Results in Engineering 16 (2022) 100481

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

A comprehensive scientometric analysis on hybrid renewable energy systems in developing regions of the world

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ARTICLE INFO

Keywords:
Renewable energy
Bibliometric analysis
Energy crises
Solar
Wind
Developing regions

ABSTRACT

Energy crises, increasing electricity prices, and having no access to the grid electricity are the leading issues in developing countries of Asia, the Middle East, and Sub-Saharan Africa. Developing hybrid renewable energy systems in off-grid or grid-connected modes is the best way to overcome developing countries' economic and energy crises. However, the development of hybrid renewable energy systems faces severe technical and related economic challenges. This article provides an updated and comprehensive resource and economic overview of developed hybrid renewable energy systems in different locations in these aforementioned regions. The resource assessment shows that for economical hybrid energy system the average annual wind speed and average annual solar radiation should be 5 m/s and 5 KWh/m^2 respectively. This paper also provides a big picture of renewable energy impacts, challenges in the architecture of hybrid systems, and key organizations working in this domain in the developing regions. According to our review, hybrid optimization model for electric renewable, particle swarm optimization and genetic algorithm are frequently used tools for the optimization and sizing of hybrid energy systems. The map of hybrid renewable energy system research in developing regions is not available. Our study gives energy scenario and clear map of hybrid energy in developing regions of the world. The scientometric review of 2000 bibliographic data obtained from the Scopus database to perform co-author and co-occurrence analysis in this study. The data is used to trace the research pattern and thus to identify the most impactful authors, institutions, and countries in the hybrid renewable energy systems domain to obtain recommendations and make policies for the future uninterrupted and carbon dioxide emission free energy systems. The results of scientometric analysis shows that the Wang X. is the most prolific author, while India and Tanta University are the most productive country and institution in this domain. The scientometric analysis result will be beneficial in determining the future research directions in the hybrid renewable energy systems field.

1. Introduction

Increasing demand for electrical energy, electricity prices, and CO_2 emission daily is the biggest challenge for the sustainable world. Electricity consumption in both developed and developing countries is increasing sharply at the rate of 1% and 5% per year respectively [1]. In 1997, 38 countries adopted KYOTO protocol to overcome this rapid climate change [2]. Nowadays, 80% of electricity is generated through the combustion process of conventional resources such as coal, oil, and gas, making electricity costlier and polluting our environment [3]. A high concentration of carbon dioxide leads to global warming [4]. It is expected that at the end of this century, the world's temperature will be increased up to 3–6° Celsius [3]. It was projected that in 2010 nearly 1.3 billion people in the world lived without access to electricity [5]. Since the last decade, many researchers across the globe have shifted their focus towards Hybrid Renewable Energy Systems (HRESs) to supply cheap, reliable, and CO_2 emission-free electricity to both grids connected and off-grid connected areas. For this purpose, many case studies have been performed to optimize HRES as of now.

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https://doi.org/10.1016/j.rineng.2022.100481
Received 1 April 2022; Received in revised form 26 May 2022; Accepted 3 June 2022
Available online 11 June 2022

Nomenclatures and abbreviation

Nomenclature Abbreviation
Cost of Electricity COE
Net Present Cost NPC
Renewable Energy RE
Hybrid Renewable Energy Systems HRESs
Sustainable Development Goals SDGs
Small Renewable Energy Program SREP
Middle East and North Africa MENA
Electric Vehicles EVs
Virtual Power Plants VPPs
Renewable Energy Sources RESs
Hybrid Optimization Model for Electric Renewable HOMER
National Renewable Energy Laboratory NREL
Particle Swarm Optimization PSO

Asian countries are blessed with the vast potential of renewable energy sources. Malaysia has great potential for renewable energy, but these renewable resources have been utilized as single sources of electricity production at small scales. In 2013, M. Fadaeenejad reported that photovoltaic-wind-battery could be the most cost-effective combination for the rural electrification of small villages in Malaysia [6]. In 2017, Hongyang Zou did a technical and economic analysis of large-scale PV power generation in China [7]. That study has been performed to fulfill the residential load of five different cities, and both grid-connected and off-grid PV system scenarios have been considered. Developing countries like Pakistan are looking for sustainable development in rural areas to meet electricity demand. In 2018, a case study was performed for a small rural area of Toba Tek Singh in Pakistan. This study shows grid-connected PV system without a backup system will be feasible [8]. Similarly, another case study consisting on solar, wind, hydro, and biomass sources has been performed which shows that off-grid system has less cost of electricity as compared to on-grid system for rural area in Ghulam Shah town, Pakistan [9].

The trend of using renewable resources for electricity generation in the Middle East is significantly increasing. Arabic countries like Saudi Arabia are heavily dependent on conventional power plants to meet the daily requirements of electricity. A techno-economic analysis for a photovoltaic grid-connected system in different locations in Saudi Arabia has been performed to find its feasibility for diminishing the use of fuel [10]. It has been reported that dual-axis PV tracking system is cost-effective and reduces carbon dioxide emission instead of a single-axis PV system with diesel for Khorfakkan, Sharjah [11]. Furthermore, a standalone photovoltaic (PV) panel with diesel as backup has been studied, which shows the least cost of electricity as compared to grid extension for the small rural communities in Palestine [12]. The Hybrid Optimization Model for Electric Renewable (HOMER) tool has been used for the techno-economics analysis to design a hybrid renewable energy system PV-wind with hydrogen as a storage option for the Bozcaada Island in Turkey [13]. A case study with six different configurations of renewable sources to fulfill the demand of Minya Governate (Egypt) has been reported [14]. After investigation, results show that off-grid PV/FC hybrid system was the most feasible combination. Now, a hybrid renewable energy system is implemented excessively where grid electricity is available. The grid-connected hybrid renewable energy system has been used for education buildings in Iran which was very cost-effective [15].

Although renewable resources such as wind and solar energy are abundant in Africa, still one-third of its population is living without having access to electricity. In Ghana, HRES of PV/FC/Battery and diesel generator as the base case is investigated to give power to the mining industries in the remote areas because grid extension is not feasible [16]. TR Ayodele also reported that wind energy would be more feasible had it been utilized in those cities of Nigeria where hydro energy is being utilized [17]. In addition, Samuel Gabra performed a techno-economic comparison between micro-grid wind and PV with diesel system, and results show that PV-diesel will be more economical for Africa [18].

Although HRES is the future, there are some challenges in implementation. In 2019, Abhishek Tiwary proposed PV-wind-biomass-battery as the most suitable combination to meet electricity demand in UK and Bulgaria [19]. However, it faced two main challenges, project cost and reliability on conventional methods. A case study in Åland Islands has been analyzed to extend wind energy generation to increase the circular economy [20]. Similarly, a Techno-economic analysis has been performed to compare the feasibility of a hybrid renewable energy system for 800 and 2000 houses in the south of Ireland [21].

This review paper has performed a detailed techno-economic and scientometric analysis of hybrid renewable energy systems in developing countries. This paper is organized into seven sections. Section 1 is about the introduction. The detailed techno-economics analysis has been discussed in section 2 that includes renewable resources availability assessment, cost of electricity, and net present cost of the projects in the developing regions of Asia, the Middle East, and Africa. Section 3 provides comprehensive information about the architecture, methodologies, and software used to develop hybrid renewable energy systems. In section 4, a scientometric analysis by co-author and co-occurrence is explained then findings and results of our research are discussed in following section 5. Section 6 gives information about the R&D, challenges, and limitations of renewable energy in various regions. Finally, conclusion is enclosed at the last section.

1.1. Global trends of hybrid renewable systems research

The first publication on hybrid renewable energy systems for electrification was in 1983, and then the number of documents increased significantly throughout the period. As illustrated Fig. 1, in the last decade of the 19th-century hybrid renewable energy system research publications were very low. However, it had experienced a sudden increase in the number of research publications in 2007. In 2021, the highest number of publications, 402, has been recorded in this domain. The increasing trend in numbers indicates the profound interest of researchers, institutions, and policymakers. Energy from fossils fuels is expensive and harms our environment, so the hybrid renewable energy systems domain is a central theme of sustainability researchers and institutions that can be explored extensively to explore the research pattern of hybrid renewable energy system research. In this paper, a co-authorship analysis by countries, institutions, and authors, while a co-occurrence analysis by keyword has been performed.

1.2. Summary of renewable energy scenario in Asia, the Middle East and Africa

In Asia, solar and wind energy resources are abundant and have been harnessed at large scale. Biogas is another highly under-used renewable source in Asia, which can be used in hybrid mode to increase the efficiency of designed HRESs. Most of countries in the Middle East experience great amount of annual solar irradiation and wind speed, which has been utilized in stand-alone or hybrid modes to fulfill the energy demands. Africa is the most underdeveloped region and most of the population heavily relies on diesel generators for the electricity. In Africa, solar resources are immense, and thus can be utilized with diesel generator as hybrid system to produce cheap, clean, and green electricity.

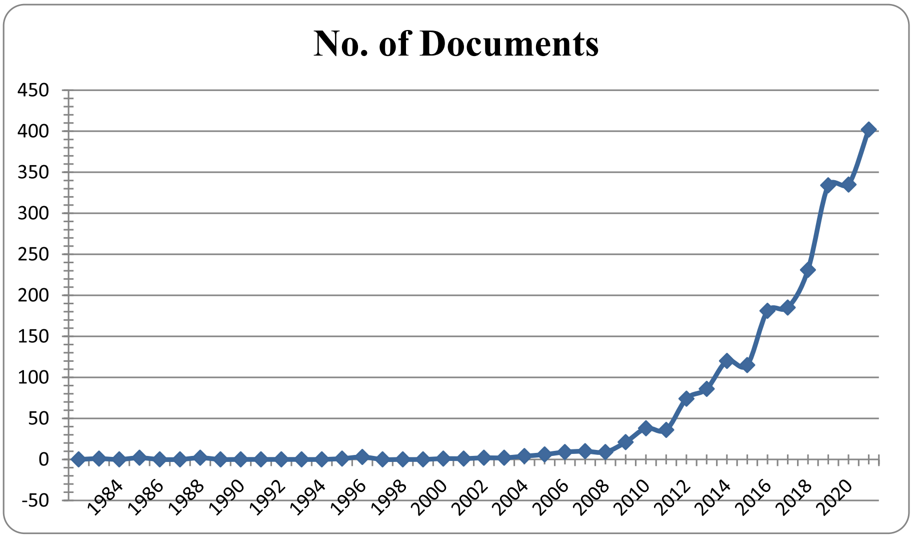

Fig. 1. The trend in hybrid renewable energy system research by publication count from 1983 to December 2021.

2. Pre-designed hybrid renewable energy systems

2.1. Pre-designed HRESs in Asia

Many hybrid renewable energy systems have been developed in Asia to meet electricity demand and rural electrification. Indonesia has considerable potential for solar and wind energy in the onshore area. In 2013, techno-economically PV/wind/diesel with a battery as a storage option was designed to meet the electricity demand for the remote area [22]. Pre-HOMER and Post-HOMER analyses have been performed to propose the optimum cost-effective renewable energy resources configuration for the rural electrification of remote village Palari, India [5]. For storage purposes, four renewable resources, hydro, PV, bio-diesel, wind, and battery, have been used, and analysis shows that off-grid generation will be more cost-effective than the grid extension. In 2015, a hybrid renewable energy system comprising of PV/wind/battery/diesel was studied for the rural electrification of remote village Siyambalanduwa (Sri Lanka) consisting of approximately 150 houses with a daily demand of 270 KWh [23]. Results show that the proposed configuration is equally acceptable for both off-grid and on-grid systems. In 2016, RETScreen and HOMER were employed for the techno-economics analysis of wind-diesel and PV-diesel energy systems Kutubdia Island, Bangladesh. Results indicate that PV-diesel configuration is more cost-effective and feasible for Kutubdia Island [24]. In 2017, HRES consisting of PV-Biomass had been techno-economically analyzed. Results show it was suitable for agriculture and resident needs for a small village in district Layyah, Pakistan [25]. Two decentralized power station in Sabah has been designed to fulfill energy demand in Malaysia [26]. Results show that PV-diesel-battery is the best configuration to meet the residential electricity demand for Pulao Banggi and Tanjung Labian in Malaysia. In 2019, a case study was performed in Dongola, Sudan, for rural electrification [27]. The obtained results show that PV/wind/diesel/battery was the optimum configuration for the residential and agriculture demand in Dongola. Another technical and economic feasibility of HRES consisting of wind/diesel/battery has been analyzed with different types of batteries to provide electricity to 280 houses in Lanzhou, China [28]. Table 1 shows the summary of some pre-designed HRESs in Asia.

2.1.1. Available renewable resources assessment indifferent regions of Asian countries

To limit greenhouse and carbon dioxide gas emissions, developments in renewable technologies are very important [29]. Prices of fossil fuels are increasing due to rapid depletion of these resources [30]. There is a need to develop new technologies and innovations to access clean, green, and cheap electricity [31]. Wind speed and solar radiations are two crucial parameters while choosing the optimum configuration of HRESs. Asian countries have great potential for wind and solar energy. It is clear from Fig. 2 that Siyambalanduwa (Sri Lanka) has the highest annual wind speed of 6 m/s, while Chattisgarh (India) has the lowest annual wind speed of 3.507 m/s. It can also be seen that only Siyambalanduwa (Sri Lanka) and Dongola (Sudan) have more wind potential than the other four regions. The annual average wind speed in Chattisgarh (India) and Temajuk (Indonesia) is almost similar, while in Kutubdia (Bangladesh) and Lanzhou (China), the annual wind speed is above 4 m/s.

According to Fig. 3, the Temajuk region in Indonesia experience the most average annual solar radiance with 8.15 KWh/ $\mathbf{m}^2$. On the other hand, Kutubdia in Bangladesh has a lower value of 4.811 KWh/$\mathbf{m}^2$ as compared to other given regions. Overall, all the mentioned regions in Fig. 3 have good average annual solar radiance, which demonstrates great potential to explore the field of solar energy.

Table 1
Summary of pre-designed HRESs in asia.

Reference	Country	Hybrid System	Application	Cost of Electricity $/KWh	Net Present Cost $
[5]	India	Hydro/PV/Bio-diesel/Wind/Battery	residential	0.42	673147
[22]	Indonesia	PV/Wind/Diesel/Battery	onshore area	0.751	30921
[23]	Sri Lanka	PV/Wind/Diesel/Battery	village	0.34	553000
[26]	Malaysia	PV/Diesel/Battery	residential	0.302	9345510
[27]	Sudan	PV/Wind/Diesel/Battery	agriculture	0.387	24160000
[28]	China	Wind/Diesel/Battery	residential	0.471	7735646

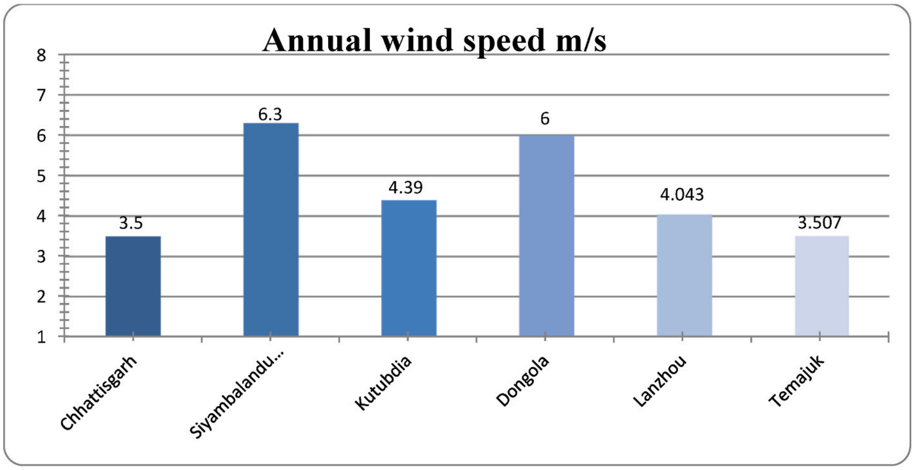

Fig. 2. Comparison of annual wind speed in different regions of Asia.

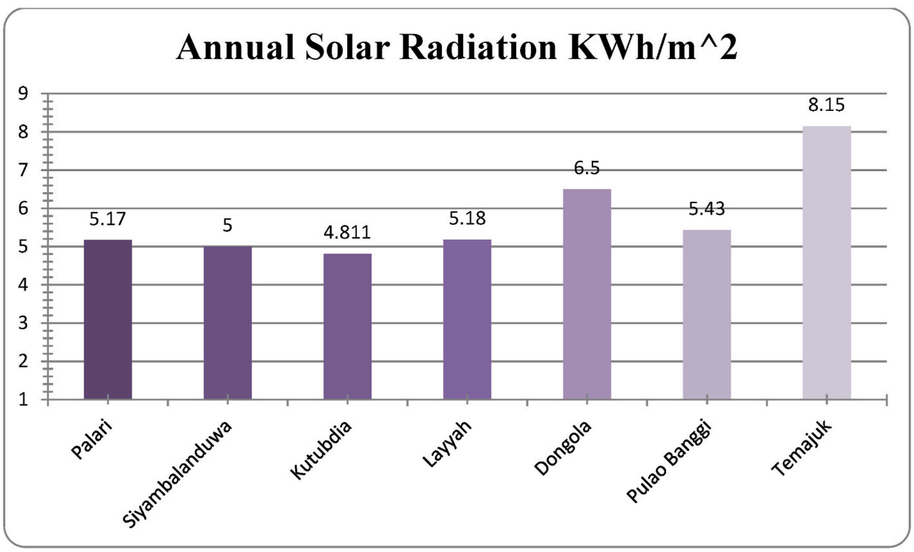

Fig. 3. Comparison of annual solar radiations in different regions of Asian countries.

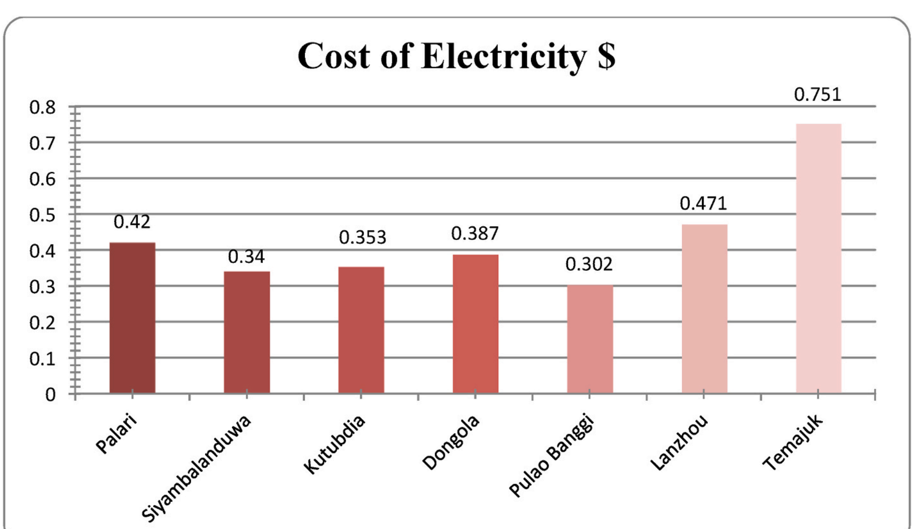

Fig. 4. Comparison of COE of different HRESs projects in Asia.

2.1.2. Cost of electricity and present net cost of developed HRESs in Asian countries

While designing the hybrid renewable energy systems, sensitive parameters such as Cost of Electricity (COE) and Net Present Cost (NPC) are essential. Every HRES aims to provide cheap electricity, while lower net present cost attracts the investors and utilities. Fig. 4 shows the COE of various HRESs projects in Asia. According to Fig. 4, the HRESs project in Pulao Banggi in Malaysia has the least COE of 0.302 $, while Temajuk (Indonesia) has a high COE of 0.751 $. COE in Palari (India) and Lanzhou (China) is 0.42$ and 0.471$ respectively. The COE in other regions mentioned is quite similar.

Net present Cost plays a vital role while the economics analysis of HRESs. Every project aims to minimize the NPC. A comparison of NPC of various projects in Asia is shown in Fig. 5. It can be noted from the Fig. 5 that the HRES project in Dongola (Sudan) has the highest NPC, while the Temajuk (Indonesia) project has the least NPC.

2.2. Pre-designed HRESs in the Middle East

Hybrid renewable energy systems depend upon the available renewable resources such as solar, wind, hydro biogas, etc. Middle East countries have excellent availability of solar and wind. In recent decades, many HRESs have been developed in different countries of the Middle East. In 2014, a hybrid system consisting of PV/diesel/battery was optimized with a Genetic Algorithm (GA) to provide electricity in remote areas of Palestine [12]. The economic analysis showed that the developed HRES was cheaper than grid extension. A technical and economic analysis of wind/PV with hydrogen production and storage was tested in Bozcaada Island, Turkey [32]. In 2015, a renewable energy configuration with a flywheel as storage was analyzed to identify its economic and environmental impacts at the Makkah city [33]. In 2016, a case study with six different configurations of renewable energy resources was performed to install at Minya Governate (Egypt) [14]. HOMER results show that PV/FC is the best configuration concerning the cost of electricity and net present cost. Yemen is the least developed country in the Middle East but has good potential for renewable energy. A hybrid system has been optimized to provide electricity to rural and desert areas in Yemen because grid extension was not possible due to political and economic issues [34]. Hydrogen gas as fuel from renewable resources is an emerging technology that will decrease carbon dioxide emissions. In Izmir, technical and economic analysis has been performed to refuel 25 electric vehicles with hydrogen gas [35]. A PV/wind/battery hybrid system has been designed to supply power to a research laboratory in KhshU Site, Iran [36]. Results show that an increase in wind speed does not impact NPC. In 2019, a techno-economic analysis of PV/hydro/diesel/battery combination was performed to provide clean and reliable electricity to a rural village in Iraq [37]. Table 2 shows a summary of pre-designed HRESs in the Middle East.

2.2.1. Available renewable resources assessment in different regions of the Middle East

Renewable technologies in PV and wind energy are more developed than other potential renewable resources such as geothermal, biogas, and Ocean Thermal Energy Conversion (OTEC). Assessment of available renewable energy resources plays an essential role while developing HRESs.

It is clear from Fig. 6 that Bozcaada and Izmir sites in Turkey have good potentials to install wind/HRES systems due to the average wind speed above 5 m/s. On the other hand, Minya Governate and KhshU sites in Egypt and Iran have a wind speed of nearly 4 m/s, which is very low and makes these sites unfavorable to make wind farms.

Fig. 7 shows the comparison of annual solar radiation in different regions of the Middle East. According to the figure, the Sakran site in Iraq has excellent potential for PV compared to other sites. Bozcaada Island has experienced the lowest annual average solar radiation of 4.36 KWh/mˆ2. Interestingly, all the below-mentioned sites in Fig. 7 indicate excellent potential for solar energy, which can be utilized efficiently by more development and investments in solar technologies in the future.

2.2.2. COE and NPC of pre-designed HRESs projects in the Middle East

The least cost of electricity attracts customers to use hybrid renewable energy systems, while low net present cost makes HRESs economically feasible for the investors. Fig. 8 shows the NPC and Fig. 9 shows the COE of pre-designed HRESs projects in the Middle East. According to Fig. 8, the hybrid renewable energy project in Makkah (Saudi Arabia) has the highest NPC; while the Fig. 9 illustrates that the Bozcaada Island project has the highest COE.

2.3. Pre-designed HRESs in Africa

Almost 600 million people in Sub-Saharan African countries live without electricity [38]. Grid extension and installation is the first and foremost choice for electrification, but less electricity demand and high installation cost make it difficult to provide electricity to about 600 million people in Sub Saharan [39]. In that case, off-grid hybrid renewable energy systems become more suitable for rural

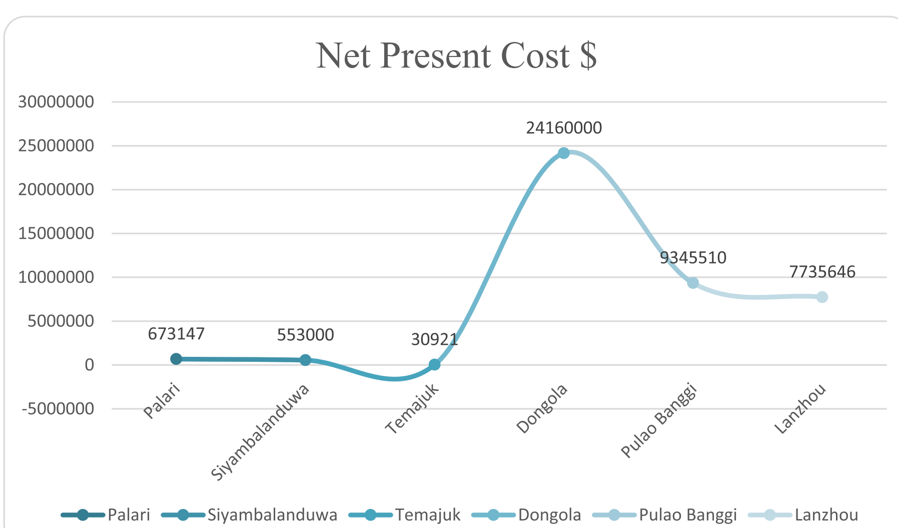

Fig. 5. Comparison of NPC of different HRESs projects in Asia.

Table 2
Summary of pre-designed HRESs in the middle east.

Reference	Country	Hybrid System	Application	Cost of Electricity $/KWh	Net Present Cost $
[12]	Palestine	PV/Diesel/Battery	Remote community	0.259	– – – –
[32]	Turkey	PV/Wind/Hydeogen	Island	0.83	11960698
[33]	Saudi Arabia	PV/Diesel/Battery	Makkah city	0.37	6278274662
[14]	Egypt	PV/FC	Residential building	0.058	50321
[34]	Yemen	PV	Rural area	0.334	62450
[35]	Turkey	Wind/PV/Battery	Hydrogen refueling station	0.146	4430000
[36]	Iran	PV/Battery	Renewable energy laboratory	0.546	8173
[37]	Iraq	PV/Hydro/Diesel/Battery	Rural electrification	0.054	113,201

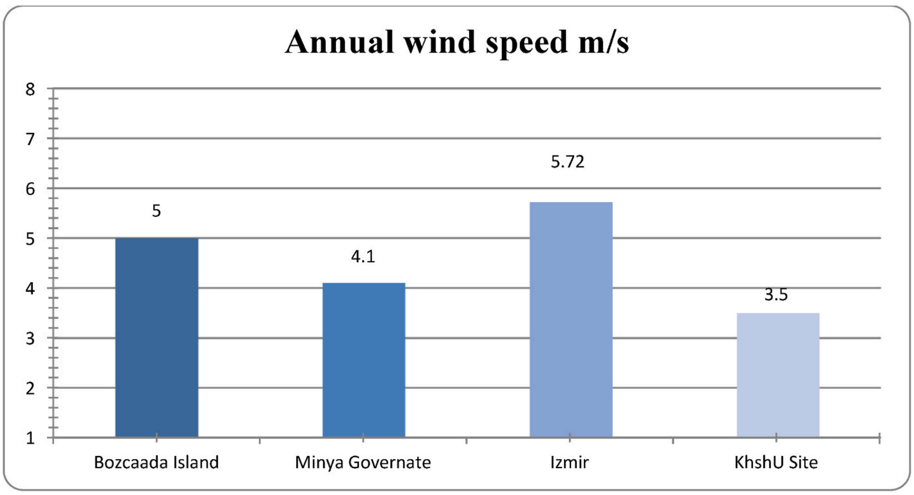

Fig. 6. Comparison of annual average wind speed in different regions in the Middle East.

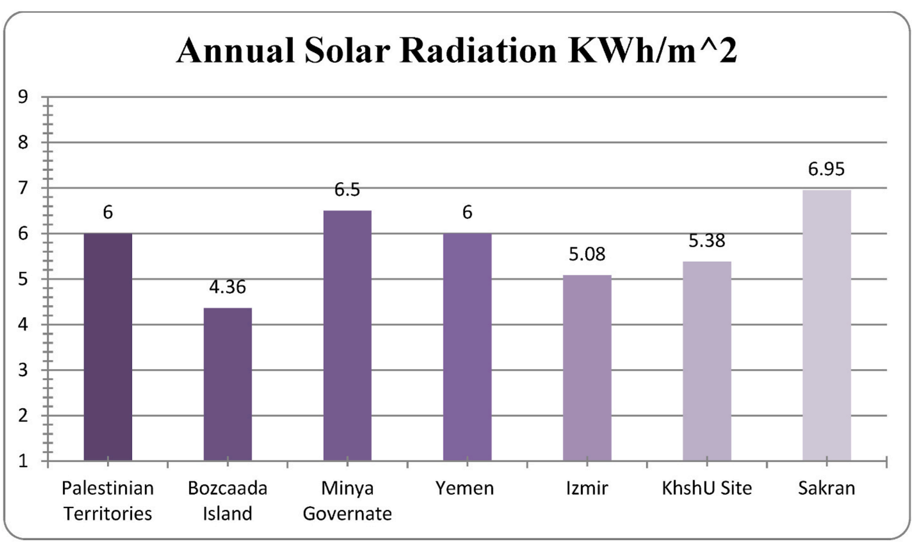

Fig. 7. Comparison of annual solar radiations in different regions in the Middle East.

electrification. Since the last two decades, many grid-independent hybrid renewable energy systems have been optimized, analyzed, and installed in Africa. In 2009, a hybrid system consisting of solar, wind, diesel, and battery was employed to meet 52.049 MWh/yr for the rural electrification of 200 families in Ethiopia [40]. Another study in Nigeria for the Plateau state revealed that PV/diesel/battery was the best possible configuration [41]. This study shows the effect of interest rate and cost of a PV system on the COE and NPC. The economic analysis of solar, wind, diesel, and battery was performed to supply electricity for the residential areas in southern Ghana [42]. The proposed system was also applicable to other locations with similar wind speeds and solar radiation potential. the economic analysis of solar, wind, diesel, and battery was performed to supply electricity for the residential areas in southern Ghana [43]. This case study examined the standalone diesel system, the standalone PV system, and the hybrid PV-diesel-battery system. Results show that PV/diesel/battery was optimum with 25% PV penetration. In southern Cameroon, HOMER software has been employed for the feasibility analysis of PV-diesel-small hydro-battery for rural electrification [44]. The developed system had similar outcomes as policymakers and investors in Cameroon. In 2019, the hybrid system

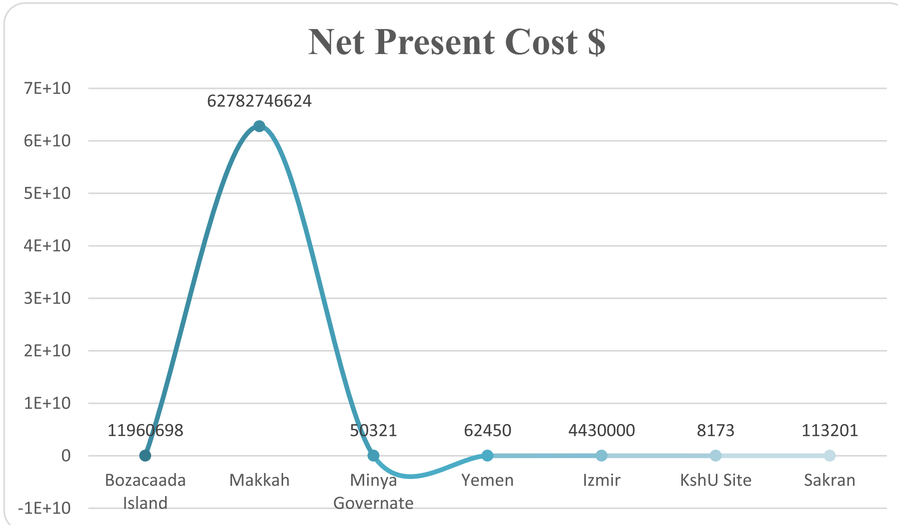

Fig. 8. Comparison of NPC of HRESs projects in the Middle East.

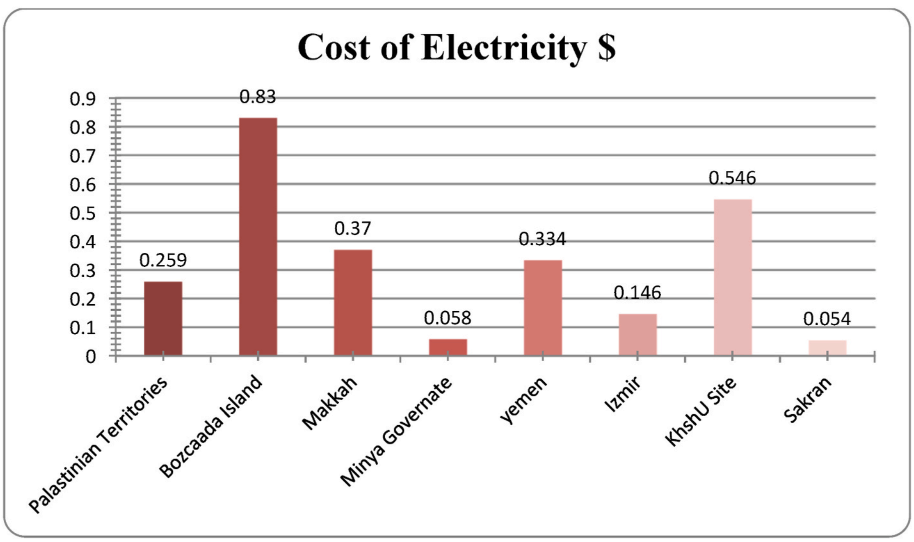

Fig. 9. Comparison of COE of HRESs projects in the Middle East.

consisting of PV, diesel, and battery systems was designed to fulfill the demand of a rural village named Fouay in Benin [45]. Table 3 shows the summary of pre-designed hybrid energy systems in Africa.

2.3.1. Available renewable resources assessment in different regions of Africa

Solar is the most abundant energy source, but there is still a need to develop more new technologies to efficiently produce clean and green electricity out of it. According to the report of IEA [46], from 2008 to 2050, solar PV technology can prevent 100 Gigatons of carbon dioxide emission in the atmosphere. So, while installing HRESs, the assessments of availabilities become critical [47]. Fig. 10 shows the solar resources in the different regions of Africa. Fuoay village in Benin experienced the most solar radiation annually. On the other hand, in North Algeria average annual solar radiation is less than other mentioned sites.

Wind is another prolific energy source and currently approximately more than 28,000 wind turbines have been installed and operating worldwide to produce electricity [46]. In installing a wind farm for electricity production, analysis of wind speed is very important [48]. Fig. 11 gives information about the annual wind speed in different sites in Africa. According to Fig. 11, Southern Ghana has the highest average annual wind speed of 5.11 m/s.

Table 3
Summary of pre-designed HRESs in africa.

Reference	Country	Hybrid System	Application	Cost of Electricity $/KWh	Net Present Cost $
[40]	Ethiopia	PV/diesel/battery	remote	0.383	239756
[41]	Nigeria	PV/diese/battery	rural and semi-urban electrification	0.348	3920000
[42]	Ghana	PV/diesel/battery	remote	0.281	3905600
[43]	Algeria	PV/diesel/battery	remote	0.26	617489
[44]	Cameroon	PV/hydro/diesel/battery	electrification of research unit	0.433	191700
[45]	Benin	PV/diesel/battery	rural electrification	0.207	555492

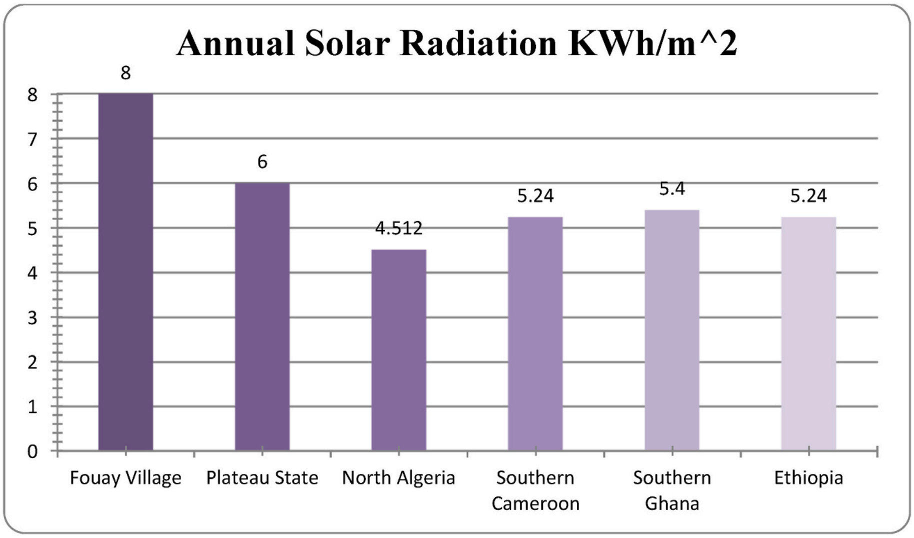

Fig. 10. Comparison of annual solar radiation in different regions in Africa.

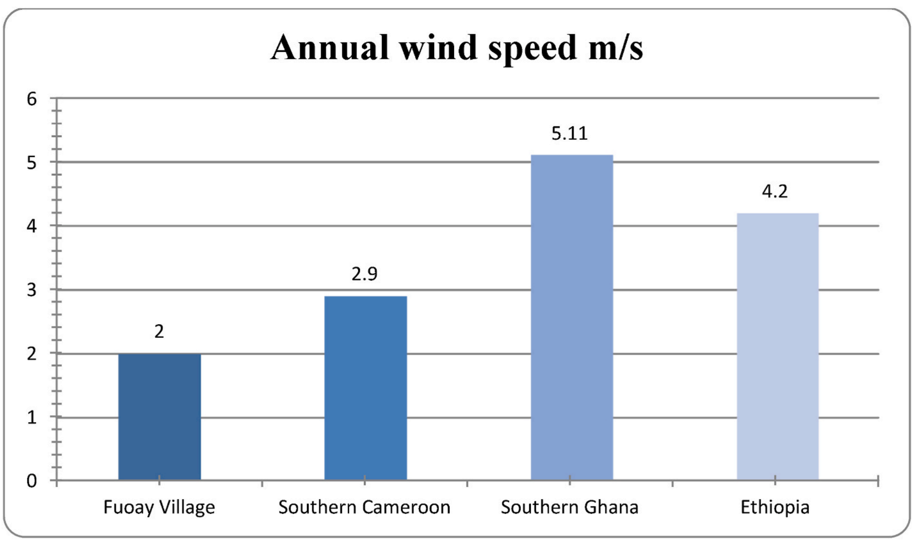

Fig. 11. Comparison of annual wind speed in different regions of Africa.

2.3.2. COE and NPC of pre-designed HRESs in Africa

There is a considerable demand for rural electrification in Africa because grid extension is almost impossible due to high investment. In this scenario, the development of Hybrid Renewable Energy Systems with the least cost of electricity and net present cost becomes exceptionally critical. Fig. 12 shows COE and Fig. 13 shows the NPC of pre-designed HRESs in Africa. According to Figs. 12 and 13, a project in Southern Ghana has the highest COE while the Plateau state's project has the highest NPC.

3. Methods in designing HRESs

An electricity generating system consisting of two or more energy resources is called a hybrid system [46]. If the generating system consists of two or more two renewable resources or the combination of both renewable resources (solar, wind, geothermal, and wave, etc.) and conventional resources (coal, oil, natural gas, diesel, etc.) is known as hybrid renewable energy system. Fig. 14 shows the general architecture of hybrid renewable energy systems.

HRES has found its application primarily for rural electrification (off-grid) and operates parallel with grid-connected electricity systems [49]. While designing a hybrid system, the more the number of renewable resources utilized, the more complexity and chance of failure will increase [50]. Many methods such as Analytical, Iterative, Probabilistic, Hybrid methods, and software have been analyzed and developed [51]. An analytical approach has been used by Kamel and Dahl [52], Diaf et al. [53], Dufo-López et al. [54], Mondol et al. [55], Kaldellis et al. [56], and Khatod et al. [57] for the optimal design of hybrid. Other researchers such as Yang et al. [58], Tina and Gagliano [59], and Celik [60] have used probabilistic methodology. The iterative method has been developed and used by Hakimi and Moghaddas Tafreshi [61], Yang et al. [62], Ashok [63], Dufo-López, and Bernal-Agustín [64], and Ekren [65]. In contrast, Katsigiannis et al. [66], Mellit et al. [67], M. Benghanem [68], Hontoria et al. [69], and Shi et al. [59] have implemented a hybrid combination methodology. Table 4 and Table 5 shows comparison of various sizing and optimization techniques, respectively.

In addition, different software has been deployed for the optimal designing of hybrid renewable energy systems. RETScreen is software developed by the Ministry of Natural Resources Canada which was used to check the feasibility of the designed system [72]. Eberhart and Kennedy introduced Particle Swarm Optimization (PSO) to optimize a non-linear function. PSO software use particle memory and the swarm's

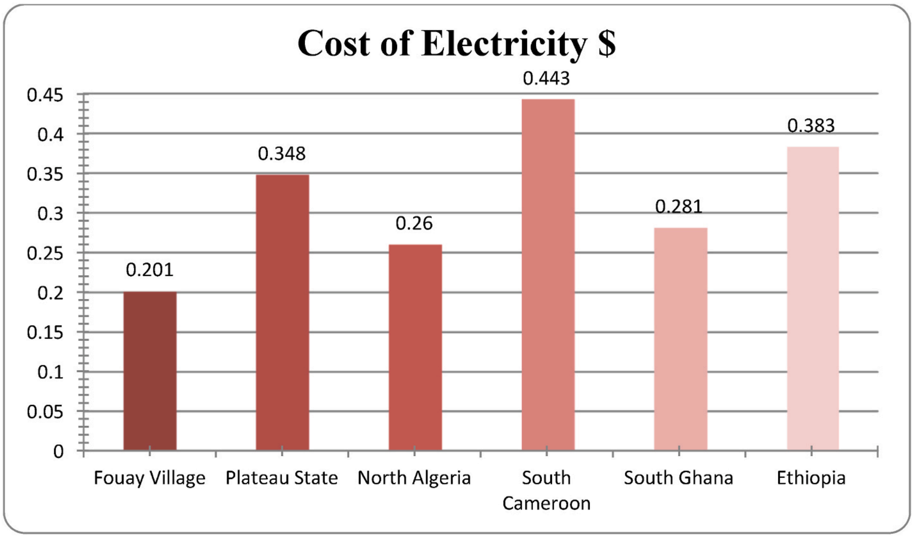

Fig. 12. Comparison of COE of HRESs projects in Africa.

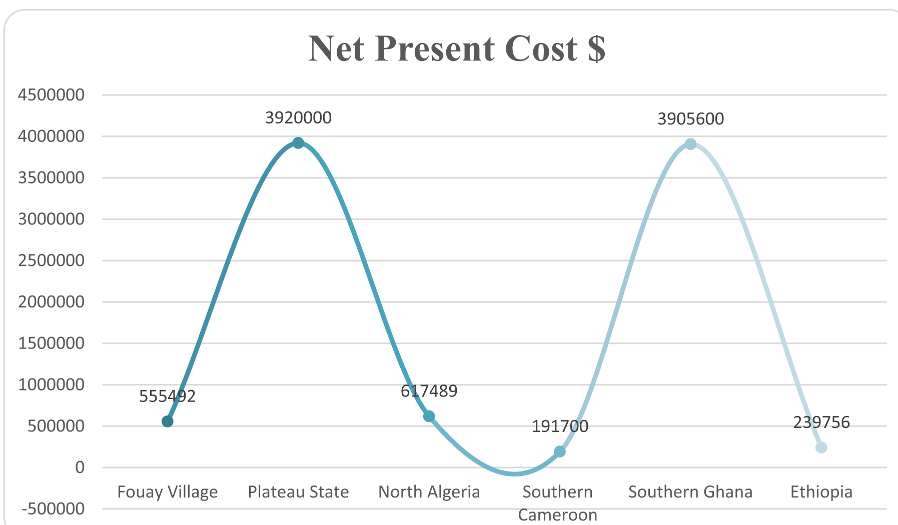

Fig. 13. Comparison of NPC of HRESs projects in Africa.

memory for the optimal solution [73]. Hybrid Optimization Model for Electric Renewable (HOMER) is a software developed by the National Renewable Energy Laboratory (NREL), which is used to design off-grid or grid-connected micro power systems for electrification [74]. After performing the simulation, HOMER displays all feasible systems regarding lifecycle cost. A MATLAB software has been employed for economic sizing and designing of PV system for buildings in Malaysia [75]. Table 6 gives information about the use of various software in different HRESs projects all over the world.

4. Methodology of scientometric analysis

Science mapping is a common method used to visualize, analyze, and model a scientific domain. This method is beneficial to visualize patterns and trends of large bibliometric data, which allows a researcher to make further discoveries in the specific scientific domain [84]. Bibliometric analysis is one of the easy way to find the current research directions those can also help to understand the scope of any particular field in the future. In addition, visual data is very beneficial in identifying the relations between authors, countries, and organizations. As a result, a scientometric analysis of hybrid energy systems was conducted, with publication records obtained from Scopus.

The selection of science mapping tools is very critical. Several tools are available, but we have used VOSviewer to visualize the large bibliometric dataset. Selecting an appropriate scientific database in a review study is also very important—some well-known databases such as Scopus, Google Scholar, and Web of Science (WoS). We have adopted Scopus databases based on our aims, objectives, methodology, and expected research outcome [85]. The search strings “Hybrid Renewable*", “Energy System*", “Rural”, “Electrification”, “Distributed Generation”, “Biomass”, “Off-grid”, “PV”, “HOMER”, “Wind”, “Geothermal” have used for the comprehensive bibliographic data extraction. The extracted database consists of 2000 research articles from 1983 to December 2021. Thereupon all the refined papers are downloaded in CSV files with complete citation information, bibliographical information, and funding details.

The VOSviewer software was used to conduct the bibliometric analysis, which Van Eck and Ludo Waltman developed. It gives an easy-to-understand graphical representation of the bibliometric data in the form of maps. According to our analysis, the first research paper in the hybrid renewable energy systems domain was published in 1983. That paper aimed to design a hybrid renewable energy system integrating PV

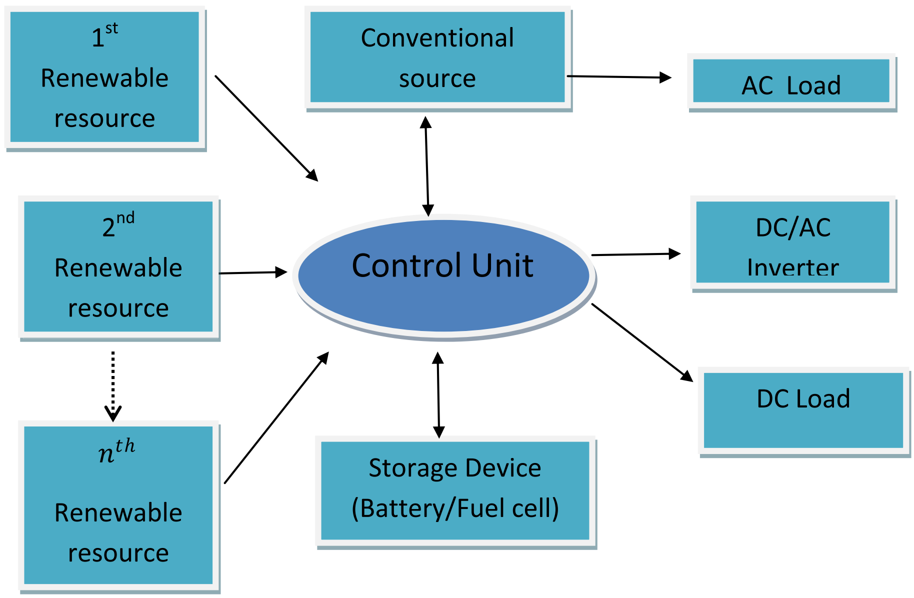

Fig. 14. General architecture of hybrid renewable energy system.

Table 4
Comparison between different sizing techniques [70].

Sizing technique	Accuracy	Time consumption	Complexity
Probabilistic method	Low	Short	Less complex
Deficiency of Power Supply Probability method	High	Short	Fairly complex
Analytical method	High	Long	Very complex
Simulation method	Fair	Short	Less complex

Table 5
Comparison between different optimization techniques [71].

Optimizing technique	Accuracy	Time consumption	Complexity
Iterative method	High	Long	Very complex
Graphic construction method	Low	Short	Less complex
Artificial Intelligence method	High	Long	Very complex
Life-cycle cost analysis	Fair	Long	Less complex

Table 6
Use of software in the development of HRESs in different locations.

Source	Author	Software	Project Locations
[76]	Barun K. Das	HOMER	Australia
[77]	Z. Abdin, W. Mérida	HOMER	Australia
[78]	Alireza Haghighat Mamaghani	HOMER	Columbia
[79]	Isidro Padrón and Deivis	HOMER	Lanzarote and Fuerteventura Islands
[80]	M. Zandi and M. Bahrami	RETScreen	Iran
[81]	Z. Said	RETScreen	United Arab Emirates
[82]	MM Samy	PSO	Egypt
[24]	Sayedus Salehin	RETScreen and HOMER	Bangladesh
[83]	Xiao Xu	PSO	China
[75]	Hadi Nabipour Afrouzi	MATLAB	Malaysia

and diesel to supply electricity to the telecommunication apparatus. After that, the number of publications on this domain was less than 10 per year till 2007. Then this domain experienced a remarkable increase in publication every year, and the highest number of publications, 402, was recorded in 2021. After obtaining the dataset, the scientometric analysis strategy was formulated, which includes (1) tracking the history of hybrid renewable energy system research by literature review; (2) bibliometric research to recognize the key researchers, institutions, and countries in this domain; (3) science mapping through VOSviewer to visualize the results of the analysis; and (4) make a qualitative discussion. Our study includes co-author analysis based on authors, organizations, and countries as a basic unit in VOSviewer. Results of scientometric analysis are explained in section 4.1 and 4.2.

4.1. *Co-author scientometric analysis results*

The co-authorship analysis is performed to examine the trend of researchers participating in the hybrid renewable energy systems research. Their impact is measured by citation, number of publications, and link strengths worldwide. Our results include co-author analysis with authors, institutions, and countries. This analysis is essential to determine whose work must be given importance to support or collaborate on new findings/ideas or refuse it and make a comparative study as necessary.

4.1.1. *Co-author scientometric analysis on HRESs research by the authors*

According to our results total of 4738 authors are working in this domain. We have refined our research by selecting a minimum 3 number of documents and citations of any author, and results indicate only 435 meet the thresholds. The largest network consists of 167 authors. Fig. 15 shows the collaboration of authors after co-authorship analysis by the authors. As illustrated in Fig. 15, the authors have a broad collaboration network. Accordingly, there are 130 clusters and 680 links.

Table 7 shows the list of most productive authors by the number of documents on hybrid renewable energy systems research. According to Table 7, Wang X. is a top-ranked author with a publication count of 20, followed by Eltamaly with a count of 18. Maheri A. is the third-ranked author, with a count of 17, Kalam and Elkadeem accompanied the fourth rank with the same number of counts of 14, however Elkadeem has more citations than Kalam and better link strength as compared to all other authors. Although Mekhilef S. is a fifth-ranked author by the number of documents, his work is the most cited one in the HRESs domain. On the other hand, Rekioua D. has 11 publications in this domain withzero link strength.

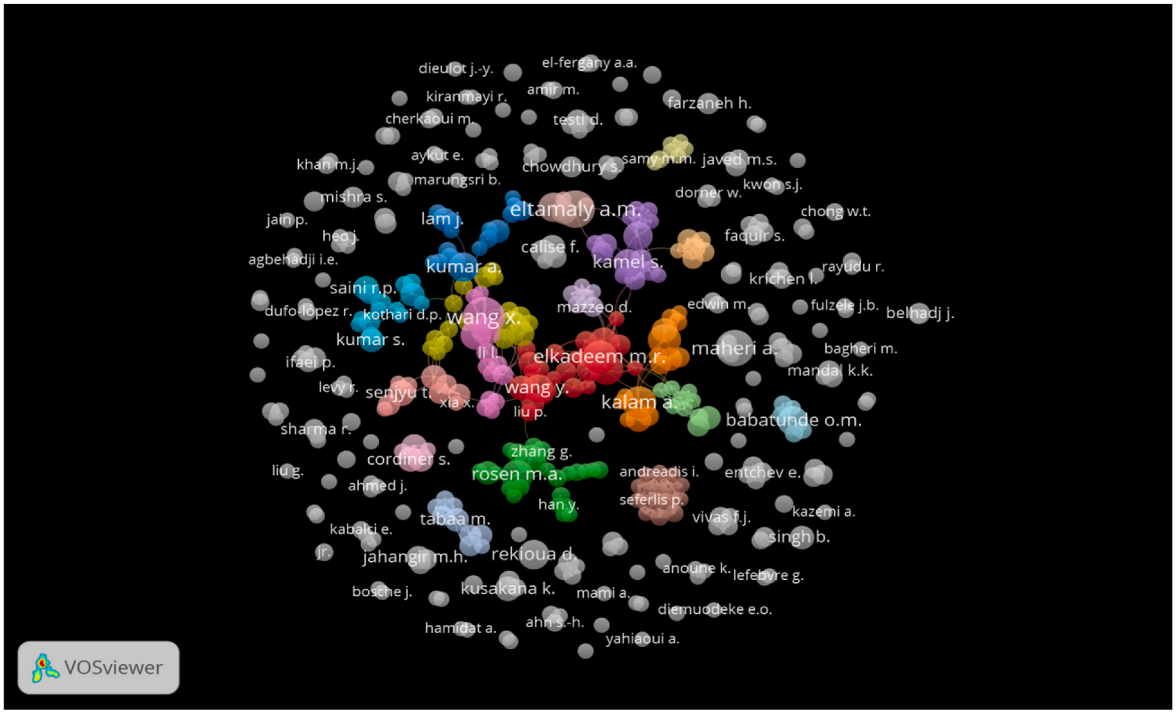

Fig. 15. Co-author scientometric analysis of hybrid renewable energy systems research by the author.

Table 7
Co-author analysis of most productive authors by the number of documents on HRESs research.

Sr.	Author	Rank	Documents	Citations	Total link strength
1	Wang X.	1st	20	421	34
2	Eltamaly A.M.	2nd	18	464	23
3	Maheri A.	3rd	17	360	9
4	Kalam A.	4th	14	158	26
5	Elkadeemm.R.	4th	14	262	52
6	Wang S.	5th	13	240	44
7	Mekhilef S.	5th	13	993	13
8	Wang R.	6th	12	296	22
9	Rosenm.A.	6th	12	692	20
10	Ekioua D.	7th	11	194	0

4.1.2. Co-author scientometric analysis on HRESs research by the institutions

Institutions have a considerable impact on any research domain. For that reason, co-authors by the institutions are carried out to investigate the pattern of the HRESs domain. According to the dataset, there is 3534 organization working on the HRESs domain. After setting the limitation of a minimum of 2 documents and 2 citations, only 248 institutes meet the thresholds. The co-author analysis result is displayed in Fig. 16, which illustrates that the largest collaborating network between the institutes consists of 23 organizations. Table 8 gives detailed information about the most productive organizations by the number of documents in the hybrid renewable energy systems research area. According to Table 8, the Faculty of Engineering at the Tanta University has the highest number of publications, 10 in the hybrid renewable energy systems domain. It can be noted that most institutions are from Egypt. It is also clear that the publications from the University of Tehran have been cited more, which indicates the quality, dedication, and focus on this domain. On the other hand, Tanta University and Mansoura University have the most extensive collaboration, and the link strength of both these institutes is 16.

4.1.3. Co-author scientometric analysis on HRESs research by the countries

Co-author scientometric analysis by the countries is performed to identify the key countries that are the significant contributors and their collaboration with other countries in this domain. This analysis is performed according to the publication count as a basic unit. VOSviewer results show that 117 countries are working in this domain. We have further refined our analysis by limiting 3 minimum citations and documents, and only 72 meet the thresholds. The density visualization result of co-author analysis by the countries has been shown in Fig. 17. Co-author scientometric analysis has been illustrated in Fig. 18 to show the collaboration and identify the most productive country in this domain. According to Fig. 18, all the countries have extensive collaboration in this research area. Table 9 provides detailed information about the number of documents, citations, and links strength of most productive countries. It is clear from Table 9, that India is the most productive country in the HRESs domain with a publication count of 488, followed by China with 164 publications. Egypt is in the third spot with 133 publication numbers. Iran and Malaysia have 128 and 102 research documents in this domain, respectively. It can be noted that there is no European country in the list of top 5 productive countries concerning the number of publications.

Interestingly, India's publication has been cited most. However, their link strength is not high compared to other countries with fewer publications and citations, such as Egypt, China, and Saudi Arabia. On the basses of Table 9 and Fig. 18, it can be concluded that Asian and Middle East countries are well focused on the HRESs domain compared to the European countries (see Table 10).

4.2. Co-occurrence analysis by keywords results

The co-occurrence scientometric analysis by keywords gives information about the keywords primarily used in the hybrid renewable energy systems research, which allows tracking the history and relation to the global trend in this domain. VOSviewer software has been used to identify and present essential keywords. The bibliographic record of keywords consists of 8808 that build a co-occurrence network of a minimum of 35 frequencies, consisting of 137 keywords, 4 clusters, and

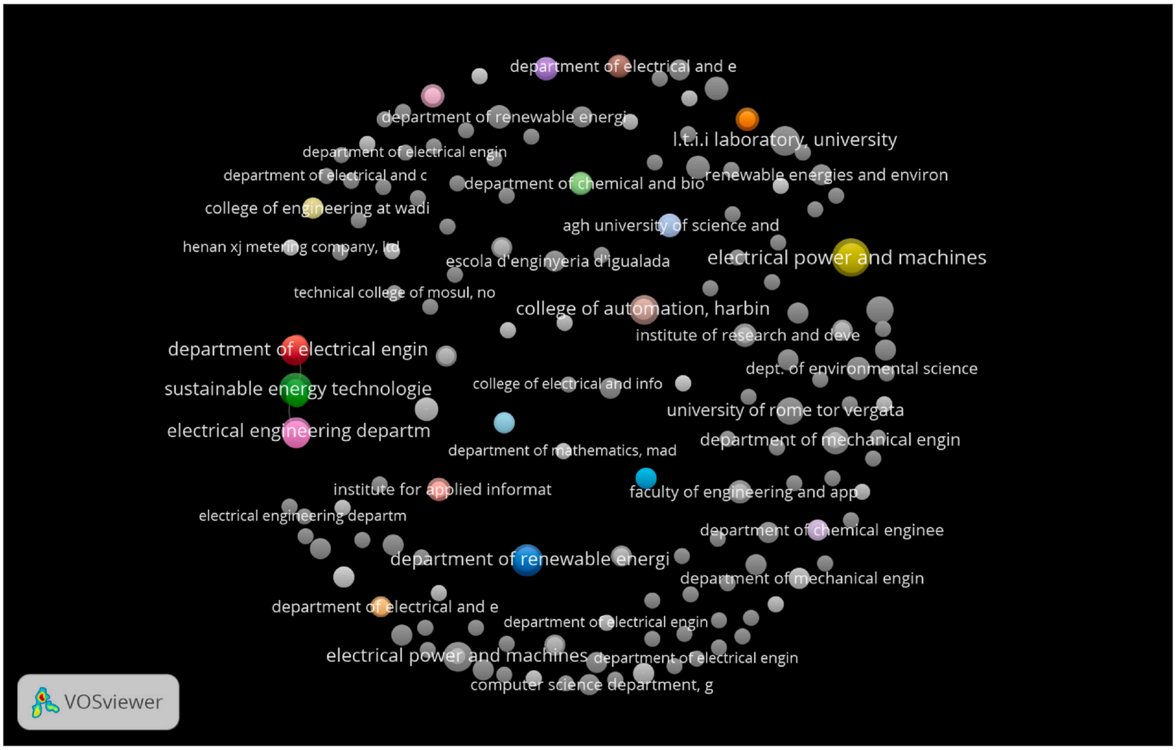

Fig. 16. Co-author scientometric analysis of hybrid renewable energy systems research by the organizations.

Table 8
Co-author analysis of most productive organizations by the number of documents on HRESs research.

Sr.	Organization	Country	Documents	Citations	Total link strength
1	Faculty of engineering, Tanta University	Egypt	10	219	16
2	King Saud University	Saudi Arabia	8	240	11
3	Faculty of new science & technologies, University of Tehran	Iran	7	590	7
4	Harbin Engineering University	China	6	106	4
5	Faculty of engineering, Aswan University	Egypt	6	21	8
6	Electrical engineering department, Mansoura University	Egypt	6	102	16
7	Faculty of engineering, Zagazig University	Egypt	6	126	1
8	University of Bejaia	Algeria	6	14	0
9	Faculty of engineering, Kafrelsheikh University	Egypt	6	196	14
10	School of electrical and electronic engineering, Huazhong University of Science and Technology	China	6	170	12

8356 links (Fig. 19). Table 10 presents the top 20 keywords after co-occurrence in the hybrid renewable energy system domain.

The top ranked co-occurrence keyword based on frequency is "renewable energy resources" with (Freq. = 999) followed by "hybrid renewable energy systems" (Freq. = 816), "hybrid systems" (Freq. = 454), "wind power" (Freq. = 385), "optimization" (Freq. = 380), "hybrid renewable energies" (Freq. = 337), "photovoltaic cells" (Freq. = 324), "renewable energies" (Freq. = 295), "renewable energy" (Freq. = 294), "wind turbines" (Freq. = 280), "electric power transmission

Table 9
Co-author countries analysis on HRESs research.

Sr.	Country	Documents	Citations	Total link strength
1	India	488	5338	72
2	China	164	3029	121
3	Egypt	133	1912	143
4	Iran	128	3719	86
5	Malaysia	102	2409	84
6	United States	92	1734	59
7	Canada	90	2553	68
8	Saudi Arabia	87	1472	118
9	United Kingdom	85	1412	69
10	Spain	71	1382	41

Table 10
Top 20 co-occurring keywords in HRESs research according to the frequency.

Sr.	Keyword	Frequency	Sr.	Keyword	Frequency
1	renewable energy resources	999	11	electric power transmission networks	276
2	hybrid renewable energy systems	816	12	solar energy	274
3	hybrid systems	454	13	hybrid renewable energy system	270
4	wind power	385	14	renewable energy source	264
5	optimization	380	15	solar power generation	264
6	hybrid renewable energies	337	16	hybrid renewable energy system (hres)	257
7	photovoltaic cells	324	17	wind	241
8	renewable energies	295	18	electric batteries	206
9	renewable energy	294	19	economic analysis	197
10	wind turbines	280	20	Costs	180

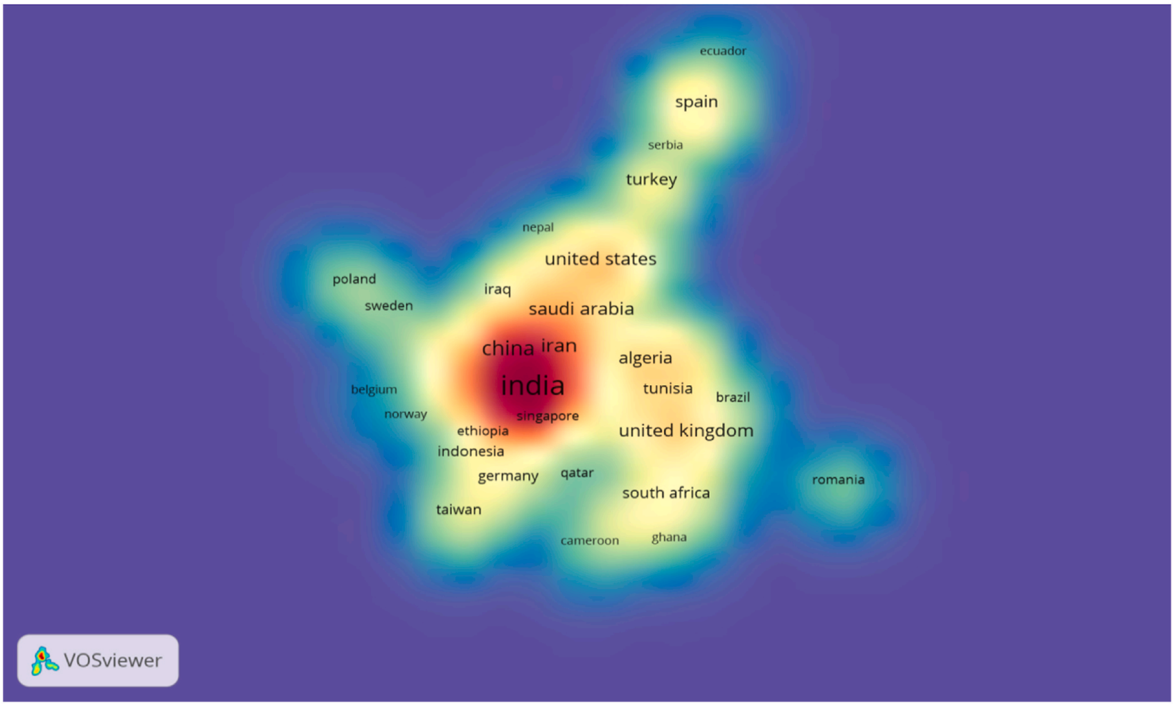

Fig. 17. Density visualization of co-author analysis on HRESs by the countries.

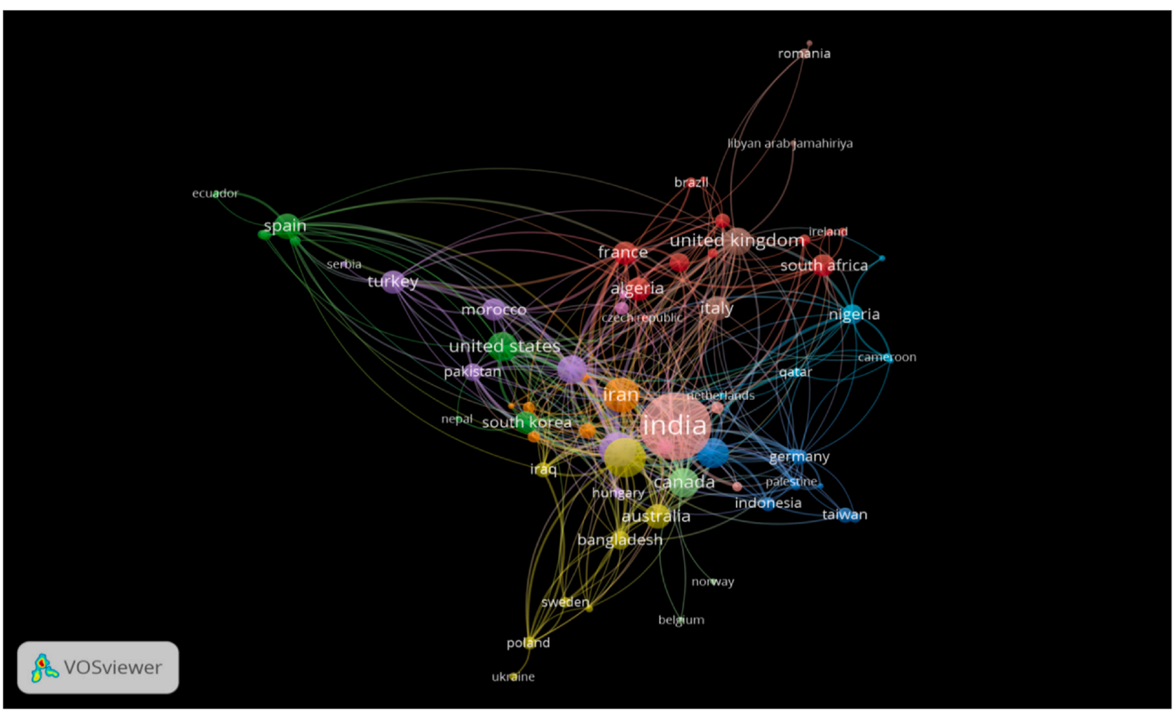

Fig. 18. Co-author scientometric analysis on hybrid renewable energy systems research by the countries.

networks" (Freq. = 276), "solar energy" (Freq. = 274), "hybrid renewable energy system" (Freq. = 270), "renewable energy source" (Freq. = 264), "solar power generation" (Freq. = 264), "hybrid renewable energy system (hres)" (Freq. = 257), "wind" (Freq. = 241), "electric batteries" (206), "economic analysis" (197) and "costs" (180). Interestingly, according to the Fig. 19 and Table 10, the keywords "renewable energy resources" and "hybrid renewable energy systems" have highest frequency and largest network.

5. Results and discussion

Suitable system architecture and economics analysis are two significant parameters in designing the hybrid renewable energy system [86]. Both these parameters depend upon the availability of renewable energy resources. This section presents a detailed analysis of these two parameters in different world regions. Annual solar radiation assessment is very important for projects with solar energy as a fundamental renewable resource. Solar radiations in different areas of Asia, the Middle East,

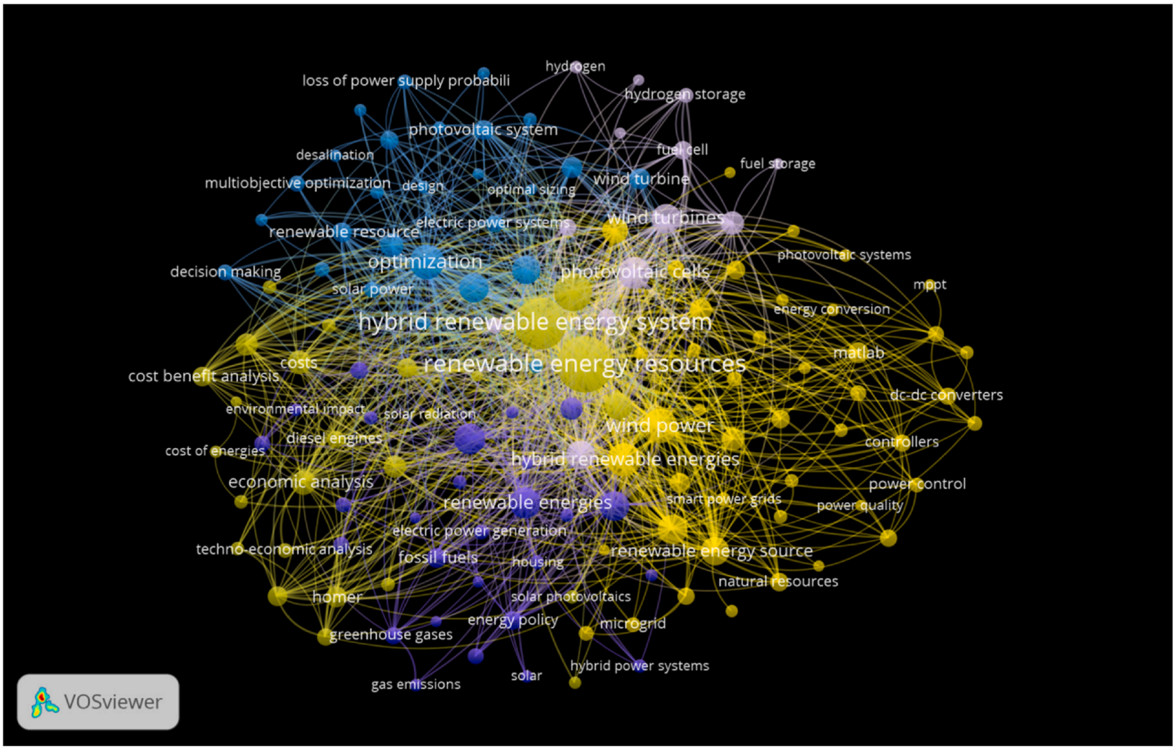

Fig. 19. Co-occurrence by keywords analysis in HRESs domain.

and Africa are compared in Figs. 3, Figs. 7 and 10 respectively. What is interesting in all these figures, almost all particular sites such as in India (Chhattisgarh), Sri Lanka (Siyambalanduwa), Bangladesh (Kutubdia), Pakistan (Layyah), Sudan (Dongola), Malaysia (Pulao Banggi), Indonesia (Temajuk) in Asia and Palestine (Palestine territories), Turkey (Bozcaada Island and Izmir), Saudi Arabia (Makkah), Egypt (Minya Governate), Yemen, Iran (KhshU site), Iraq (Sakran), Benin (Fouay village), Nigeria (Plateau state), North Algeria, Southern Cameroon, Southern Ghana, and Ethiopia have annual solar radiations greater than 5 KWh/mˆ2 which indicates the great potential of solar energy and nearby sites can also be explored to develop new renewable projects in Asia, Middle East, and Africa.

The annual average wind speed record is also very critical in wind-based renewable projects. The annual wind speed of different regions in Asian Middle East and African countries has been illustrated in Figs. 2, Figs. 6 and 11. According to the Fig. 2, some regions in Asian countries like Sri Lanka (Siyambalanduwa) and Sudan (Dongola) have a wind speed of 6.3 m/s and 6 m/s, which indicates a huge potential for wind energy, and it has been used to fulfill load requirement of village and irrigations purpose. From Fig. 6, it can be noted that Izmir has excellent wind energy potential in the Middle East with an annual wind speed of (5.72 m/s). On the other hand, Southern Ghana and Ethiopia regions in Africa have sufficient annual wind speeds of 5.11 m/s and 4.2 m/s, respectively (Fig. 11). Although some sites in different regions in the world have great potential for wind and solar energy or a combination of both these resources, the implementation of these projects has more considerable land requirements. To design a feasible hybrid system, it is also essential to assess the land requirement and the availability of renewable resources [87]. Wind speeds of at least 5 m/s should be averaged annually to use wind turbines efficiently in a single-source or hybrid-source electricity system. According to the mentioned sites, Africa has a meager average annual wind speed, which is not feasible in Africa. However, the PV system is acceptable because average annual solar radiations are high (Fig. 10).

Net present cost and cost of electricity are important for economic analysis. The COE is tabulated in Figs. 4, Figs. 9 and 12 show the cost of electricity, while information about the net present cost of different hybrid energy systems in Asia, the Middle East, and Africa could be found from Figs. 5, Figs. 8 and 13. The COE and NPC depend upon the combination of the design system, and it depends upon the available resources. Renewable resources are inconsistent providing uninterrupted power supply and therefore, dependency on diesel is very high. According to the Table 1, Table 2, and Table 3 all designed systems have diesel generators which have a bigger impact on COE and NPC. If the price of the diesel increases, then the COE and NPC also increase and vice versa. In Ghana, the hybrid system has a COE of US$ 0.212/KWh at the diesel price of US$ 0.80/liter, but it was increased to US$ 0.287/KWh at diesel price of US$ 1.50/liter [88]. When we design an off-grid hybrid renewable energy system, the cost of electricity should be less than the cost of grid-connected electricity to attract customers, and lower NPC can encourage utilities to develop clean and green energy systems. In Ref. [12], it has been discussed that the COE of designed HRES was COE 0.259 $/KWh while the grid electricity price was 0.19 $/KWh, which makes that system unacceptable. Although the COE was high, the designed systems could produce clean electricity.

Net present cost includes initial, operation, and maintenance costs. Figs. 5, Figs. 8 and 13 show the NPC of various projects in Asia, the Middle East, and Africa. Projects like in Asia [27], It can be noted from above mentioned figures that the net present cost (NPC) of the hybrid renewable energy system in Asia such as Sudan (Dongola NPC = 24,160,000 $), Malaysia (Pulao Banggi NPC = 9,345,510 $) and China (Lanzhou NPC = 7,735,646 $), in the Middle East; Saudi Arabia (Makkah NPC = 6,278,274,662 $), in Africa; Nigeria (Plateau state = 3,920,000 $), Ghana (Southern Ghana = 3,905,600 $) was very high as compare to other projects. Solar and wind technologies are more developed and utilized on a large scale. As the technologies are more developed, the price of the PV system will decrease in the future [89], which will ultimately decrease the NPC. It is vital to keep the net present cost of HRESs as low as possible to make it economically feasible to attract the attention of investors and stakeholders.

Since the last decade, many countries have formulated policies towards the sustainable energy system to encounter climate change. In addition, renewable energy will play a vital role in the circular economy in the future. So many researchers and organizations have paid particular attention to these social issues. Our study has performed bibliometric analysis to identify the research pattern, top authors, and institutions working in this domain. In our research, we have extracted 2000 research articles from the Scopus database to execute the bibliometric analysis. VOSviewer software has been used to visualize the pattern and collaborations in hybrid renewable energy systems research. Table 7 gives information about the top 10 authors working on hybrid renewable energy systems. Wang X. has the highest number of publications, followed by the Eltamaly. Although Mekhilef S. has only his work has been cited 993 times. Table 8 shows the list of the top 10 organizations working in the hybrid renewable energy systems domain. It can be noted that 5 out of 10 institutions are from Egypt.

Interestingly, no USA and European institutions are working actively. Table 9 shows the data of the top 10 countries in this domain. According to Table 9, India is leading in this research domain with 488 documents. It is also clear from Table 9, USA is at the sixth spot, which indicates who possesses the best technologies and sufficient resources and is also looking for a sustainable energy source. This paper will help make policies according to the availability of renewable resources of any country, which can play an essential role in minimizing energy crises and climate change in the future.

6. R&D, challenges and limitations of renewable energy in asia, the Middle East and africa

The energy transition is accelerating due to the detrimental impacts of fossil fuels on the economy and environment worldwide. The development of hybrid renewable energy systems is necessary for the energy transition. This paper explores the characteristics which can play role in the development of hybrid renewable energy systems. The analysis depicts that the core elements in the development of HRESs are resources and technology. In the 21st century, the energy sector will consist of Renewable Energy Sources (RES); most of them could be hydroelectricity, PV, and wind energy to feed household demand. The household requirement could be only 20%, while the surplus energy can contribute to the economy. Although renewable resources such as wind and solar are abundant, but their efficiency is low due to under-developed renewable technologies. To tackle these technical issues, more research is required to design optimized renewable technologies and highly efficient batteries are required to use store this energy. The year 2019 was the hottest year on the earth [90]. To overcome this rapid climate change, not only energy transition should be accelerated but also awareness should be performed to minimize the consumption of fossil fuels.

In the future, hybrid renewable energy systems will be highly digitalized, decentralized, and flexible. Hybrid energy systems will be used for the electrification of the end-use sector and will make massive expansion of interconnections and involves in the creation of a regional market. The development of hybrid renewable energy systems is linked to the infrastructure developments. Facilities such as smart charging networks for Electric Vehicles (EVs), Virtual Power Plants (VPPs), and installation of high voltages transmission lines will be required to dispatch electricity to the demand area. The absence of this infrastructure will not commercialize the low carbon technologies for the energy transition. Hybrid energy systems also opened opportunities in the field of ICT and energy technologies, as well as in the field of new batteries formation and to design high-performance materials. New business models related to the electricity market are evolved including virtual power plants and aggregators for electricity storage devices. Low carbon technologies and the cost of components are still big problems in this development. The energy sector has huge potential to play role in the economy, so the contribution from the governments in the formation of policies and strong investment in R&D is still required.

Now many developing countries are formulating policies to achieve Sustainable Development Goals (SDGs) a to assess energy systems [91]. A hybrid systems has been designed to investigate its feasibility in two capitals of Iran to meet sustainable development goals [92]. To increase the contribution of renewable energy in Southeast Asia, Asia-Pacific Economic Cooperation (APEC) has set a new goal of achieving 23% renewable energy share by 2025 [93]. Many countries in Asia are making policies and setting targets to increase the contribution of renewable energy in the energy sector. According to Ref. [94], the Government of Indonesia has a goal to achieve 23% renewable energy by 2025. Singapore has set a target to get 80% renewable energy from PV and wind by 2030 [95]. In 2001, Malaysia had started a Small Renewable Energy Program (SREP) for the utilization of renewable energy. In 2011, Malaysia utilized only 1% renewable energy, but it is expected to increase up to 13% by 2030 [96]. Likewise, in other Asian countries, Thailand also has set a target to use 40% energy from solar and biomass by 2036 [97]. The economic and industrial growth of any country depends upon energy resources [98]. The United Nations (UN) sustainable energy for all (SE4All) has set a goal to make electricity access universally by 2030. Countries in the Middle East and North Africa (MENA) regions have shown considerable economic growth in recent years. MENA countries have initiated many programs to increase the role of renewable energy in the country's economy. African countries such as Algeria and Morocco are expecting to utilize 27% and 52% renewable energy by 2030. On the other hand, heavily oil-dependent countries in the Middle like Bahrain, UAE, and Qatar had formulated their policies and set targets to get 5%, 20%, and 25% renewable energy respectively by 2030 [99].

Although many countries have initiated RE program, but development in the field of Renewable Energy (RE) is still facing severe technical and economic challenges. For example, bad weather, high ambient temperature, large land requirements and short lifespan of batteries are the biggest challenges in developing PV systems. Similarly, wind energy resource is affected by low average wind speed and requires huge land to install wind turbine. Likewise, biomass is also one of the promising renewable resources, but it is difficult to harvest, collect and process. Biomass development requires financial assistance but due to low number of market players is making it challenging to developed. Thus, it is necessary to identify latest optimum designs and formulating strategies to increase a share of biomass in renewable energy [100]. To increase the efficiency designed energy system, renewable energy resources are used in hybrid mode. The designed hybrid systems must be economical which can generate cheap electricity as compared to grid electricity. Hybrid systems are complex and it is difficult to find the best combination, and lack of well-trained personals is also a challenge in this field [101].

7. Conclusion

Hybrid renewable energy systems research has received significant attention in Asia, the Middle East and Africa due to increasing electricity prices, rural electrification, and rapid global climate change over the last 10 years. According to our review, for designing the cost-effective hybrid energy system consisting of PV array or wind turbine, the region should experience at least 5 KWh/mˆ2 solar radiations and 5 m/s wind speed annually. In addition, HOMER, GA and PSO are frequently used software for the sizing and optimizations of hybrid systems. This study also provides a scientometric analysis of hybrid renewable energy systems using 2000 bibliographic records extracted from the Scopus database. Several scientometric analyses, such as co-authorship and co-occurrence, were utilized to identify and explore the trends in hybrid renewable energy systems research. Results shows that Wang X. was recognized as the most prolific author in this domain. India, China, and Egypt are the most productive countries in hybrid renewable energy systems research. Tanta University, Kind Saud University, and the University of Tehran are the most productive institution in this domain. The University of Tehran has the highest number of citations, 590. Although

India has topped the list in terms of the number of documents, Egypt has comprehensive collaboration and extensive links with other countries in this domain. According to co-author analysis, most institutions and countries are from the Middle East and Asia in hybrid renewable energy systems research. In contrast, the co-occurrence analysis revealed that "renewable energy resources" is the most frequently used keyword with 999 times in this domain. According to our observation, the focus of research is highly towards profit, and reliability of system. Thus, there is lack of study about interdisciplinary methodologies those consider various sustainability aspects which are essential for the effective planning of hybrid renewable energy systems. In Africa one-third populations is living without the electricity, so hybrid renewable energy systems can be installed if designed HRESs have high COE and NPC because it can provide rural electrification and can minimize emission of carbon dioxide. In Asia and the Middle East grid electricity is expensive, so HRES could be designed accordingly to produce cheap and clean electricity. In future, renewable energy will have great impact in circular economy, so developing countries should invest more in exploitation of renewable sources and research and development of sustainable energy systems to strengthen their economy by attracting the investors in this field.

Credit author statement

Hadi Nabipour Afrouzi: Supervision, Revising the first draft, **Madni Sohail**: Preparing the first draft, Editing, **Kamyar Mehranzamir**: Validation, Reviewing and Editing, **Jubaer Ahmed**: Reviewing and Editing, proofread, **Mujahid Tabassum**: Reviewing and Editing and **Md Bazlul Mobin Siddique**: Validation, and Reviewing, proofread.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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