, which is a serious threat to the sustainable development of human society. In this context, renewable energy systems have been widely applied especially for generating electricity. Among them, HPWESS, which adopts both solar energy and wind energy as primary energy resources, raises the dependability of the power supply and lessens the storage capacity for single energy resources, and gets rid of dependence on the utility grid. At the beginning of the 21st century, researchers started to explore this special kind of HRES. Case studies of HPWESS have been conducted generally by techno-economic analysis, which showed the feasibility of hybrid renewable systems. Meanwhile, power management strategies for HPWESS were developed to handle the complicated energy flux, which aims to operate the energy system efficiently. Thanks to researchers' efforts, HPWESS became a viable power supply option for remote islands and rural electrification of remote villages, moreover, HPWESS was established for hydrogen production and seawater desalination, which are beneficial for achieving sustainable development goals of the UN.

At the same time, there were some limitations existing in the former studies on HPWESS. The feasibility of the hybrid energy systems was usually evaluated by techno-economic analysis, which did not consider the potential impact on environmental and human development which are both essential factors for sustainable development. To comprehensively assess the performance of HPWESS, an overall framework considering economic, technical, environmental, and human development criteria should be constructed to determine the appropriate configuration. Most previous studies simply adopted supply-side management to conduct optimization of the hybrid energy systems, which ignored the actual power need of users and resulted in a mismatch of power generated and power consumed. To improve the power management of HPWESS and operate the systems more efficiently, power consumption fluctuation on the demand side should be integrated with renewable energy provision on the supply side to design more efficient energy systems. There are many choices for energy storage components which is an essential part for HPWESS to adjust the imbalance between generation and demand, however, the components for utilizing solar energy and wind energy were merely limited to PV panels and horizontal axis wind turbines (HAWT), respectively. Vertical axis wind turbines or bladeless wind turbines could be alternative plans for HPWESS that are operated on buildings or around people since the optional devices have merits like low noise and ease of installation and maintenance compared to HAWT. As for the generator of solar energy, energy and exergy analysis revealed that among all the components, the PV panels have the lowest conversion efficiency in HPWESS, which is far behind others' efficiency [61–64]. Advanced generators of solar energy that improve the photovoltaic conversion efficiency or use discarded thermal energy of insolation to generate additional power are expected to develop, which will promote the efficiency of the whole power system.

Today, the configurations of HRES are determined according to specific load demand, which may not meet the load requirement when energy consumption increases. How to expand the capacity of hybrid energy systems to satisfy various energy loads should be considered in the future. To enhance the reliability of power supply, hybrid energy systems can be integrated with existing grids. The integration needs a proper power management strategy to improve the performance of HRES. Furthermore, periodic maintenance of components such as wind turbines, PV panels, storage units, etc., will keep hybrid energy systems operating in the expected status. Thus, the maintenance schedule and corresponding cost are needed to be taken into account during the design process of HRES.

As mentioned above, to further promote the development of hybrid energy systems, researchers may pay attention to some issues. Firstly, the demand and supply side should be integrated to design the energy systems for higher suitability between energy production and consumption. Secondly, an overall framework considering economic, technical, environmental, and human development criteria should be constructed, which will present a comprehensive evaluation of energy systems. In addition to PV panels and HAWT, advanced generators for solar energy and wind energy should be developed to attain better performance of the hybrid energy systems.

### *3.5 Limitations of the Bibliometric Analysis*

Bibliometrics, such as the h-index or times cited, offer a particular perspective on the impact and influence of research. Nevertheless, due to the nature of research practices and scholarly publishing mechanisms, these metrics may not always be entirely precise and comprehensive.

Considering that no one article database includes all articles ever published, the results obtained from CiteSpace which sets the Web of Science as the input database cannot analyze all the relations between publications in a specific field. Moreover, a scholar's output may consist of only a few "units", but these few works can have a profound influence on a specific field and greatly contribute to the advancement of scholarship in that discipline. The application of standardized metrics, such as the h-index, may face challenges in accurately evaluating such scenarios. In certain disciplines, extensive research teams may generate numerous research papers, with each paper involving dozens or even hundreds of authors. Consequently, the impact metrics of team members may appear exceptionally high, but they may not necessarily reflect the individual significance and prominence of each researcher within the field.

## 4 Conclusion

As a widespread renewable resource, solar energy or wind energy is generally utilized in power systems to supply electricity. To improve the dependability and efficiency of power systems as well as to lessen energy storage capacity, hybrid solar-wind power systems working in standalone mode are more viable for remote areas in which the power grid is difficult to extend. Many research projects have been done in recent twenty years to develop the special HRES to meet energy demand for remote districts such as remote rural communities and remote islands. The paper aims to offer a systematic review of research on standalone hybrid solar-wind energy systems for scientists and engineers to obtain a comprehensive understanding to promote the systems in the future. More than 1,500 published articles extracted from the WOS database are taken into consideration. The search record is analyzed by bibliometric methodology and processed by the CiteSpace software to demonstrate the output in the form of figures and tables. Productive countries and highly cited authors are figured out, and hot topics in the research field are shown by landscape view and timeline view. Besides, emerging trends and new developments for the particular HRES are predicted based on the analysis of citation bursts of keywords and articles. The study of this paper helps researchers and policymakers to promote the utilization of renewable energy in the future, which will be beneficial for reducing carbon emissions and sustainable development of human society. The key findings of the paper are concluded as follows:

- Published articles in the field involved more than 130 countries and more than 4,000 authors, which reveals a worldwide interest in the utilization of HRES, especially for districts far away from the power grid. The top 10 productive countries and the two 20 highly cited authors are identified. It is found that developing countries pay more attention to taking advantage of HRES in remote areas.

- Eight clusters (hot topics) for standalone hybrid solar-wind energy systems are generated by processing the search record, i.e., #0 hybrid renewable energy system, #1 techno-economic analysis, #2 feasibility study, #3 power management strategies, #4 case study, #5 hydrogen production, #6 remote islands, #7 electrification option.
- Two hotspot articles for each hot topic are marked in the landscape view. The content of these articles is summarized and listed in Table 3, which shows the selected articles are highly associated with the cluster label. It proves that cluster analysis of the software is credible for processing numerous data for classifying meaningful groups.
- Every cluster is arranged in a line from the timeline view. Representative references of the largest three clusters as well as the cluster about hydrogen production are discussed, which presents an intuitive sense of the development of hot topics along with time.
- Based on citation bursts analysis, the top 20 keywords with the strongest citation bursts as well as the top 20 references with the strongest citation bursts are demonstrated. Considering the most recent keywords and references with citation bursts, it is predicted that emerging trends and new developments for standalone hybrid solar-wind energy systems include performance analysis especially techno-economic analysis, the development of microgrid comprised by hybrid energy system, the application of HOMER software for modeling and optimization of the system.
- HPWESS became a viable power supply option for remote islands and rural electrification of remote villages, moreover, HPWESS was established for hydrogen production and seawater desalination, which are beneficial for achieving the sustainable development goals of the UN.
- To further promote the development of HRES and determine the appropriate configuration, the demand and supply sides should be integrated into the design of the energy system. Meanwhile, an overall framework considering economic, technical, environmental, and human development criteria should be constructed. In addition to PV panels and HAWT, advanced generators for solar energy and wind energy should be developed to attain better performance of the hybrid energy system.

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**Availability of Data and Materials:** The authors have no authority to share the data.

**Conflicts of Interest:** The authors declare that they have no conflicts of interest to report regarding the present study.

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