Environmental Science and Pollution Research (2022) 29:59328–59362
https://doi.org/10.1007/s11356-022-20125-0

RESEARCH ARTICLE

Investigating evolutionary trends and characteristics of renewable energy research in Africa: a bibliometric analysis from 1999 to 2021

Sandylove Afrane[1] · Jeffrey Dankwa Ampah[1] · Emmanuel Mensah Aboagye[2]

Received: 28 July 2021 / Accepted: 3 April 2022 / Published online: 6 April 2022

Abstract

Several countries across the African continent have been challenged with energy crises for decades. A growing number of studies have identified renewable energy as a sustainable way for Africa to address its persisting energy situation while combating climate change, as the continent has in abundance some of the common renewable energy resources. Little has been reported in the body of literature to quantitatively and qualitatively map the knowledge domain of this growing research field. In the current study, we conduct a bibliometric analysis on research documents extracted from the Web of Science Core Collection to identify trends and characteristics of the knowledge domain related to renewable energy in Africa from 1999 to 2021. Using two different software (VOSviewer and ITgInsight), we report the contribution of journals, countries, institutions, and authors and their collaboration patterns. We also perform co-citation and keyword analysis to identify the intellectual base and central themes of this research field. The results from the study revealed a growing interest in Africa's renewable energy, with about 90% of the total publication from within the last decade. Renewable & Sustainable Energy Reviews was identified as the most productive as well as the most influential journal in this field. The most contributing countries in this field were South Africa, USA, and Algeria. Centre de Developpement Des Energies Renouvelables, a research institute in Algeria, emerged as the most productive and influential institution. The analysis of research hotspots under different categories revealed that "solar energy," "CO_2 emissions," and "rural electrification" are the topics that have gained maximum attention over the years. Keyword evolution analysis also identified "economic growth" and "green hydrogen production" as emerging topics that will play a major role in future studies. We conclude our work by providing specific suggestions and strategies to help bridge the gap which exists in the quantity and quality of renewable energy research between Africa and the rest of the world.

Keywords Africa · Renewable energy · Bibliometric analysis · Research trend · Electricity

Abbreviations

ANN	Artificial neural network
BMBF	Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research)
CDER	Centre de Developpement Des Energies Renouvelables
CO2	Carbon dioxide
CO2eq	Carbon dioxide equivalent
CSP	Concentrated solar power
EJ	Exajoule
GDP	Gross domestic product
GHG	Greenhouse gases
GIS	Geographical information system
GTP	Growth and transformation plan
GW	Gigawatt
H2	Hydrogen
HOMER	Hybrid Optimization of Multiple Energy Resources
JCR	Journal citation report
LCA	Life cycle analysis
MCP	Multiple country publication
MENA	Middle East and North Africa
MW	Megawatt
PV	Photo-voltaic
R&D	Research and development

Responsible Editor: Philippe Garrigues

✉ Jeffrey Dankwa Ampah
jeffampah@live.com

[1] School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China

[2] Zhongnan University of Economics and Law, Wuhan 430000, Hubei, China

REMP	Renewable Energy Master Plan
SCP	Single country publication
SDG	Sustainable Development Goals
TC	Total citation
USAID	United States Agency for International Development
USD	United States dollars
WoSCC	Web of Science Core Collection

Introduction

Background

Over-dependence on conventional fossil fuels and the sharp increase in demand for energy worldwide poses a major challenge to sustainable development (Abbasi et al. 2020, 2021c). Due to the high population growth rate and economic development, global energy demand is expected to more than double by 2050 (Lewis and Nocera 2006, Whitesides and Crabtree 2007). At the present rate of demand, gasoline will be depleted in 50 years, natural gas in 65 years, and coal in 200 years (Soetaert and Vandamme 2009). The use of fossil fuels also contributes massively to the emission of greenhouse gases (GHG) and other pollutants into the atmosphere. Carbon dioxide (CO_2) is responsible for over 75% of global GHG emissions. CO_2 causes anthropogenic global warming, as well as extreme weather events (floods, torrential rains, heat waves, and droughts) that have happened often in the last decade (Abbasi et al. 2022; Iqbal et al. 2021). These challenges have ignited the interest of international bodies and local governments in renewable energy sources. As part of the sustainable development goals, the United Nations has made a great effort to combat this problem by setting a new target to "promote affordable, reliable, sustainable, and modern energy for all" by 2030 (Sustainable Development Goal 7). Most countries, both developed and developing, have made huge investments in renewable energy conversion technologies to alleviate potential energy crises and protect the environment. Emerging economies, particularly China and India, are actively leading the global renewable energy shift by demonstrating the strongest commitment to wind and solar development (REN21 2017). The overall global investment in 2017 was \$279.8 billion (excluding hydropower stations higher than 5 MW), with a year-on-year increase of 2% (IEA 2018). In 2017, global renewable energy power consumption increased at a rate of 5.62% per year, which was 2.95 times faster than primary energy consumption (BP 2021). Forecasts by researchers show the share of renewable energy sources in the global energy supply would reach 34.7% by 2030 and 47.7% by 2040 (Demirbas 2009).

Energy report from IEA (2019) indicates that Africa accounts for just 4% of global power supply investment despite the large population of about 1.29 billion people residing in this region. In order to adapt to the rapid rate of economic growth, the total power generation demand in Africa has been increasing substantially, with a growth of 18% projected in 2025 compared to 2016 (Xu et al. 2019). Compared to the rest of the world, Africa has not fully exploited the benefits of renewable energy sources due to technical and economic constraints as well as social factors like political instability and unclear policies. According to de Vries et al. (2007), the average growth rate of global modern renewable energy production surpasses that of Africa by 8.43% from 1996 to 2018. In 2017, the African Development Bank (2018) reported that the continent's estimated power generation potential is 350 GW for hydroelectric, 110 GW for wind, 15 GW for geothermal, and 1000 GW for solar. Despite the high renewable energy potential in most African countries, over 548 million people across the continent still have no access to electricity, and 900 million rely on traditional solid biomass for cooking (IEA 2020). During the previous two decades, the power crisis in Africa has been a major concern and has contributed massively to the slow economic development of most parts of the continent. About 39 Sub-Saharan African countries have lost up to 2 percentage points in yearly real per capita gross domestic product (GDP) growth due to power outages (IMF 2019). Moreover, factors like high population growth, low adaptability to change, and impending water crises make Africa the most vulnerable continent to the impacts of global warming and climate change (Niang et al. 2008). Therefore, the development of renewable energy in Africa is crucial for securing energy independence and improving socio-economic development of countries while reducing pollution at both local and global levels, thus lessening the impact of climate change.

This insight has caused some of the largest economies in Africa, such as South Africa, Egypt, Morocco Kenya, and Ethiopia to actively open up investment opportunities in this space within their countries. In the previous 10 years, Africa's renewable energy sector has drawn USD 34.7 billion in investments, with South Africa, Morocco, and Egypt leading the way (Linklaters 2021). Examples of major renewable energy projects that aim to be at the top of global rankings for installed renewable capacity include; the Noor concentrated solar power plant in Morocco, the Lake Turkana wind farm in Kenya, and the Grand Renaissance Dam in Ethiopia (total planned capacities of 500, 310 MW, and 6.45 GW respectively) (Hafner et al. 2018). Even though the renewable energy market in most of Africa is still in its emerging state, more and more countries have made efforts to set targets for renewables. Senegal and Ghana have set to reach 20% and 10% share of renewables in total power generation, respectively (Hafner et al. 2018). Many African countries have enacted clean energy policies that include tax benefits, public contributions, loans, and grants. Delegates from 46 countries in Africa, including 25 energy ministers, endorsed the Abu Dhabi Communiqué on Renewable Energy for Accelerating Africa's Development in 2011 (IRENA 2011).

It is evident from the aforementioned discussions that there is a growing and urgent need for renewable energy development across the African continent. Against this backdrop, several conventional review papers exist in the literature to discuss potential pathways, policies, opportunities, and challenges relating to Africa's roadmap to fully harnessing its renewable energy resources for the socio-economic development of the continent. Using Mali, Egypt, South Africa, and Nigeria as case studies, Bugaje (2006) presented the opportunities for sustainable development in Africa through renewable energy development. Similarly, with a focus on Nigeria, Egypt, and South Africa, Aliyu et al. (2018) discussed renewable energy development in Africa. A focused literature review between the periods 2013 and 2018 was conducted by Ouedraogo (2019) to highlight renewable energy development in Africa with emphasis on the opportunities, barriers, and challenges. By adopting a review and conceptual framework, Soumonni and Ojah (2022) explore renewable energy development in Sub-Saharan Africa from the perspective of innovative and mission-oriented financing. In a similar fashion, Mohammed et al. (2013) with a focus on Sub-Saharan Africa reviewed the status of renewable energy consumption and developmental challenges in the region. Ibrahim et al. (2021) add to the existing discussion on Africa's dependence on renewable energy production for energy supply using Ghana, South Africa, and Cameroon as case studies. Earlier review papers also emphasized Africa's photovoltaic industry and its development (Gope et al. 1997). Amuzu-Sefordzi et al. (2018) also shed light from a socio-technical perspective on the adoption of decentralized renewable energy technologies in Africa. In the review paper of Suberu et al. (2013), the sustainability of renewable energy resources in Sub-Saharan Africa, the region's status of renewable energy applications, and the management importance of renewable energy power generation integration planning are discussed. Also included in the review are the benefits of integrating renewable energy into the Sub-Saharan Africa power sector, as well as certain conceptual problems impacting its integration in the area. De Angelis et al. (2021) presented a critical review of renewable energy potentials in Africa in relation to freshwater scarcity and availability (divided into rainfall, river discharge, and groundwater recharge) to encourage the development of a comprehensive data collection to assist water–energy policymakers.

Significant contributions have been made to the existing literature by the above-mentioned review papers together with several others. However, despite their key contributions, these types of review papers have a general limitation in common. It is hard to organize, fully analyse, and statistically measure the evolution of the topic pattern and characteristics across a vast number of research over a lengthy period of time in conventional review articles (Zeng et al. 2021). Moreover, since these publications require a narrow field of inquiry, they often comprise fewer articles for review, ranging from the tens (e.g., 30) to the lower hundreds (e.g., 100–400) (Snyder 2019). They could also be affected by other researchers' interpretive bias (MacCoun 1998). When doing a literature review on the evolution of any theory or concept over time, it is critical to include the development component by posing questions such as, "How is the area of research evolving?" What future research areas have been emphasized in significant research articles? What are the major research areas? What are the most often cited research subjects and articles? What is the link between the key articles? (Goyal et al. 2021). In this way, traditional literature studies are better suited to narrow or specialized research subjects. More information might be obtained by qualitatively and quantitatively reviewing the present literature, as well as examining and tracing the evolution of a large number of published studies (Ampah et al. 2021). As a result, a comprehensive review of the whole corpus of literature might help organize existing knowledge and identify future research gaps (Meyer 2020). These drawbacks of traditional reviews might be addressed effectively by applying modern review approaches such as bibliometric analysis (Donthu et al. 2021).

In light of the above facts, it became apparent that there are important but ignored areas in the studies of Africa's renewable energy development from the standpoint of evolutionary trends and research hotspots. To the best of our knowledge, only two studies have made an attempt to fill this gap in research, i.e., Adedayo et al. (2021) and Pouris (2016). However, in both studies, the emphasis has not been solely directed to renewable and sustainable energy resources whiles the area of scope is limited to only Nigeria and South Africa, respectively. Justification for the selection of Africa in the current work is attributed to the findings reported in previous bibliometric studies in the field of cleaner fuels and energy. In the following works (just to mention a few) (Afrane et al. 2021; Ampah et al. 2021; Jin et al. 2021; Mao et al. 2018, 2015a, b; Zhang et al. 2018), the contribution of Africa to the growth of cleaner alternative fuel development in contrast to other continents such as North America, Asia, and Europe is heavily underrepresented. In terms of financial resources and technological advancements, these regions are miles ahead of Africa; hence, their research output and contribution are significantly higher. As such Africa's contribution to the development of the field would always be underrepresented when the continent's research output is reviewed simultaneously with that of the developed economies. The growth in Africa's renewable energy development can be effectively traced and monitored if the continent's research output is assessed alone. Moreover, the strategy provides the opportunity to identify key reasons areas where the continent could improve in order to drive renewable energy research forward close to that of the leading countries outside the continent. Singling out Africa in the current work helps to qualitatively and quantitatively examine and appraise the growth patterns of the renewable energy research sector and find the overlooked regions to expose internal structures and hidden implications for future development. This way, a variety of quantitative metrics, such as highly prolific and prominent authors, most contributing countries/regions, top institutions, funding agencies, core journals, and significant publications, are studied. Through keyword and reference analysis, this study may also give in-depth insight and direction for researchers, as well as methodically highlight the fundamental areas in Africa's renewable energy market that deserve greater attention. As a consequence, we hope that the current effort will pave the way for the advancement of Africa's renewable energy research as a means of improving the continent's socioeconomic growth.

A brief overview of the energy situation in Africa and policy development for renewable energy

Energy consumption has a significant contribution to economic growth (Abbasi and Adedoyin 2021, Abbasi et al. 2021d). Africa's population and economic development have sustained rapid growth over the years, and this has had far-reaching regional and global implications for the continent's energy sector. In 2018, Africa's GDP was estimated at 7 trillion dollars, projected to reach 17 trillion dollars by 2040 (IEA 2019). Higher GDPs imply higher energy needs as major sectors of the economy such as transportation, industries, and agriculture increase their consumption rate. The 54 countries in Africa have been grouped into four main regions; North, East, West, Central, and Southern Africa. Different regions experience different energy issues based on their population and GDP. For instance, in 2013, North Africa's GDP per capita was about three to five times higher, with fewer than 2% of the population lacking access to electricity. In comparison, about half of the population in West Africa, three quarters in East Africa, and the majority of the population in Southern Africa (with the exception of South Africa) lacked access to electricity with relatively lower GDP and a higher population than North Africa (IRENA 2015). Electricity is a key element of economic development that serves as a drive for any country's advancement in all economic sectors (Abbasi et al. 2021a, 2021b). Africa's current electricity demand stands at 700TWh, with North African economies and South Africa accounting for more than 70%.

The current energy needs of Africa are mainly met through a mix of biomass and fossil fuels. About 45% of Africa's total primary energy supply comes from biomass. Coal and natural gas account for about 14% and 16%, respectively, while oil accounts for about 23%. The share of renewables is almost negligible with hydropower, wind, and solar contributing approximately 2% of Africa's total primary energy supply in Africa (IEA 2019). A large percentage of energy demand in North Africa is met by oil and natural gas with a high potential for solar and wind energy, as shown in Fig. 1a. The situation is similar in West Africa for coal and natural gas but with a major contribution from hydropower. Reports show that hydropower will continue to play an important role in all parts of Africa except perhaps in the north. Energy supply in Southern Africa is mainly from coal, while Central and East Africa are dominated by hydropower and wind energy. Considering the fundamental role of electricity in contemporary society and its cleanness and flexibility for a wide range of applications, gaining universal access to electricity easily and cost-effectively can be considered the single most critical energy-related goal for African policymakers. Figure 1b shows the electricity generation by various sources in Africa from 1999 to 2018 (IEA 2019). It is evident from the trend that there is a sharp increase in the total electricity generation from all sources. Before 2014, the contribution of renewable energy sources to Africa's electricity mix was very minimal apart from hydropower. However, solar and wind energy have realized a sharp growth from 2014. Similarly, electricity generation from geothermal and biofuels has also risen significantly, although at a much slower rate.

To scale up renewable energy development in Africa, states, policymakers, and stakeholders must create mechanisms that maximize socio-economic benefit. Several African countries have created national energy policies and initiatives, although the frequency with which they are revised and applied consistently varies (Aliyu et al. 2018). Renewable energy policy may be classified into two broad categories: technical push and market pull (He et al. 2018). Market-pull policies try to stimulate the adoption of renewable technologies by creating demand for them and they include incentives and initiatives are mostly in the form of tax benefits, public contributions, loans, and grants. Technology-push policies, on the other hand, promote increased incentives to offer additional knowledge and innovation to the field. Energy self-sufficiency necessitates the continued, concerted efforts of the academic community in collaboration with public sector policymakers and private sector stakeholders. Significant efforts have been made by both the international academic community and some African countries to promote renewable energy research as part of

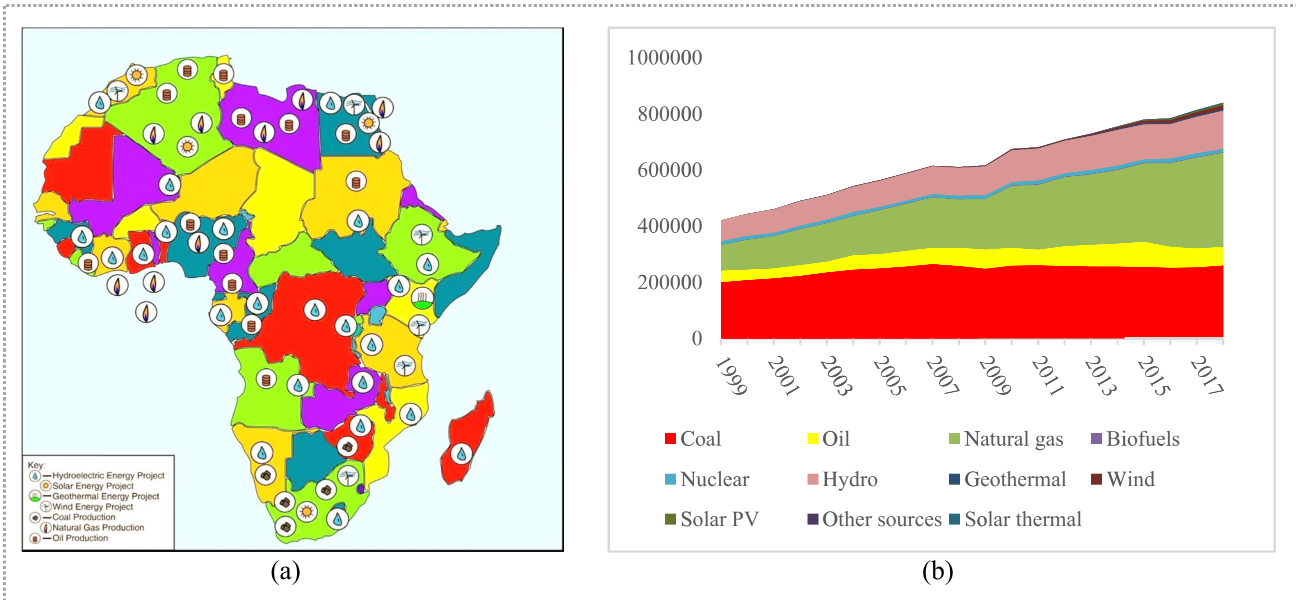


Fig. 1 Description of energy sources in Africa: **a** Geographical distribution of energy sources across the continent, **b** Electricity generation by source (Gigawatt hour) in Africa (IEA 2019)

their energy policies and programs. Examples of such international programs include the Africa-EU Renewable Energy and Innovation research symposium which was held in Algeria in 2016. About 135 foreign experts from 30 African and European nations attended the event, representing universities, research institutes, the public sector, industrial groups, and international organizations. The symposium helped to connect existing research to real market demands, facilitate cooperative research initiatives, and increase access for African delegates to available financial and support instruments (Hayek and Ferrini 2016). The German Federal Ministry of Education and Research (BMBF) also partnered with the Southern African Development Community and the Economic Community of West African States (ECOWAS) to launch H_2 Power-Africa, a green hydrogen effort with the goal of investigating the possibilities for renewable energy in Southern and West Africa (IRENA and AfDB 2022).

Domestic efforts by African countries include the full implementation of the National Energy Policy and Laws in Nigeria from 2003 included the establishment of four new research centers in different parts of the country which helped promote research in this field (Adedayo et al. 2021). The government of South Africa has shown its commitment towards research by introducing the National Research and Development (R&D) Strategy in 2002, and the South African Research Chairs initiative in 2005 in an attempt to boost scientific and innovation activities (Jeenah and Pouris 2008). In recognition that research and innovation in the field of renewable energy technologies are critical for the national energy policy and will stimulate the essential structural changes for the transition of Moroccan industry towards the emerging market of clean energy technologies, the Moroccan government plans to double government investment in renewable energy applied research and innovation over 5 years, from 40 million € in 2012–2017 to 80 million € by 2018–2023 (Mission Innovation 2021). In 2019, the Egyptian Ministry of Higher Education and Scientific Research established a partnership with USAID's Centre of Excellence for Energy to reinforce education and research that is critical to Egypt's economic development, provide scholarships for students to pursue studies in energy-related fields and improve curricula, new courses, and degree programs that address 21st-century energy sector challenges (USAID 2019). As part of the overall Diversification Strategy of Kenya Electricity Generating Company (KenGen), which is the leading electricity generation company in the Eastern Africa region, the company launched a state-of-the-art R&D Centre at Tana Power Station in Muranga County, in an effort to increase the research and innovation, especially in the field of clean energy technologies (KenGen 2021). These initiatives and programs, among many others, have not only influenced research productivity in many countries, but have also contributed to certain countries' significant achievement in achieving a sustainable energy transition through strategic energy planning and policy formulation.

Methodology

The bibliometric approach comprises the most comprehensive quantitative analysis of science and is an effective tool for quantifying the contribution of different components within a particular research field (Zhou et al. 2007). This study employs a bibliometric review method to assess the output, impact, structure, and development of a given field of study by using various tools and software to analyze published research data. In this section, we describe the steps taken to identify and map the knowledge domain related to Africa's renewable energy research in order to present a review that meets the objectives of this study.

Bibliometric analysis framework

Typically, there are two main categories of analyzing bibliographic data namely; performance analysis and science mapping (Cobo et al. 2011; Donthu et al. 2021). The performance analysis examines the contributions of various authors, institutions, and countries/regions to a certain research subject (Ramos-Rodríguez and Ruíz-Navarro 2004). In the current study, we employ performance analysis to identify the evolution of the research field, the most productive authors, institutions, and countries, as well as the field's most contributing journals. Science mapping, on the other hand, analyses the connections between the various components of research (Baker et al. 2021). The techniques adopted for science mapping in this paper include co-authorship analysis, citation analysis, co-citation analysis, co-word analysis. A summary of the research design which includes the bibliometric toolbox is presented in Fig. 2.

Data sources and collection methods

Bibliometric analysis employs mathematical and computational approaches to investigate the characteristics and trends of a document system by evaluating individual records as the research object (Du et al. 2014). The data in this study was collected from the Core Collection of Web of Science (WoS), compiled by Thomas Reuters and integrated into the ISI Web of Knowledge. WoS is a commonly used database that provides statistics on document types and languages, countries, institutions and authors, funding agencies, journals, and subject categories. It allows downloading of a full record and cited references of publications in text format for mapping and data analysis in other software. Academic publications on renewable energy in Africa from 1999 to 2021 were retrieved on the 26th of January 2022. The search query was searched for in the titles, abstracts, and keywords to address the problem of neologisms since the identifiers are recorded in the title, abstract, or keywords. The search query as well as the inclusion and exclusion criteria are presented in Table 1. The initial search when the timespan was set from 1999 to 2021 produced 6842 research documents which after being refined by the inclusion and exclusion criteria remained 5322 documents.

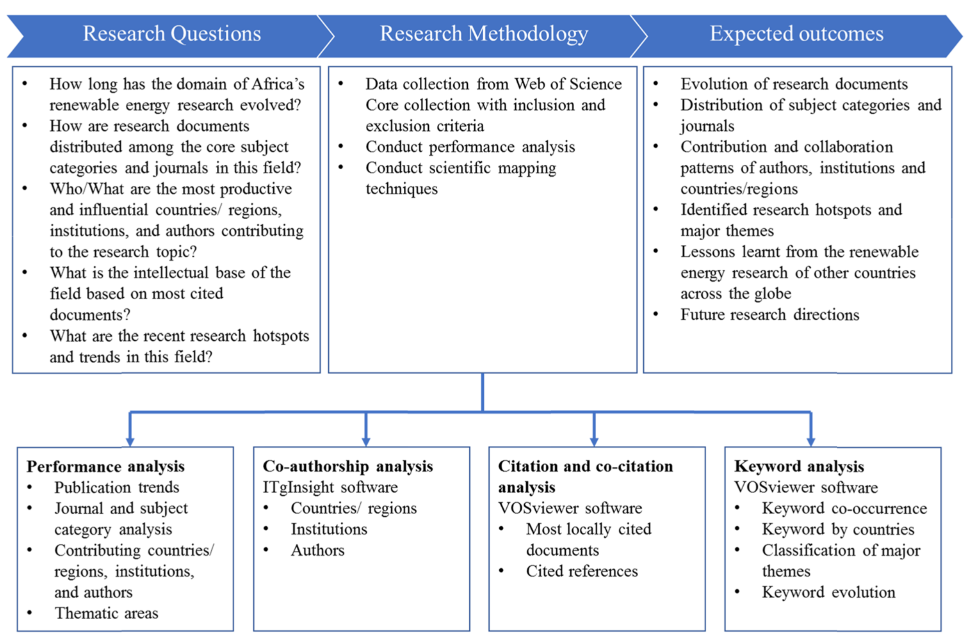


Fig. 2 Flow chart of research design

Table 1 Search process from data source

Process	Details	Number of documents
Search query (WoS Core Collection)	TS = ((“renewable energ*” OR “sustainable energ*” OR “green energ*” OR “low carbon energ*” OR “solar energ*” OR “wind energ*” OR “hydropower” OR “bioenerg*” OR “geothermal energ*” OR “nuclear energ*” OR “waste to energ*”) AND (africa* OR Algeria OR Egypt OR Libya OR Morocco OR Sudan OR Tunisia OR Angola OR Cameroon OR “Central African Republic” OR Chad OR Congo OR Guinea OR Gabon OR “São Tomé & Principe” OR Botswana OR Lesotho OR Namibia OR “South Africa” OR Swaziland OR Burundi OR Comoros OR Djibouti OR Ethiopia OR Eritrea OR Kenya OR Madagascar OR Malawi OR Mauritius OR Mozambique OR Rwanda OR Seychelles OR Somalia OR Tanzania OR Uganda OR Zambia OR Zimbabwe OR Benin OR “Burkina Faso” OR “Cape Verde” OR “Côte D’Ivoire” OR Gambia OR Ghana OR Liberia OR Mali OR Mauritania OR Niger OR Nigeria OR Senegal OR “Sierra Leone” OR Togo)). Timespan: 1999–2021	6842
Screening	Refine by Web of Science categories: Energy Fuels OR Green Sustainable Science Technology OR Environmental Sciences OR Engineering Electrical Electronic OR Environmental Studies OR Thermodynamics OR Economics OR Engineering Chemical OR Water Resources OR Engineering Environmental	5368
	Refine by Document type: Articles, Proceedings papers, Review articles	5322

Data analysis

The ITgInsight (Yuqin et al. 2015) and VOSviewer (van Eck and Waltman 2010) software were used to analyze and visualize data downloaded from the Web of Science Core collection. These programs are designed to identify patterns, frequencies, and trends in a large amount of information available in the literature. They have been integrated with co-citation, co-authorship, co-occurrence, mutual network analysis, and many other indicators for analyzing collaborations and links. Moreover, they support databases from China National Knowledge Infrastructure, Chinese Social Sciences Citation Index, Scopus, and Web of Science. We used the ITgInsight software for further data cleaning and visualization of co-authorship links of countries/regions, institutions, and authors while the VOSviewer software was used for visualization of co-citation network and keyword co-occurrence network.

The academic influence of research constituents (countries, institutions, authors, and journals) in the field was analyzed using the following indicators: total citations (TC), h-index, and impact factor. The h-index and impact factor indicators are a good measure of authors, journals, or research papers’ performance. Hirsch’s h-index was introduced as a reliable criterion for assessing the cumulative impact and value of an individual’s scientific performance, and it has the advantage of being empirical (Hirsch 2005). In this context, an individual is linked to publications and may be an author, institution, country, journal, etc. The h-index denotes a period over which h of an individual’s articles have been cited at least h times (Braun et al. 2006). Eugene Garfield also proposed the impact factor as a measure for journals in 1955 (Garfield 1955). It represents the cumulative number of citations of papers published by this source over a 2-year span (Amin and Mabe 2004, Garfield 2006). Since it shows a clear association with the content of the articles written in a journal, impact factor is regarded as a significant index for assessing scholars and the influence of an article. In this study, the impact factor was obtained from the Journal Citation Report (JCR) 2020 edition.

Results and discussion

General characteristics of documents

The search generated a total of 5368 publications on renewable energy research in Africa from 1999 to 2021, out of which 5322 representing 99.14% were articles, proceedings, and reviews while the remaining document types include book reviews, editorial materials, and news items as shown in Fig. 3. Articles, proceedings, and review papers normally carry the trends and development of research; therefore, we excluded the remaining document types and focused only on these three for further analysis. About 99.64% of the documents were published in English, with the remaining 0.36% representing French, German, and Spanish.

Table 2 summarizes the general statistics of the selected dataset related to Africa’s renewable energy research which provides an overview of critical indicators. The selected documents were published in a total of 649 sources including different journals, conference proceedings, books, etc.

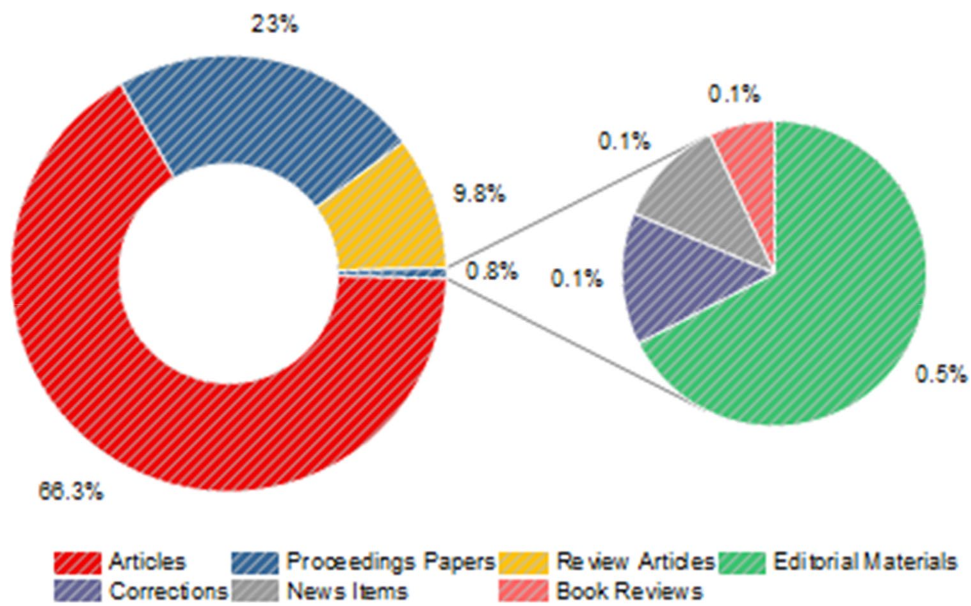


Fig. 3 Distribution of publications by document type

Table 2 Summary of the main information regarding the dataset

Description	Results
Timespan	1999:2021
Sources (journals, books, etc.)	964
Documents	5322
Average years from publication	5.67
Average citations per document	16.97
Average citations per year per document	2.655
References	160,348
Keywords plus	5028
Author's keywords	11,314
Countries/regions	144
Institutions	4189
Authors	12,561
Authors of single-authored documents	480
Authors of multi-authored documents	12,081
Single-authored documents	576
Documents per author	0.424
Authors per document	2.36
Collaboration index	2.55

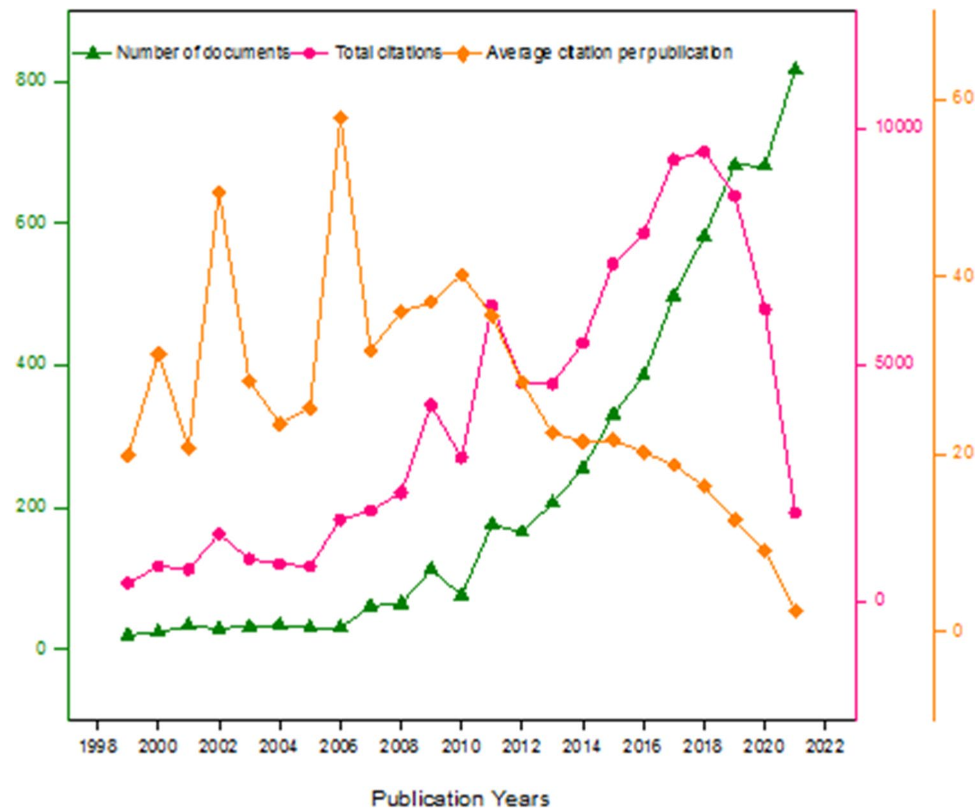
by 5379 authors from 4189 institutions and 144 countries. The total number of citations and average citations per document for the selected documents were 90,407 and 16.97, respectively.

Trends of research documents

The evolution of the research field in terms of the number of documents and respective citations published annually from 1999 to 2021 is shown in Fig. 4. As can be seen, the number of documents published rose significantly from 20 in 1999 to 817 in 2021. A growing interest in Africa's renewable energy from the start of the second millennium was largely fueled by two major significant events; the first one being the sharp surge in oil prices, which reached a high of US$33.16/ barrel in 2000 and the second being the repeated crises encountered by most power providers in various African countries (Karekezi and Kithyoma 2003). During that period, petroleum imports as a proportion of export revenues for various countries in Africa increased from roughly 15–20 to 30–40% (AFREPREN 2001). Moreover, countries like Ethiopia, Kenya, Malawi, Nigeria, and Tanzania experienced significant electricity rationing during that same period, which negatively impacted their economy significantly (Karekezi 2002). Therefore, the quick development of renewables became a key response alternative for solving Africa's energy concerns. Although the growth of research publications in this field was quite slow in the first decade, the numbers increased sharply from 2011. The documents within the last decade account for 89.76% of the total publications, with an average annual publication volume of 477.7 documents. This is an indication of how much researchers have gained massive interest in Africa's renewable energy development, especially in the last decade. This trend is expected to continue for the long term as interest in this research field rises.

On the other hand, the annual total citations of the documents were seen to fluctuate throughout the years and reached a peak in 2018, indicating that the 518 documents published in 2018 have received the highest total number of citations so far. However, 2018 among other years from 2014 to 2021 recorded the lowest figures for average citation per document while the highest figures were recorded in the

Fig. 4 Development of publications from 1999 to 2020



years 2000, 2002, and 2006, showing that the relatively low number of documents in the earlier years have received a relatively high number of citations and vice versa.

Distribution of documents in journals and subject categories

The field of renewable energy is fast evolving, and research has demonstrated significant shifts in numerous disciplines. The initial search revealed a total of 178 subject categories related to Africa's renewable energy research; however, we limited this figure to the top ten subject categories in order to analyze research publications within the most relevant scope of literature to meet the intended objectives of this study. Figure 5 shows the distribution of the top ten subject categories with respect to the number of publications. *Energy & Fuels* ranked first accounting for 35.9% of the total number of publications, followed by *Green Sustainable Science Technology* (17.8%) and *Environmental Sciences* (13.1%). This outcome is not surprising since the subject of *Energy & Fuels* mainly involves the development, production, use, application, conversion, and management of non-renewable fuels (e.g., coal, petroleum, and gas) and renewable energy sources (e.g., solar, wind, biomass, geothermal, hydroelectric), except for nuclear energy and nuclear technology (Yaoyang & Boeing 2013). Publications related to *Economics, Water Resources, Thermodynamics, and Engineering*

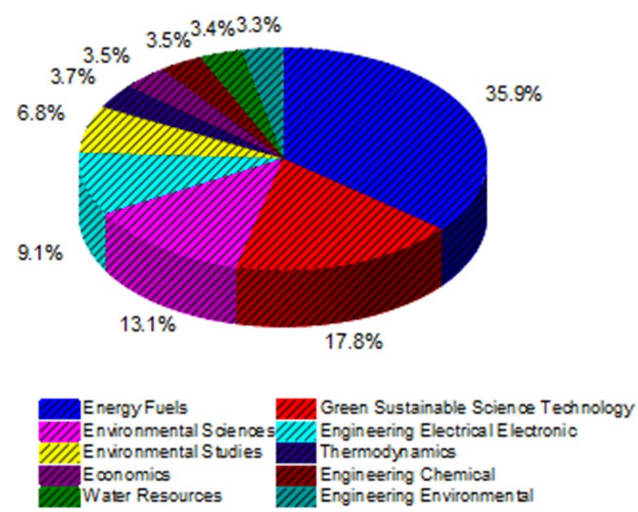


Fig. 5 Distribution of documents in the top 10 subject categories

(Electrical/Electronic, Chemical, and Environmental) also play a major role in Africa's renewable energy research.

The productivity and influence of the top 20 journals in terms of the number of documents which corresponds to 44.49% of the total documents are shown in Fig. 6. Each of these twenty journals has published more than thirty renewable energy research documents related to Africa. The three topmost journals in terms of the number of publications

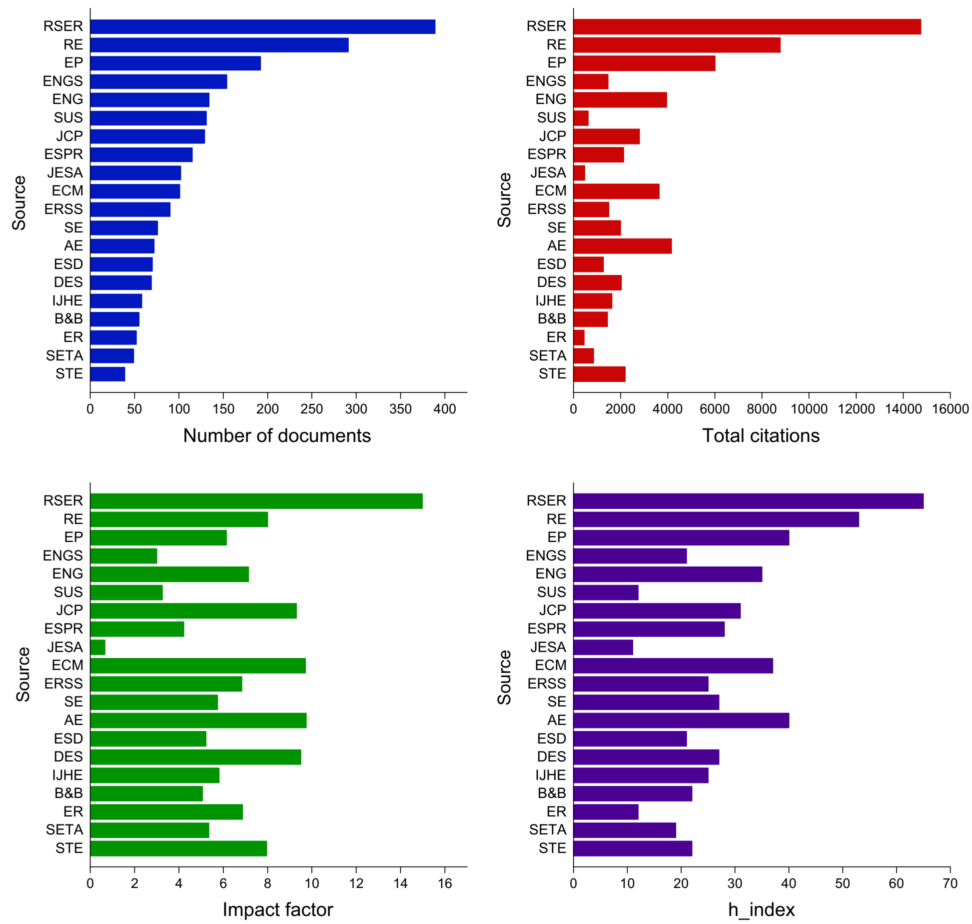


Fig. 6 Performance of top 20 most productive journals**.** (*Note*: RSER, *Renewable & Sustainable Energy Reviews*; RE, *Renewable Energy*; EP, *Energy Policy*; ENGS, *Energies*; ENG, *Energy*; SUS, *Sustainability*; JCP, *Journal of Cleaner Production*; ESPR, *Environmental Science and Pollution Research*; JESA, *Journal of Energy in Southern Africa;* ECM, *Energy Conversion and Management*; ERSS, *Energy Research & Social Science*; SE, *Solar Energy*; AE, *Applied Energy*; ESD, *Energy for Sustainable Development*; DES, *Desalination*; IJHE, *International Journal of Hydrogen Energy*; B&B, *Biomass & Bioenergy*; ER, *Energy Reports*; SETA, *Sustainable Energy Technologies and Assessments*; STE, *Science of the Total Environment*)

were *Renewable & Sustainable Energy Reviews, Renewable Energy,* and *Energy Policy*. The influence of *Renewable & Sustainable Energy Reviews* in this research field is very noteworthy as it ranked first not only in terms of the number of documents but also in terms of total citation, h-index, and impact factor. The impact factor has become a useful tool for determining the quality distribution of documents in a field and journals with high impact factors also tend to perform relatively well in terms of the number of citations and h-index. For instance, in this study, *Energy Conversion and Management* which ranks 10th in terms of the number of publications but has the second-highest impact factor was ranked 6th and 5th with regards to total citations and h-index, respectively. On the other hand, the *Journal of Energy in Southern Africa* with the lowest impact factor of 0.661 also recorded the second-lowest number of citations and the lowest h-index among the top 20 journals even though it ranked 9th in terms of the number of documents. In this research field, 16 out of the top 20 journals and more than 1866 documents (35%) have an impact factor above 5. This indicates the distribution of high-quality research documents in this domain which are likely to become hot and highly demanded papers in their corresponding subject categories due to the increasingly high number of citations. It is worth noting that some of the journal titles also give a clear indication of specific research directions or study areas that may be hotspots in this domain, for instance, "*Solar Energy*," "*Biomass & Bioenergy*," "*Desalination*," "*International Journal of Hydrogen Energy*," and "*Journal of Energy in Southern Africa*."

Performance and cooperation analysis of countries, institutions, and authors

Countries/regions

Statistical information on country/region distributions in Africa's renewable energy research is beneficial in providing knowledge on research productivity, influence, and collaborations. As shown in Fig. 7, authors from different countries across the globe have contributed to the knowledge domain of Africa's renewable energy research. The performance of the top 20 countries with the highest research output is displayed in Table 3. The top 20 countries consist of eight countries from both Africa and Europe, three from Asia, and one from America. South Africa ranks first in

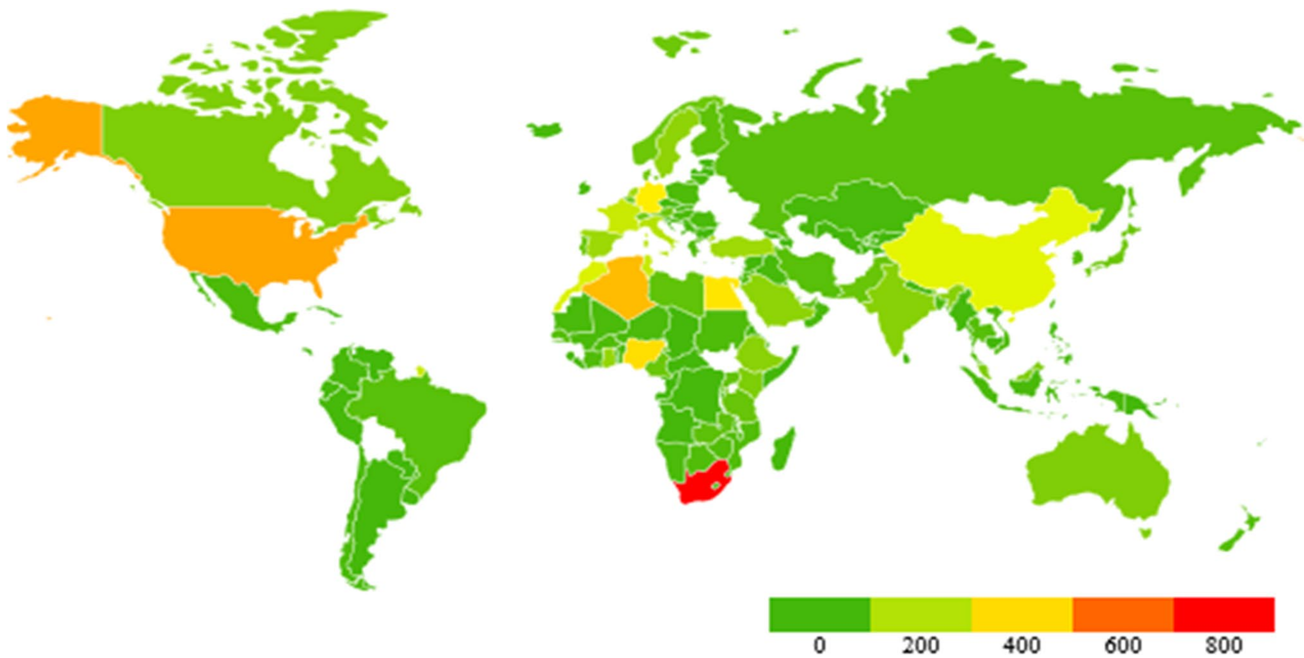


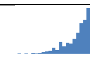
Fig. 7 Global distribution of published documents

terms of the number of documents by contributing 14.5% of the total documents in the dataset, followed by the USA (9.18%) and Algeria (8.47%). Other African countries in the top 20 include Nigeria, Egypt, Morocco, Tunisia, Ghana, and Ethiopia. As noted in the "Bibliometric analysis framework" section, the majority of these top contributing African countries also have strategic policies and initiatives for renewable energy research as part of their national energy policy framework, which explains their relatively good academic performance. The advancement of renewable energy development in these countries is also reflected in their performance in renewable energy research when compared to other African countries with lesser research output. Even though there is still an enormous renewable energy potential to be exploited, countries like South Africa, Algeria, Egypt, Morocco, and Ethiopia have made significant progress in recent times through the implementation of several policies incentives, and initiatives (IRENA 2021). This indicates the crucial role research plays in a country's renewable energy development in terms of strategic planning and policy formulation. In terms of sub-regions, North Africa was the most represented on the list of the top 20 countries, while Central Africa was the least with no representative country. This could be attributed to North Africa's relatively high GDP which has been identified by Meo et al. (2013) to have a positive correlation with R&D.

With regards to country/region production over time, it can be seen that South Africa has dominated the field since the beginning even though the number of documents has been increasing more rapidly in the last 12 years. In mid-2002, the Department of Minerals and Energy in South Africa recognized the need to begin a rapid transition to renewable energy and enacted a renewable energy policy, i.e., the Renewable Energy White Paper (Winkler 2005). This led to the re-enactment of the White Paper on Renewable Energy, National Energy Act of South Africa 2008 (Department of Energy 2019) which arguably boosted research output on renewable energy from 2009 and has fast risen since then along with the development of several renewable energy policies. Nigeria has also been active in this field since 2003 following the full implementation of the National Energy Policy Act which resulted in the establishment of four additional research centers (Adedayo et al. 2021); however, the introduction of the National Renewable Energy and Energy Efficiency Policy in 2015 (Federal Republic of Nigeria 2015) caused an exponential rise in research documents related to Nigeria's renewable energy development from 2016 to the current year under study. Ghana, Ethiopia and Morocco have only recently established themselves in this field but considering their growth rates in the last few years, they are expected to become key countries in Africa's renewable energy research in future. China's research publications have also lately begun to dominate this field, publishing the maximum number of documents from a non-African country in the past 3 years.

The impact of research documents on countries/regions in this field was assessed by analyzing their total citations and h-index. Research documents affiliated to the USA recorded the highest number of citations and the highest h-index, followed by Germany and Algeria. Generally, publications

Table 3 Performance of top 20 most productive countries

Country	Number of documents	Total citations	h-index	Corresponding author's country	Single-country	Multi-country	Evolution
South Africa	769	7490	42	627	490	137	
USA	488	10235	53	282	171	111	
Algeria	452	7980	45	415	308	107	
England	417	7273	43	313	184	129	
Nigeria	394	6041	43	265	195	70	
Egypt	380	5596	41	288	216	72	
Germany	367	8405	48	246	133	113	
Peoples R China	292	4671	37	245	135	110	
Morocco	274	2473	27	228	185	43	
France	239	4588	39	92	38	54	
Tunisia	239	4781	38	204	159	45	
Italy	204	5108	36	134	66	68	
Netherlands	168	4765	34	94	50	44	
Turkey	164	4927	38	68	49	19	
Spain	160	3906	38	89	48	41	
Ghana	146	2439	27	69	40	29	
Sweden	135	3356	33	84	33	51	
Saudi Arabia	133	3031	31	55	15	40	
Ethiopia	126	1743	23	84	44	40	
India	122	1652	24	58	35	23	

from the European countries received a relatively higher number of citations compared to other regions except for the USA. This shows the high influence of their research publications in the renewable energy field. Even though China ranked 8th in terms of productivity, its academic influence was observed to be relatively lower in terms of h-index (12th).

The table also shows the number of articles based on corresponding authors' countries used to analyze single-country publications (SCP) which denotes intra-country collaborations and multi-country publications (MCP) which denotes international collaborations. With the leading number of documents, South Africa had 490 SCP and 137 MCP with an MCP ratio of 0.219. Among the African countries, Ethiopia obtained the highest MCP ratio of 0.476 indicating that about 47% of its publications were produced in collaboration with other countries. Countries from North Africa demonstrated relatively low collaborative efforts compare to other

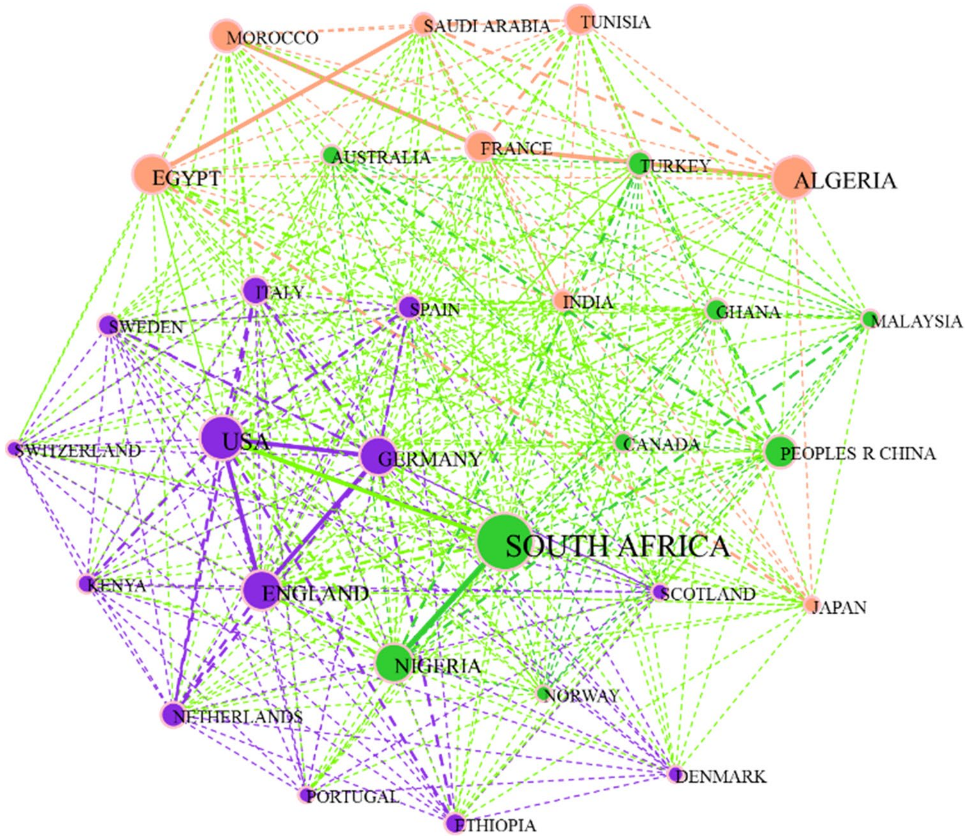


Fig. 8 Academic collaboration among the top 30 most productive countries

countries. Generally, Sweden had the highest MCP ratio with 51 MCP and 33 SCP, followed by France and Malaysia.

Figure 8 illustrates the cooperation network among the 30 most productive countries. The various colors represent the cluster to which the countries are assigned based on the frequency of their relations, the node size represents the number of publications, and the lines connecting the circles depict connections. The thicker the lines connecting them, the stronger the link between the two countries is. The network map was divided into three major clusters. The nodes found in the center of the map indicate a high level of centrality which means that these countries have the most extensive collaboration and communication with other countries in this domain, most of whom happen to be the largest contributors to the field. The three strongest countries in terms of co-authorship links were the USA, England, and Germany. This shows that foreign collaborations have played a major role in the development of Africa's renewable energy research, particularly from the USA and most European countries. Among the African countries, South Africa had the highest total link strength, followed by Nigeria and Egypt.

The main collaboration patterns between the four most productive African countries among the top 20 countries from each sub-region and the top 30 countries are shown in Fig. 9. It can be observed that South Africa has the highest academic link with Nigeria with 60 joint publications, followed by USA and England. Algeria has the highest collaboration with France, Saudi Arabia, and Spain. After South Africa, Nigeria has the strongest collaboration with England, Malaysia, and the USA. This observation was found to be consistent with a bibliometric study of energy research in Nigeria by Adedayo et al. (2021). Ethiopia also demonstrated strong collaborations with USA, Germany, and Norway. It is worth mentioning that the most productive African countries tend to collaborate more with countries outside Africa and have rather fewer intra-continent collaborations. Collaborations exist when there is a mutual benefit that stands to be gained by all parties forming the partnership. A drawback to renewable energy growth in Africa mostly lies in the lack of research funding and availability of advanced technologies albeit the huge number of experts. Against this backdrop, intra-collaborations within Africa are relatively limited as most of these African countries are inclined to collaborate with countries where research funding and advanced technologies are readily available, and these countries are mostly found in Europe, North America, and Asia, China to be specific. However, African countries by virtue of their similarities in demographics and natural resources can further develop their renewable energy market and field if more intra-continent ties are fostered.

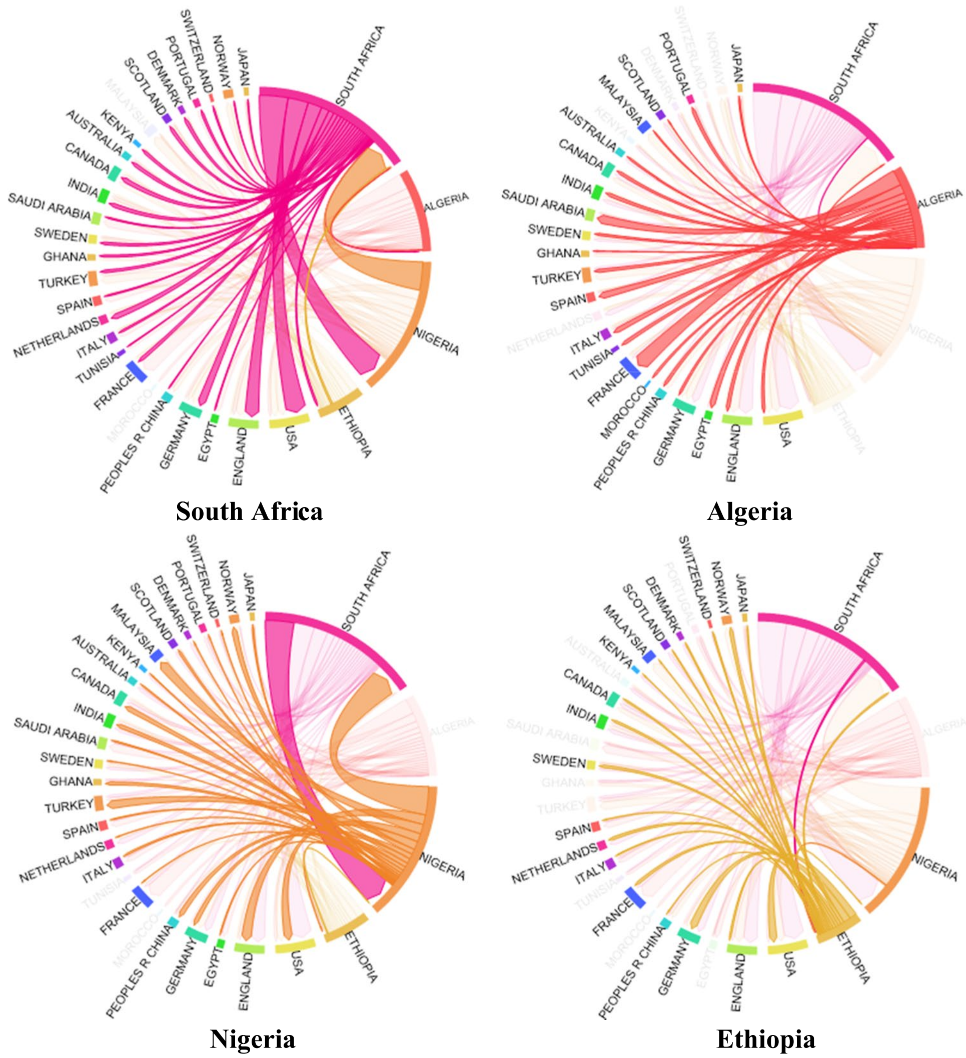


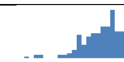
Fig. 9 Collaboration patterns of the most contributing African countries from the four sub-regions

Institutions

Renewable energy in Africa has been largely researched across 4189 institutions, however, the top 20 most productive institutions alone account for 26.6% of the total number of documents in the dataset. Table 4 shows the research output and influence of the 20 most productive institutions. Among these institutions seven can be found in South Africa, three in Tunisia, two each in Algeria, Nigeria, and Morocco, and one each in England, Netherlands, Egypt, Ghana, and Denmark. The Algerian institution, Centre de Developpement Des Energies Renouvelables (CDER), which is a research center solely devoted to the development of renewable energy has contributed the highest number of documents in this field. Six out of the seven South African institutions ranked 2nd to 7th in terms of research productivity and have altogether produced 10.2% of the total documents. The evolution of research documents shows that the productivity of most institutions has been fluctuating over the years and only a few of them like the University of Cape Town and the University of Johannesburg have rather maintained some consistent growth. In terms of the academic influence of the research documents from the institutions based on total citations and h-index, CDER still maintained its first position in both measuring indicators, followed by Utrecht University and the University of Cape Town. Even though some institutions had relatively high research output, their academic influence in the field was found to be the weakest among the top 20, for example, Tshwane University of Technology, University of Johannesburg, and Mohammed V University in Rabat. On the other hand, countries such as Utrecht University, Universite de Tunis El Manar, and the University of Ibadan which had a relatively lower number of documents among the top 20 performed much better in terms of total citations and h-index.

The collaboration network map of the 30 most productive institutions is shown in Fig. 10. The map reveals four main clustered networks indicated by four different colors with

Table 4 Performance of top 20 most productive institutions

Institutions	Number of documents	Total citations	h-index	Evolution
Centre de Developpement Des Energies Renouvelables	191	3989	35	
University of Cape Town	125	1582	22	
Stellenbosch University	124	1191	19	
University of Johannesburg	94	584	11	
University of Pretoria	72	1352	20	
Tshwane University of Technology	67	239	8	
University of Kwazulu Natal	65	686	15	
Covenant University	61	1331	21	
Mohammed V University in Rabat	61	346	10	
University of London	59	858	18	
Universite de Sfax	57	885	17	
Utrecht University	54	2372	24	
Sidi Mohamed Ben Abdellah University of Fez	53	841	17	
Universite de Tunis El Manar	50	1275	17	
University of Ibadan	48	1328	18	
Cairo University	47	486	16	
Kwame Nkrumah University Science Technology	47	793	17	
Universite Kasdi Merbah Ouargla	47	650	16	
Technical University of Denmark	46	661	16	
Council for Scientific Industrial Research South Africa	45	634	15	

five other different colors of single nodes, indicating institutions with no collaborations among the top 30. The largest cluster with the highest number of nodes represented in red involves institutions from different countries including England, Denmark, Netherlands, Ghana, Egypt, Sweden, and Mauritius. The collaborations links in this cluster are relatively weaker compared to other clusters. The strongest link among them was found between University College, London, and University of Manchester both in England with 10 joint publications. The second-largest cluster represented in green is a collaboration network of four South African institutions and three institutions from Nigeria. This observation further highlights the strong academic link between South Africa and Nigeria as mentioned in the previous section and in other studies (Adedayo et al. 2021; Pouris 2016). In this cluster, the strongest link denoted by the thickest line can be seen between the Tshwane University of Technology in South Africa and the University of Ibadan in Nigeria with a

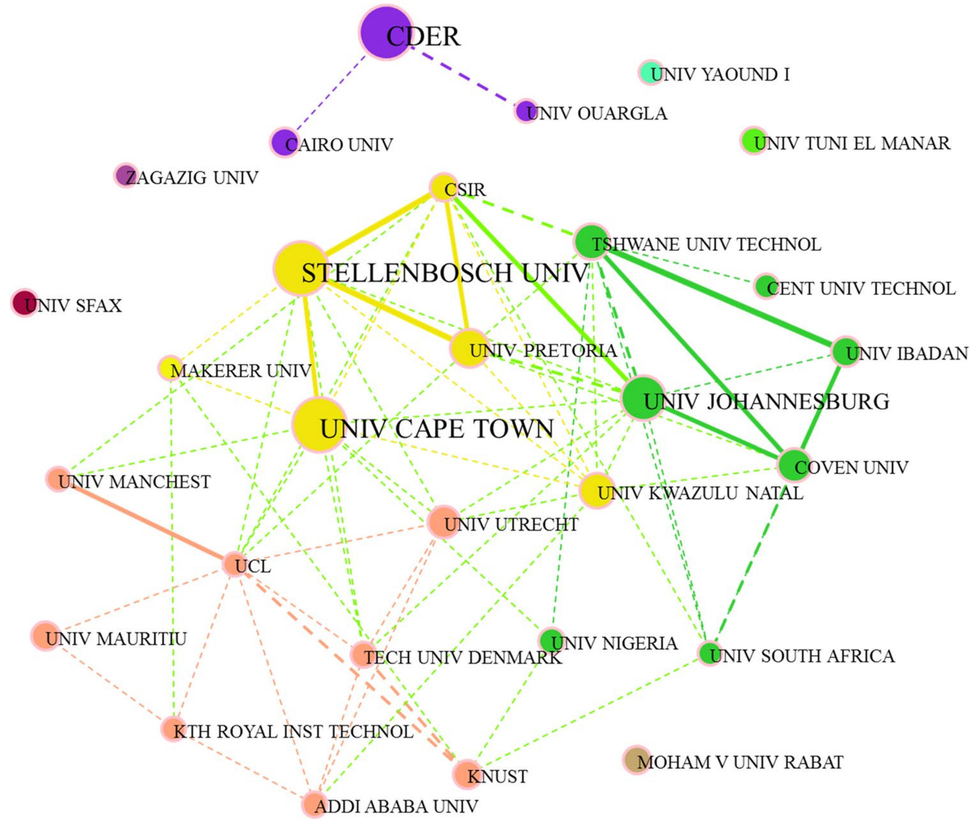


Fig. 10 Academic collaboration among top 30 most productive institutions

total of 16 joint publications. The third cluster (yellow) was also the most prominent in terms of collaborative links. This cluster consisted of four of the top South African institutions and one institution from the USA. The strongest links were found between Stellenbosch University and the University of Pretoria and Stellenbosch University and CSIR both with 20 joint publications each. The fourth cluster and last network were made up of just three nodes of North African institutions; two from Algeria and one from Egypt. CDER which is the institution with the highest research output in this field was found to be much weaker in terms of collaborations, with only six joint publications with Universite Kasdi Merbah Ouargla and two with Cairo University. Overall, it was observed that most institutions had more domestic cooperation than multi-national cooperation.

Authors

This study revealed 12,561 authors in this research field, 15 of whom had more than 15 research documents each and have altogether contributed about 6.6% of the total documents. The performance of the 15 most productive authors based on research output is displayed in Table 5. The most prolific authors were predominantly affiliated with institutions in South Africa and Morocco. The top three authors in terms of research productivity are Chowdhury, S.P., Brent A.C., and Kusakana K. with 51, 40, and 34 research documents, respectively. It is not surprising that all three authors are affiliated with South African institutions (University of Cape Town, Stellenbosch University Central University of Technology). Despite ranking 13th in research output and only being active in the field in the last few years, Sarkodie S.A. has played a substantial role in this research field as the most academically influential author with the highest number of citations among the top 15, followed by Adaramola M.S. and Allouhi A. Chowdury S.P. on the other hand despite being the leading author in research output ranked 13th in terms of total citations, indicating a relatively weaker academic influence in the field.

The collaboration network map of the 50 most productive authors is shown in Fig. 11. The network map was divided into many different clusters since several authors had no collaborations at all among the top 50. The largest cluster with the highest number of nodes consisted of five authors including; Sarkodie S.A., Bekun F.V., Adams S., Ozturk I., and Owusu P.A. The second largest cluster involved four authors: Stambouli A.B, Himri S., Himri Y., and Merzouk N. A.; however, the thickness of the lines connecting the nodes shows that collaborations were strongest among the first three. The remaining authors cooperated with either one or two more authors. The most prominent cluster with the strongest link strength was the collaboration among Allouhi

Table 5 Performance of top 15 most productive authors

Author	Number of documents	Total citations	h-index	Evolution
Chowdhury, S.P.	51	122	8	
Brent, A.C	40	605	12	
Kusakana, K.	34	534	11	
Ayodele T.R.	24	389	9	
Adaramola M.S.	23	946	16	
Allouhi A	21	692	14	
Lin BQ	21	385	11	
Bennouna E.	20	61	6	
Jamil A.	18	687	15	
Kousksou T.	18	680	15	
Settou N	18	298	11	
Bekun F.V.	17	600	11	
Ghennioui, A.	16	47	4	
Sarkodie S.A.	16	1134	11	
Sovacool B.K.	16	329	11	

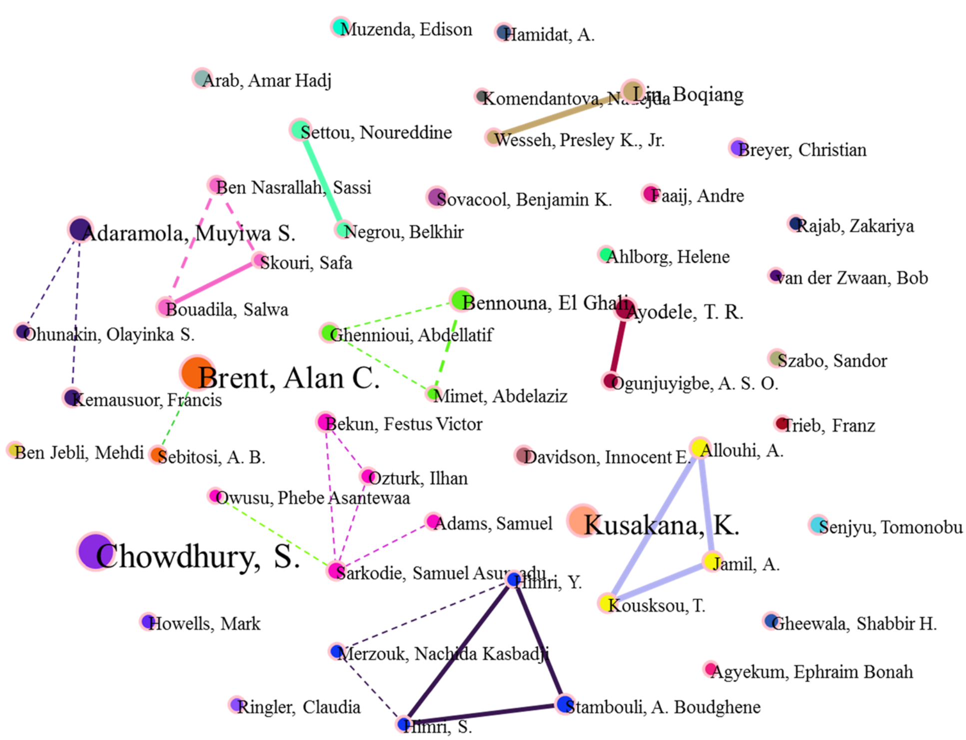


Fig. 11 Academic collaboration among top 50 most productive authors

A., Jamil A., and Kousksou T. with 14 joint publications. Both Allouhi A. and Jamil A. were found to be affiliated to Sidi Mohamed Ben Abdellah University of Fez in Morocco while Kousksou T. is affiliated to Université de Pau et des Pays de l'Adour in France. These three prolific authors have closely worked together in the field of solar energy, particularly solar cooling and refrigeration in Morocco. The collaboration map showed that top authors in terms of research output like Chowdhury, S.P., and Kusakana, K., have mostly completed their research independently with no collaboration with other top authors in the field.

Citation analysis

Most cited documents

While there are many studies in a research field, the relatively small number of highly cited articles could represent the research direction of follow-on publications (Schwartz et al. 2005). Table 6 shows the main information regarding the ten most cited documents of Africa's renewable energy research from 1999 to 2021. Half of the ten most cited documents were published before 2011. The earliest document on the list is also the most cited document in the field with 502 citations and published in *Renewable & Sustainable Energy Reviews* (Barbier 2002). This paper is a very comprehensive review article with a lot of detailed information on the internal structure of the earth, and the heat transfer processes within the mantle and crust as well as depicts the locations of geothermal fields throughout the world. According to Barbier (2002), electricity generation from geothermal sources could contribute substantially to the electrical consumption of most developing countries with relatively high geothermal potential like Kenya which at that time had about 8% share of national capacity from geothermal sources.

Table 6 Top 10 most cited articles

Paper type	Paper title	Journal	Times Cited	Country	Ref
Review article	Geothermal energy technology and current status: an overview	*Renewable & Sustainable Energy Reviews*	502	Italy	Barbier (2002)
Research article	The global potential of bioenergy on abandoned agriculture lands	*Environmental Science & Technology*	403	USA	Campbell et al. (2008)
Review article	A bottom-up assessment and review of global bio-energy potentials to 2050	*Progress in Energy and Combustion Science*	390	Netherlands	Smeets et al. (2007)
Research article	Energy consumption, pollutant emissions and economic growth in South Africa	*Energy Economics*	352	England	Menyah and Wolde-Rufael (2010)
Research article	Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries	*Science of the Total Environment*	339	Australia	Sarkodie and Strezov (2019)
Review article	CO_2 emissions, renewable energy and the Environmental Kuznets Curve, a panel cointegration approach	*Renewable & Sustainable Energy Reviews*	305	Japan	Zoundi (2017)
Review article	Energy for sustainable development: A case of developing countries	*Renewable & Sustainable Energy Reviews*	295	Turkey	Kaygusuz (2012)
Research article	Land Availability for Biofuel Production	*Environmental Science & Technology*	264	USA	Cai et al. (2011)
Research article	The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bioenergy in energy supply	*Ecological Economics*	258	Netherlands	Gerbens-Leenes et al. (2009)
Research article	Feasibility study of small Hydro/PV/Wind hybrid system for off-grid rural electrification in Ethiopia	*Applied Energy*	255	Ethiopia	Bekele and Tadesse (2012)

The most recently published document on the list ranked 5th in terms of total citations with 339 citations within the last years (Sarkodie and Strezov 2019). This article focused on assessing the impact of foreign direct investment inflows, economic growth, and energy consumption on greenhouse gas emissions from 1982 to 2016 for the top five leading developing countries in greenhouse gas emissions from fuel combustion using panel data regression with Driscoll-Kraay standard errors, U test estimation approach and panel quantile regression with non-additive fixed-effects. Their findings revealed that inflows of foreign direct investment combined with clean technological transfer and improvements in labor and environmental management practices will aid developing countries in achieving their sustainable development goals while increasing energy efficiency, the adoption of renewable energy technologies, and the use of carbon capture and storage for fossil fuel and biomass energy-generating processes are all important factors in reducing greenhouse gas emissions. Two more documents on the list of the top 10 most cited documents also focused on assessing the relationship between economic growth, energy use (renewable energy), and pollutant (CO_2) emissions in African countries particularly, South Africa (Menyah and Wolde-Rufael 2010, Zoundi 2017). South Africa's share in global warming has attracted urgent attention since 2005 as its per capita emissions of 9 tons CO_2e per person rose above the global average of 5.8 tons and six times more than the average of sub-Saharan Africa with 1.4 tons (Ziuku and Meyer 2012). Many studies have since then been directed towards this topic evidenced by the number of citations received by these articles in the past few years. The conclusions of Menyah and Wolde-Rufael (2010), the fourth most cited paper, suggested that it is possible to satisfy South Africa's energy needs while still reducing CO_2 emissions by introducing energy alternatives to coal the country's primary source of CO_2 emissions. Furthermore, improving energy efficiency and using the country's renewable energy resources could be promising choices for addressing the country's major energy and environmental challenges. The estimates of Zoundi (2017) also indicated that renewable energy, with a negative impact on CO_2 emissions and a growing long-term effect, remains a viable alternative to the use of conventional fossil fuels. In the medium and long run, however, the influence of renewable energy is dwarfed by primary energy use, implying more global synergy for meeting environmental concerns. The influence of these three articles shows that the relationship between economic growth, CO_2 emissions and renewable energy in Africa have been a defining research topic in the last few years.

The theme of bioenergy potential, production, and development dominated the top 10 most cited articles in terms of renewable energy resources. For several people in Africa, both in rural and urban regions, biomass has been and continues to be their primary source of energy. Sub-Saharan Africa, in particular, has a wide range of bioenergy feedstocks with tremendous potential to address the continent's growing need for modern energy services. The study conducted by Campbell et al. (2008) is the second most cited document in this field, which estimated the global potential for bioenergy on abandoned agriculture lands to be less than 8% of current primary energy demand, based on historical land use data, satellite-derived land cover data, and global ecosystem modeling. This study found that for most countries in North America, Europe, and Asia, national bioenergy potential was less than 10% of primary energy demand, however, in some African countries where grasslands were quite productive and fossil fuel use then was low, it represented several times the current energy demand. In the review article by Smeets et al. (2007), the authors also analyzed the bioenergy potential in 2050 for various regions across the globe. The results of this study indicated that Sub-Saharan Africa is among the regions with the highest bioenergy potential on surplus agricultural land (31–317 EJ year^{-1}). Commercial bioenergy development in Africa, however, has been exceedingly limited, with a poor success rate, and a thorough grasp of the prerequisites and prospects for accelerating bioenergy growth is still largely lacking.

The only notable countries reflected in the titles of two of the most cited publications were South Africa and Ethiopia (Bekele and Tadesse 2012, Menyah and Wolde-Rufael 2010). The most prominent journal on the list was *Renewable & Sustainable Energy Reviews*, which is not surprising considering its influence in the field, as highlighted in the previous section. Apart from one study which was published in Ethiopia, none of the other most cited documents on the list is from Africa; instead, they are affiliated to the USA, Netherlands, England, Italy, Turkey, Australia, and Japan. Among the top 20 most productive institutions, Utrecht University is the only one that represents one document in the list (Smeets et al. 2007). It is also interesting to note that only one author (Sarkodie S.A) among the top 15 most productive authors is represented on the list of the most cited documents. These observations indicate that the impact of certain authors, institutions, and countries in this research field is influenced by factors other than research output, highlighting the value of using several metrics.

Co-citation analysis of most cited references

Co-citation refers to the number of times two documents are cited together by a third document (Small 1973). Co-citation analysis is a scientific mapping approach that assumes that papers that are often referenced together are thematically comparable (Hjørland 2013). The least number of citations per document was set to 20 in the co-citation analysis of cited references. Out of the 160,348 references, only 393 fit

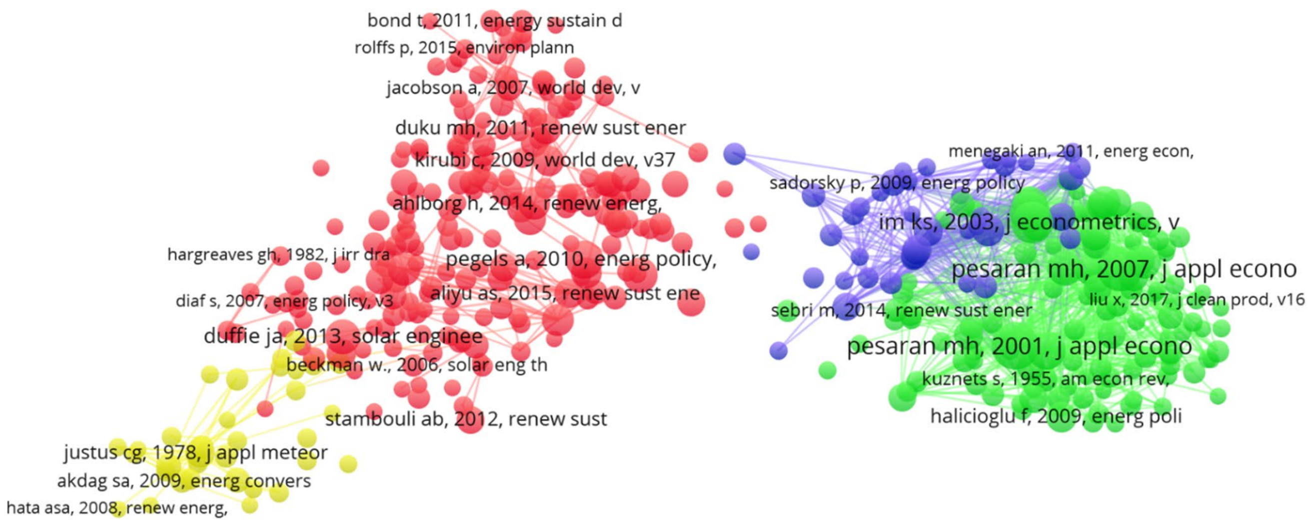


Fig. 12 Co-citation network among the top cited references

the criteria. Figure 12 shows the co-citation network map among the top-cited references. The color indicates the cluster to which the cited references are attributed according to the strength of their relationships, the size of the circle corresponds the number of citations, and the lines between the circles represents links. There were four major clusters identified. The largest cluster (red) with the highest number of nodes (203 references) was led by Pegels (2010) with 70 co-citations. This document focused on determining the potentials, barriers, and options for support for renewable energy development in South Africa. The study showed that renewable energy resources, particularly solar energy, are abundant in South Africa, and utilizing this resource would assist in addressing both the emissions and energy supply challenges. However, the implementation of renewable energy policy statements such as feed-in tariffs to solve the economic challenges of renewable energy development are expected to be faced with various political and technical challenges. This study therefore proposed key recommendations for South African policymakers to address these challenges. The majority of documents in this cluster were published in energy-related journals particularly *Renewable & Sustainable Energy Reviews*, *Energy Policy*, and *Solar Energy*.

The second cluster was included 115 nodes and was led by Pesaran et al. (2001) which is also the document with the highest co-citations (102) in this field. This research offers a new way to verify the presence of a level relationship between a dependent variable and a set of regressors when it is not known with certainty whether the underlying regressors are trend- or first-difference stationary. Documents in this cluster were published in journals under both *Energy & Fuels* and *Economics*. The third cluster consisted of 40 nodes and was led by both Levin et al. (2002) and Im and Pesaran (2003). These documents basically focus on the panel unit root test in the power parity hypothesis. The study of integrated series in panel data has progressed significantly and has been applied to various disciplines. Several studies have since applied panel unit root test in this field of research from different perspectives, particularly for determining the relationships among energy consumption, CO_2 emission, and economic growth and mostly focusing on the Sub-Saharan African region (Adams et al. 2016, Esso and Keho 2016, Oluoch et al. 2021). Majority of the documents in this cluster were published in the *Journal of Econometrics* and *Energy Policy*. The fourth cluster consisted of a network of 33 references mainly focused on methods for estimating wind speed frequency distribution (Justus et al. 1978) is the oldest and also, most cited document in the cluster which provides methods for computing the two Weibull parameters (scale factor c and shape factor k) from basic wind statistics.

Author keyword analysis

It is critical to thoroughly analyze the keywords of research documents in order to have a better knowledge of the major areas of a topic in a scientific study area for a certain time period, as they contain important facts about current research (Wei et al. 2015). Author keywords mostly define the main idea of a research field, and they are used to evaluate trends in a particular field of study (Chen et al. 2016). The 5322 documents in the dataset revealed a total of 11,314 author keywords. Keywords that appeared only once accounted for 77.7% of the total number of author keywords while the remaining appeared more than once, indicating huge diversity in research topics. Table 7 shows a list of the top 20 author keywords according to the frequency of their occurrences. The top three keywords with the highest occurrences

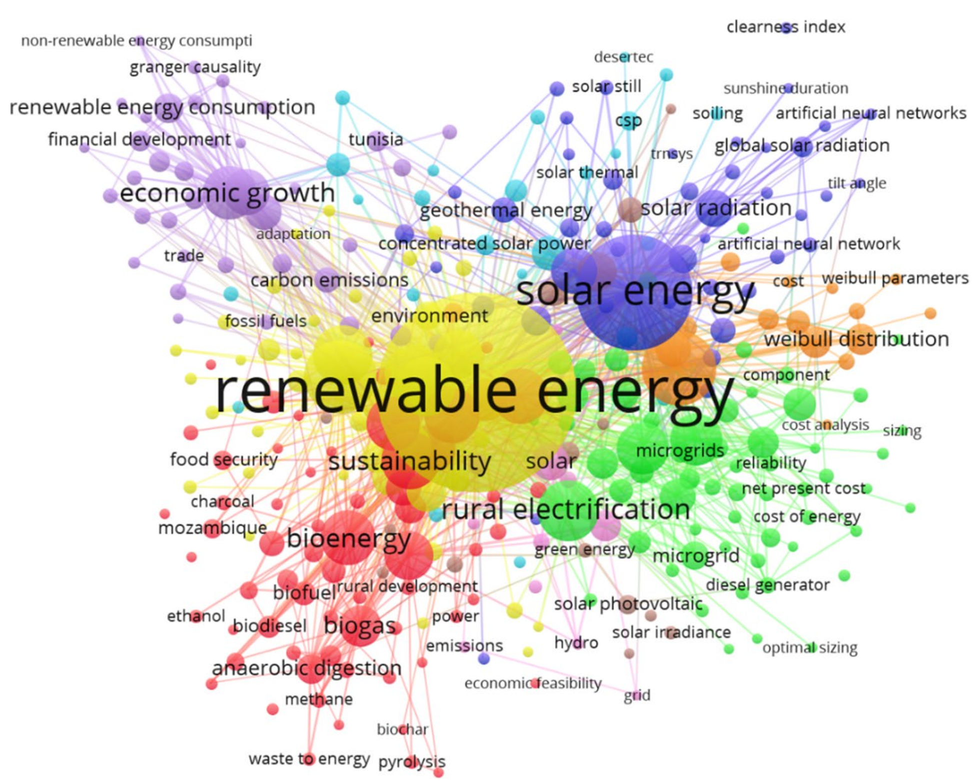
Table 7 Number of occurrences for the 20 most frequently used author keywords

Keywords	Occurrences	Keywords	Occurrences
Renewable Energy	913	Energy	120
Solar Energy	385	Nigeria	119
Wind Energy	191	Hydropower	116
Africa	185	Optimization	112
Rural Electrification	138	Photovoltaic	111
Climate Change	135	Economic Growth	105
Sustainable Development	134	Sub-Saharan Africa	104
Sustainability	133	Biomass	102
South Africa	129	Energy Efficiency	98
Bioenergy	123	Desalination	92

were "renewable energy," "solar energy," and "wind energy" with 913, 385, and 191 occurrences, respectively.

The minimum number of appearances of a keyword was set at 10 for the evaluation of the co-occurrence of author keywords and only 315 keywords out of the total fit the criteria. Figure 13 illustrates a network map of the most frequently used author keywords in the domain of Africa's renewable energy research from 1999 to 2021. The different colors in the figure represent different clusters to which the author keywords are assigned based on the frequency of their associations. The circle size represents the number of publications, and the line connecting the circles represents links between keywords. The analysis produced five major clusters and four minor clusters which contained less than 30 items. The largest cluster (red) consisted of 66 keywords predominantly related to bioenergy such as biogas, biofuel, anaerobic digestion, charcoal, agricultural residue, waste-to-energy, methane, etc. This cluster also consisted of various keywords related to evaluation methods such as life cycle assessment, multi-criteria decision, remote sensing, swot analysis, etc. The second cluster (green) contained 59 keywords that were centered around renewable energy technologies for rural electrification and energy storage. The keywords in this cluster included photovoltaic, wind turbine, battery storage, diesel generator, distributed energy, fuel cell, microgrid, HOMER, optimization, smart grid, off-grid, etc. The third cluster (blue) which consisted of 44 keywords was led by solar energy and included other keywords like solar radiation, solar desalination, solar collector, temperature, Southern Africa, Sudan, forecasting, efficiency, modelling, artificial neural network, etc. The fourth cluster (yellow) was made up of 42 keywords including renewable energy, Africa, climate change, energy efficiency, energy policy, governance, environment, sustainable development, education, etc. The last major cluster (purple) consisted of 38 keywords which were led by economic growth and included other keywords like financial development, renewable energy consumption, trade, ecological footprint, carbon emissions, human capital, MENA countries, and Tunisia.

Fig. 13 Co-occurrence network of the most frequently used author keywords



Keyword analysis by countries/sub-regions

The distribution of the 30 most frequent keywords was analyzed for research documents affiliated to the top four African countries from each subregion and visualized in four different word clouds (a, b, c, d) as shown in Fig. 14. The size of the keywords is proportional to their frequency of occurrence. The purpose is to study the dynamism of literature in the most contributing African countries in order to understand the main research direction of each of these countries and the relationship among them. An overall observation shows that while there are some variations in keywords occurrence among the four countries, the three most frequently occurred keywords mentioned in the previous section (renewable energy, solar energy, and wind energy) were found to be present in all the various word charts. Since renewable energy is the main topic of study, it is not surprising that it was recorded as the most frequently occurring keyword, however for solar energy and wind energy, it can be deduced from this study that they are the most frequently studied renewable energy sources in Africa. Other common keywords among the various word charts include “climate change,” “sustainable development,” and “solar PV.”

South Africa has contributed the most to this field and therefore has the highest number of author keywords. The distribution of keywords in Fig. 14a shows that renewable energy research in South Africa has mostly focused on solar energy, followed by wind energy and bioenergy. Solar photovoltaic appeared to be the most studied renewable energy technology in South Africa. Solar energy is one of the most promising renewable energy sources in South Africa (Aliyu et al. 2018). South Africa has made the highest progress in solar development in Africa so far with a cumulative PV capacity of 5.99 GW at the end of 2020 (IRENA and AfDB 2022). In rural areas of South Africa, photovoltaic (PV) has been widely employed for lighting, household appliances, telecommunication, and water pumps in houses and institutions (Akinbami et al. 2021). The current 10-year energy strategy released by South Africa’s Department of Energy, the Integrated Resource Plan, seeks to install an additional 6 GW of PV by 2030, in order to boost PV installed capacity from 3% of total power supply now to 11% by 2030 (Bellini 2021). Apart from South Africa, other southern African countries including Zambia, Zimbabwe, Botswana, Namibia, and the Democratic Republic of Congo are rapidly growing their solar infrastructure and are on track to exceed 1 GW of installed capacity in the near future (IRENA and AfDB 2022). For many decades, the wind has also been an important source of energy in South Africa, where early inhabitants, mostly farmers, utilized windmills to pump water for agricultural reasons (van der Linde 1996). Per the Integrated Resource Plan, wind energy capacity is projected to rise from roughly 1.98 GW to 17.7 GW by 2030, accounting for 22.5% of the energy mix. Other prominent topics of interest in South Africa’s renewable

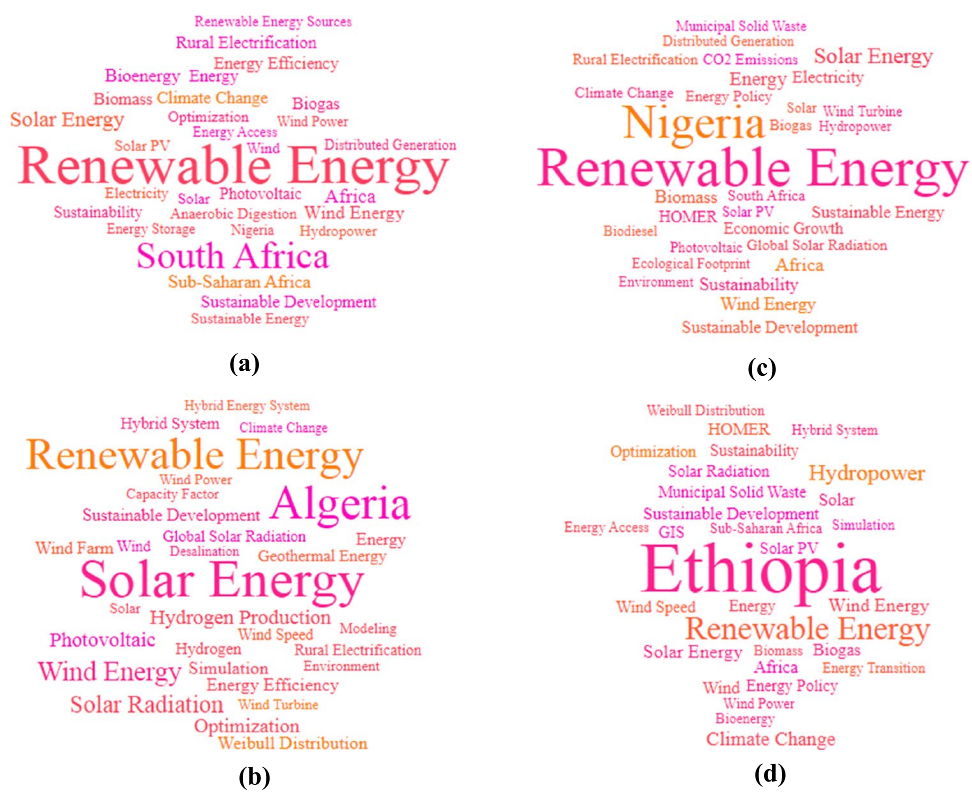


Fig. 14 a–d The frequency of keyword occurrence related to renewable energy research in four African countries energy research include rural electrification, sustainable development, climate change, and energy efficiency. As the largest contributor of greenhouse gas (GHG) emissions in Africa, improving energy-efficient technologies and renewable energy sources for reducing GHG emissions and promoting sustainable development has been the core focus in several renewable energy studies in South Africa. The National Energy Act 34 of 2008 and the Electricity Regulation Act 4 of 2006 both feature energy efficiency measures and strategies (du Plessis 2015). The keyword distribution also shows that literature on renewable energy from South Africa has not only been limited to South Africa but extends to cover sub-Saharan Africa, particularly Nigeria.

The word chart in Fig. 14b shows the distribution of keywords in research documents affiliated to Algeria in North Africa. Solar energy was ranked as the most frequently occurring keyword even above renewable energy. This shows how much attention has been given to the topic of solar energy as a renewable energy source in Algeria with more evidence from other frequently occurring solar-related keywords such as solar radiation and photovoltaic. Due to the abundance of sunlight throughout the year, especially in the Sahara zone, the climatic conditions in Algeria are deemed very suitable for the development of solar energy (Stambouli et al. 2012). Because of these conditions, the potential for energy production is immense in comparison to regional and global energy demands (Himri et al. 2009). The Algerian government has set up various renewable energy policies in hopes of achieving 40% renewable energy penetration in 2030 and amongst these policies is the introduction of the new feed-in tariff for solar PV and wind in 2014 (Bouznit et al. 2020). In 2020, the progress of solar PV was recorded as 13.3% of the target capacity, which exceeds the progress of all the other renewable sources in Algeria (Zahraoui et al. 2021). Algeria, as well as other North African nations such as Egypt and Morocco, is a fast-gaining ground in the solar energy market, avidly competing with South Africa and other prominent non-African countries in the field (IRENA and AfDB 2022). Wind energy occurred as the second most frequently studied renewable energy source with other related keywords like Weibull distribution and wind farm while geothermal energy occurred as the third. The frequency of occurrence of hydrogen production in research documents from Algeria was also worth noticing. According to Boudries and Dizene (2008), Algeria is a country rich in natural resources, with a wide range of hydrogen production alternatives. Hydrogen is a major tipping point particularly in the solar future of Africa and because of its exceptional irradiation, Algeria is well positioned to play a key role in both Africa and the global solar-based green hydrogen industry. Therefore, several studies in this domain have begun to shift focus to this research topic in recent years.

From Fig. 14c, it can be seen that solar energy was ranked as the most frequently used keyword in terms of renewable energy sources, followed by wind energy, biomass, and hydropower. This observation is consistent with the results of Adedayo et al. (2021) in their analysis of the most studied energy sources in Nigeria. Nigeria aims to produce 30% of its electricity from renewable sources by 2030, and solar power is expected to generate 15.27% of the total electricity consumption by then Bamisile et al. (2017). This is because solar energy has the highest potential among the renewable energy sources in Nigeria (Shaaban and Petinrin 2014). Even though Nigeria's present solar energy deployment is very small in comparison to South Africa's, Nigeria is only beginning to improve its solar energy potential under its National Energy Policy. The situation is similar for wind energy; despite the abundance of this resource in Nigeria, it is mostly utilized for irrigation and residential water supply in rural regions (Idris et al. 2012; Shaaban and Petinrin 2014). Nigeria's 2011 Renewable Energy Master Plan seeks to install 40 MW for wind energy by 2025. Biomass is considered Nigeria's principal energy source, contributing over 78% of the country's total primary energy consumption with 32% and 40% from firewood and charcoal, respectively (Sokan-Adeaga and Ana 2015). Even though biomass is certainly a key renewable energy resource, the sustainability of its production and efficiency of its use has been questioned severally and over the years, research focus has shifted more towards the conversion of biomass into other cleaner forms, particularly biogas and biodiesel rather than the use of fuelwood. A critical observation of the keyword frequency also shows that renewable energy research in Nigeria has mostly centered around sustainable development, economic growth, rural electrification, and climate change mitigation. This could be attributed to the formulation of the Renewable Energy Master plan (REMP) for Nigeria in 2006 which sought to provide a comprehensive framework for developing RE that will ensure (1) the national agenda on emission reduction, (2) stimulating economic growth, and (3) expanding the scope and quality of services available in rural areas.

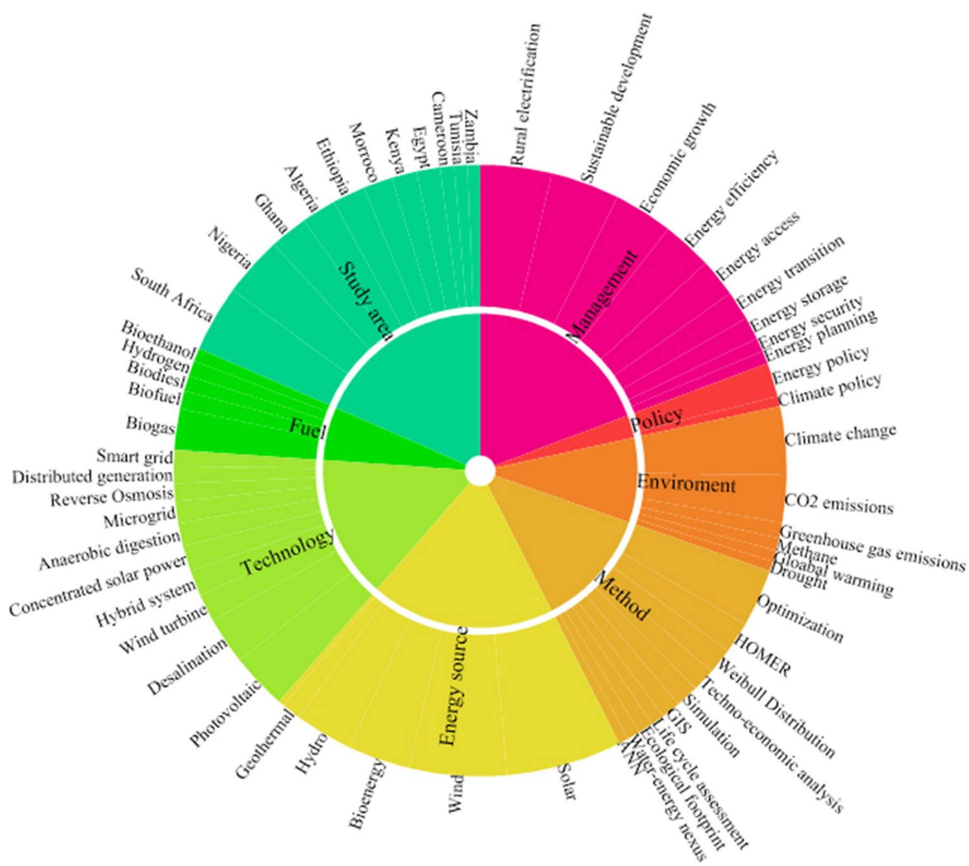
Figure 14d shows the frequency of keyword occurrence in research documents affiliated with Ethiopia. Unlike the previous three countries, hydropower was found to be the most frequently used keyword in terms of renewable energy resources, followed by solar energy and wind energy. This is not surprising as Ethiopia ranks first in total installed hydropower capacity in Africa with about 90% of its electricity generation coming from hydroelectric sources (IRENA and AfDB 2022). Ethiopia is one of the countries in East Africa with numerous rivers, lakes, and abundant water resources, accounting for 20% of Africa's total technically possible potential (Hailu and Kumsa 2021). According to Tucho et al.

(2014), hydropower has been largely favored in its contribution to the overall energy system of Ethiopia due to its technical efficiency of up to 90% and relatively advanced technology compared to solar photovoltaic and wind turbines. Ethiopia has a huge potential for solar and wind energy and is also among the few countries in Africa with substantial potential of geothermal energy resources to be effectively exploited for production of electricity. However, only an insignificant percentage of the potential of these resources have been utilized so far. The present installed capacity of wind energy stands at 324 MW, geothermal at 7.3 MW and just around 14 MW of solar photovoltaic has been used for telecommunications, lighting, and powering water pumps in rural regions, as well as for water heating in urban areas (Hailu and Kumsa 2021). The Ethiopian government has established a comprehensive national strategy known as the Growth and Transformation Plan (GTP-I and GTP-II) since 2010, which includes energy policy as a major component (Tiruye et al. 2021). As part of the plan, Ethiopia has invested over $100 million in renewable energy and has become the fifth-highest renewable energy investor in Africa (Hameer and Ejigu 2020). The government plans to shift away from inefficient biomass use and replace the major hydropower supply with geothermal and wind energy. The list of the top keywords also shows that major themes in Ethiopia's renewable research mostly center on climate change, energy transition, and energy access. This is because energy access has been a major issue in most East African countries and Ethiopia is no exception with just around 48% of its population having access to electricity and less than 10% with access to clean cooking fuels and technologies (IRENA and AfDB 2022). Therefore, energy access, along with climate change mitigation has been the greatest motivation for renewable energy transition and diversification in Ethiopia to improve efforts towards the utilization of available energy for significant socio-economic development.

Classifications and evolution of major themes

The author keywords that appeared more than ten times were collected and categorized under three broad topics namely; purpose, object, and assessment. Under the three major topics, the author keywords were further classified into management, policy, environment, energy source, technology, fuel, study area, and method-related keywords. The domain classification was done to reveal the dominant topics under each category and the relationship between various categories. Figure 15 presents the various classifications and their related keywords. In order to understand the dynamics of topics over time to be able to predict future hotspots in

Fig. 15 Classifications of author keywords



this area of study, we divided the years under review, i.e., 1999–2021, into four different timelines. The evolution of keywords in the various stages was analyzed and depicted in Fig. 16. The thematic classifications are elaborated in the subsequent sub-sections.

Renewable energy sources In terms of energy sources, solar energy was the most studied topic, followed by wind energy, bioenergy, and hydropower. Geothermal and nuclear energy were the least studied sources. Despite the fact that solar energy has been a major topic from the beginning of the

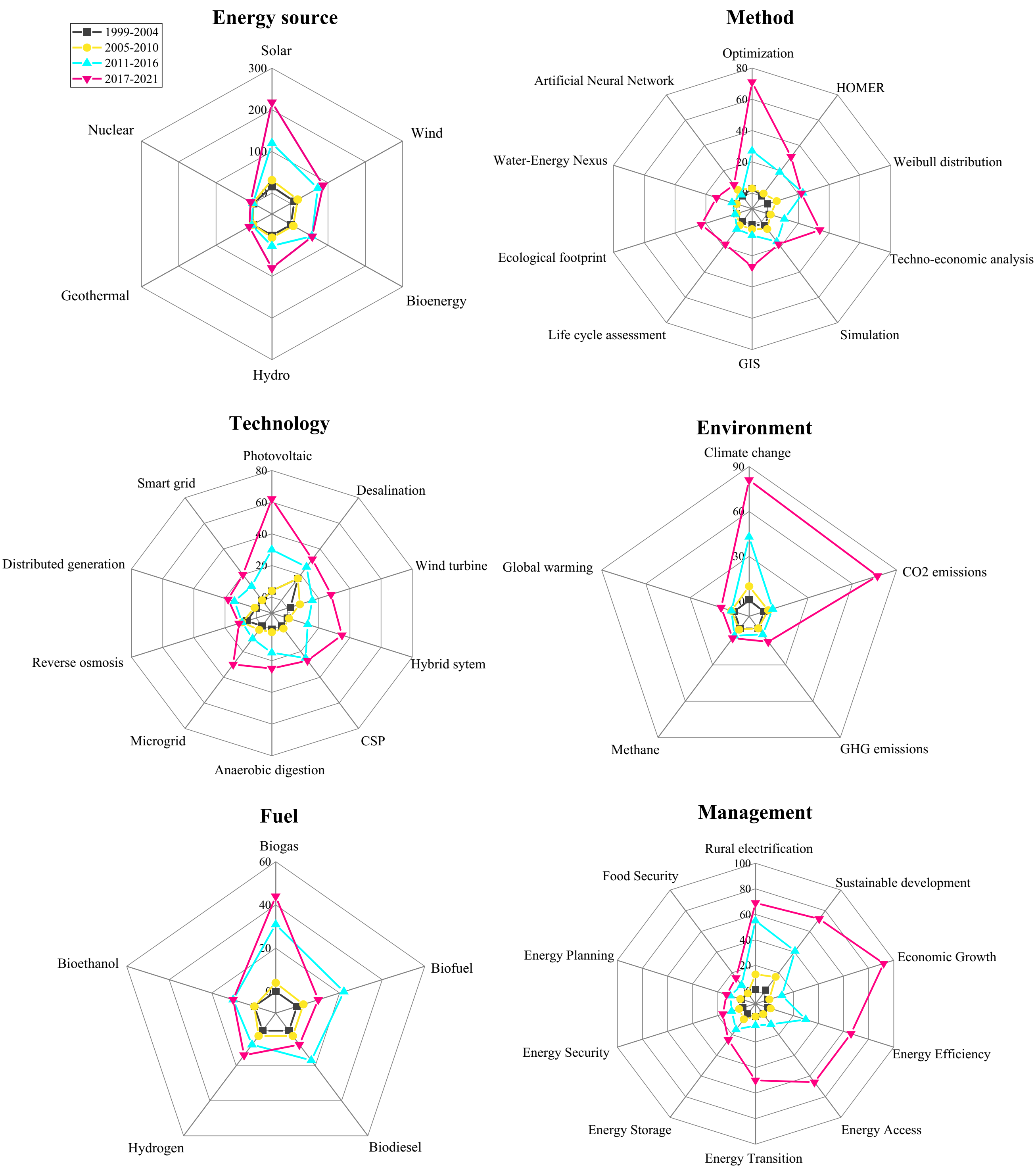


Fig. 16 Development of author keywords in four different stages

study period, interest in the field has been growing at a rapid pace in the last 10 years and, therefore, is expected to remain a hot topic in future studies. This trend may also be seen in wind energy and hydropower. The occurrence of bioenergy, on the other hand, has become less frequent in relation to the number of documents produced in the last 5 years. This is most likely due to the replacement of the term with more specific kinds of bioenergy, such as biogas and biofuels.

Africa has vast renewable energy resources, with the potential to reach 310 GW by 2030, putting the continent at the forefront of renewable energy production globally, given the nearly limitless potential of solar (10 TW), hydro (350 GW), wind (110 GW), and geothermal energy sources (15 GW) (Hafner et al. 2018). Hydropower has been Africa's most extensively used renewable energy source for power generation. Hydropower output has, however, become more unreliable as a result of climate change. Moreover, the sustainability of large hydro (which constitutes the largest share of hydropower capacity in Africa) has been questioned severally over the years. Based on the current statistical review of BP (2021), the development of solar and wind energy in Africa has been on the rapid rise since 2014 compared to other renewable energy sources. Wind and solar power have just lately become commercially feasible, and while they are both weather-dependent, Africa's solar energy potential, in particular, remains high owing to the continent's geographical position. This realization has motivated more recent studies in this research field towards the direction of solar and wind energy. Furthermore, solar energy has the highest level of development among the renewable energy sources in South Africa and most parts of North Africa and since both regions dominate the research field, this could be another reason for the proliferation of literature on solar energy. Studies on geothermal energy on the other hand were only limited to a few countries from East and North Africa, particularly Algeria, Tunisia, and Kenya. The East Africa Rift System holds the region's geothermal resources, with an untapped potential estimated at 15 GW (BGR 2016). Kenya is by far the country with the highest installed capacity of electrical energy from geothermal sources in Africa (IEA 2019).

Renewable energy technologies Not surprisingly, the most frequently used keyword under the 'technology' category is photovoltaic which is directly related to solar energy. Photovoltaic (PV) and concentrated solar power (CSP), often known as solar thermal energy, are two well-known methods for generating electrical energy from solar radiation. In terms of total installed capacity in Africa, solar PV is way ahead of CSP due to a number of reasons which include reduced solar PV prices (BP 2021). Over the last 5 years, the cost of solar PV has decreased significantly, mostly due to considerable price reductions in modules, owing to enhanced research and development, and more market participants, and this has made the technology more attractive to the African energy market. South Africa is home to the majority of the largest solar PV plants in Africa. Desalination occurred as the second technology-related keyword. The integration of renewable energy sources like solar, wind, and geothermal energy with desalination systems offer excellent potential for addressing water shortages and might be a feasible solution to climate change and water scarcity concerns (Eltawil et al. 2009). Solar energy has been found as a feasible energy source for generating fresh water from salty water, particularly in several African countries, which are located in semi-arid and sunny climates (Al-Kharabsheh 2003). Therefore, several studies in this field have been directed towards solar desalination as compared to other renewable energy sources. In the first two stages (1999–2010), desalination and reverse osmosis were the most popular technology-related keywords. This demonstrates the urgency of this topic in the first decade; however, during the last decade, the use of these two terms has gradually decreased especially, reverse osmosis.

The third most researched keyword in terms of technology was wind turbine, which is also the sole technology for generating wind energy in Africa. Anaerobic digestion occurred as the most researched bioenergy technology. Hybrid systems, microgrids, and smart grids play an important role in Africa's renewable energy research. This is because rural areas in most African countries lack access to electricity due to the high cost of grid extension for equal distribution to these low population density and dispersed houses (Motjoadi et al. 2020). Renewable energy-powered microgrids and hybrid systems are considered optimal alternatives for supplying electricity to a smaller rural population at a very cheap cost compared to the needed cost for a conventional generator (Come Zebra et al. 2021). One of the ten most-cited documents focused on assessing the feasibility of a small Hydro/PV/Wind hybrid system for off-grid rural electrification in Ethiopia (Bekele and Tadesse 2012).

Fuels The majority of the keywords classified as "fuel" were biomass-based fuels. Biogas ranked first followed by biofuel, biodiesel, hydrogen, and bioethanol. The African continent, especially sub-Saharan Africa is endowed with a wide range of bioenergy feedstocks with tremendous potential to address the continent's growing need for modern energy services. As a result, throughout the last two decades, there has been a regional drive for the development and long-term distribution of biofuels such as biogas, biodiesel, bioethanol (Dahunsi et al. 2020). Biogas has received the highest level of attention in this field due to the feasibility of its application in various sectors such as household, industrial, and agriculture as well as its numerous environmental and health benefits especially in reducing GHG emissions (Shaaban and Petinrin 2014). The commonly identified feedstock used in the production of biogas includes livestock and agro-processing residue, municipal solid waste, and energy crops. Technologies for biogas production in Africa are limited to household biogas digesters while commercial medium to large-scale biodigesters are still in their early stages in only a few countries like South Africa, Kenya, and Ghana (Kemausuor et al. 2018).

Since 2011, there has been a considerable growth in research interest in biogas, which is projected to continue in the near future. Hydrogen has also seen a positive development in recent years and has the potential to become a major topic in Africa's renewable energy research. The German Federal Ministry of Education and Research (BMBF) has partnered with the Southern African Development Community and the Economic Community of West African States to launch H2 Power-Africa, a green hydrogen effort. The initiative's goal is to investigate the possibilities for renewable energy in Southern and West Africa (IRENA and AfDB 2022). North African countries such as Algeria, Egypt, Morocco, and Tunisia are also considering using their proximity to Europe to supply green hydrogen to a bigger market. The term "biofuel" has been less popular in recent years, with "biodiesel" and "bioethanol" taking its place. During the last 5 years, bioethanol has surpassed biodiesel as the most popularly studied biofuel in Africa.

Methods "Optimization" appeared to be the most commonly used keyword in terms of research methods in this field, followed by "HOMER," a software application for designing and evaluating options for off-grid and on-grid power systems for remote, stand-alone, and distributed generation applications. Other popular keywords related to evaluation methods and models used in this field include techno-economic analysis, GIS, simulation, Weibull distribution, and life cycle assessment (LCA). LCA has been introduced in Africa's renewable energy research to analyze the environmental effect of energy generation from various sources, allowing producers to make more informed decisions about environmental protection (Góralczyk 2003). Research models such as ecological footprint analysis, water-energy nexus, GIS, and artificial neural network (ANN)–based models are becoming increasingly popular in the last few years. ANN is a modeling and prediction tool that is generally recognized as a strategy for tackling complicated and ill-defined problems (Fadare and Irimisose 2010). ANN has been used in a number of studies in this research field mainly for modeling and forecasting energy resources and their indicators such as consumption, demand, and potential (Bamisile et al. 2021, Fadare and Irimisose 2010, Mensour et al. 2017). The use of Weibull distribution and simulation, on the other hand, has slowly reduced in recent years.

Management With respect to the "management" category, research themes were focused mainly on rural electrification, sustainable development, economic growth, energy efficiency, and energy access. Since a large percentage (about 14%) of Africa's population still live in rural regions, the necessity of supplying stable and clean energy to rural areas cannot be overstated (World Bank 2015). In recent years, governments and policymakers have been paying much attention to renewable energy alternatives like solar energy (both photovoltaic and thermal), wind turbines, and micro-hydro power for generating electricity as viable options for improving the lives of the rural population. Rural electrification is a critical initiative for improving the socio-economic situation of rural areas in African countries as studies have emphasized its role in fostering economic growth and livelihood security by supplying electricity as a productive input in agriculture and rural industries, as well as assisting in the improvement of overall quality of life (Nouni et al. 2008). The achievement of sustainable development in all facets of life is a key barrier for human civilization. In 2012, the United Nations created the Sustainable Development Goals framework to reinforce existing goals and achieve long-term progress (Abbasi et al. 2021e). Some development has recently been made on providing a standardized set of energy indicators for sustainable development considering the economy, society, and environmental components. These quantitative indicators for comparing the sustainability of renewable energy technologies include the price of generated power, GHG emissions, renewable energy availability, energy conversion efficiency, land needs, and water usage (Varun et al. 2010). A comprehensive overview of renewable energy and sustainable development in West Africa by Gyamfi et al. (2018) indicated that renewables in West Africa have the prospect to help achieve the SDGs, as evidenced by the potential of renewable energy resources in the region.

The trend of keywords over time shows that economic growth has become a hot topic in Africa's renewable energy research in the last few years, overtaking all other keywords in this category. Several studies in this field are beginning to focus on the relationship between economic growth and renewable energy among other indicators in different parts of the continent due to its associated policy implications. The significance of energy in economic growth is critical (Abbasi et al. 2021f, 2021g). Some of these studies have revealed a positive impact of renewable energy development on economic growth in related countries (Gyimah et al. 2022, Qudrat-Ullah and Nevo 2021, Riti et al. 2022). Other studies, however, found no effect of renewable energy on economic growth (İnal et al. 2022), while some studies also found a negative impact of renewable energy consumption on economic growth (Maji et al. 2019). The results of these studies were attributed to the under-utilization of the renewable energy potential and the over-utilization of unclean and inefficient renewable energy sources such as burning of wood biomass by the countries under study. The keywords “energy efficiency,” “energy access,” and “energy transition” have also experienced significant growth in interest during the last stage.

Policy In terms of policy-related keywords, the majority of documents focused on energy policies while a few mentioned climate policies. A comprehensive and consistent energy policy is critical for a country’s optimal use of its energy resources. The majority of African countries have begun to implement policies aimed at incorporating renewable energy into the energy mix. For some countries, energy policy is sometimes a component of a wider plan aimed at minimizing poverty and stimulating economic growth (Aliyu et al. 2018). Renewable energy research in Africa mostly focuses on two major types of policies namely enabling policies and deployment policies. Enabling policies involve a set of policies that span across all sectors and provide favorable conditions for the rapid implementation of energy transition solutions. Examples of such policies include specific renewable energy targets, energy efficiency measures, and measures to raise awareness among consumers. About 40 countries in Africa have set renewable energy targets mostly geared towards the electricity sector (IRENA and AfDB 2022). Deployment policies, on the other hand, involve regulations that drive demand in the renewable energy market as well as economic and financial incentives that make renewable energy solutions more affordable. Such policies include tax incentives, customs, and import duty exemptions, feed-in tariffs, auctions, and net metering. These types of policies are common throughout Africa, although they are applied more frequently in East and West Africa (IRENA and AfDB 2022).

Environmental impacts The most frequently used keyword associated with environmental impacts was climate change, followed by CO_2 emissions, greenhouse gas emissions, methane, global warming, and drought. Even though Africa shares the least blame for the global climate crisis, the region has been identified as the most vulnerable to the consequences of climate change due to factors like population increase and its associated human activities, overreliance on subsistence farming, limited ability to adapt to change, and imminent water problems (IPCC 2007). South Africa is Africa’s leading GHG emitter, and its role in global warming has attracted global attention since 2005 when its per capita emissions of 9 tons CO_2e per person surpassed the global average of 5.8 tons and was also six times higher than the sub-Saharan African average of 1.4 tons (World Resources Institute 2009). In 2019, the South African government introduced the Carbon Tax Act, which imposes specific charges on GHGs emitted by fuel combustion and industrial operations with the potential to cut emissions by 33% by 2035 compared to the baseline (Ntombela et al. 2019). Furthermore, South Africa plans to shut down many coal-fired power stations by 2030 as it diversifies its energy mix to include solar and wind projects (Roelf 2021). Majority of other African countries have also developed targets to increase clean energy consumption and reduce GHG emissions, which has resulted in a slew of policy frameworks.

In recent years, more research is being directed towards finding the relationship between renewable energy consumption, CO_2 emissions, and economic growth in different parts of Africa. Several of these studies have highlighted the importance of increasing the usage of renewable energy in place of fossil fuels to combat the problem of CO_2 emissions from fossil-based sources (Adewuyi and Awodumi 2017, Menyah and Wolde-Rufael 2010, Zoundi 2017). Various studies have found ample evidence to support the fact that renewable energy sources, such as solar, wind, and small hydropower, do not contribute to CO_2 emissions during the production chain, and unlike fossil fuel energy, the amount of renewable energy sources on the earth’s surface is not limited (Akella et al. 2009; Demirbaş 2006; Sayigh 1999).

Study area Based on the frequency of author keywords from all the documents in the dataset, South Africa was found to be the most commonly studied area, followed by Nigeria, Ghana, Algeria Ethiopia, Morocco, Kenya, Egypt, Cameroon, and Tunisia. Nigeria and South Africa are Africa’s two largest economies, accounting for over 37% of the continent’s primary energy usage; hence, their progress in renewable energy transition has a significant impact on the region’s energy situation (IRENA 2012). This might explain why there are so many research documents from this field targeted at these two countries. Countries like Ghana, Ethiopia, Morocco, and Kenya have also been receiving a lot of attention in recent years due to their strong efforts towards renewable energy development. Even though Ghana’s renewable energy installed capacity is still quite low compared to leading countries like South Africa, Egypt, Kenya, and Ethiopia, the country is performing very well in terms of policies and frameworks for incentives and efforts for renewable energy development (Aboagye et al. 2021). Morocco has become one of the key countries in Africa currently leading the way in the development and generation of renewable resources, especially solar energy. Morocco has the world’s largest concentrated solar plant, the Ouarzazate Solar Power Plant with a capacity of 580 MW, which has made a significant contribution to the country’s renewable energy goal of 2020 (African Development Bank 2014). Ethiopia has made tremendous progress in the development of renewable resources by investing heavily in various solar, wind, and geothermal projects. Kenya has also made significant investments in geothermal energy production, which provides low-cost, low-emission electricity. By 2020, Kenya was the sole significant generator of energy from geothermal power in Africa with a generating capacity of 823.8 MW (IRENA and AfDB 2022).

The way forward for Africa's renewable energy research

Africa's renewable energy development is clearly still in its infancy. Besides hydropower, contemporary renewable energy (solar, wind, geothermal, and modern bioenergy) is almost negligible in Africa's energy mix (IRENA and AfDB 2022). Moreover, only a few countries have achieved substantial progress in renewable energy, whereas the bulk of African countries has made little to no progress at all. The majority of renewable energy projects are also small-scale or in the initial phases of development. Relevant authorities and policymakers, as well as other international entities, are working to accelerate the adoption and use of renewable energy technologies in order to enhance energy access while actively reducing global GHG emissions. It is impossible to overestimate the importance of capacity building and applied research in advancing this adoption. This comprises new technology development, optimization, and distribution; novel finance methods for renewable energy projects; and evidence for establishing an effective renewable energy policy.

Renewable energy research in Africa has undoubtedly seen significant progress, particularly in the previous decade and this has stirred the region's renewable energy development in the right direction. However, a wide gap still exists in the quantity and quality of research output between Africa and the rest of the world in this field of study. Furthermore, renewable energy research in Africa is mainly concentrated around a few countries with relatively high GDP across the region. The poor performance of research output in Africa is attributed to a number of reasons. First of all, the general inadequate policies and programs directly related to research and development of renewable energy. Even the few existing ones are also characterized by a lack of implementation. In advanced economies, more effort has been directed towards implementing effective policies that drive the region's research on renewable energy forward. For instance, the EU's Energy Union strategy has a key component referred to as the "Accelerating Clean Energy Innovation Communication" (European Commission and Directorate-General for Research and Innovation 2017). The communication includes new far-reaching policies to help Europe move to a competitive low-carbon economy faster by enhancing the regulatory and commercial climate and increasing investment in clean-energy R&D. China which is part of the leading countries in clean energy research has a number of national energy R&D policies which seek to raise the standards of energy R&D, provide energy solutions for national economic and social growth, and encourage technological commercialization (Gao et al. 2020). The African governments must step up by integrating relevant R&D programs and policies into national energy strategies to drive research and innovation in order to keep up the pace with the leading countries in this field.

Secondly, despite the availability of funds, sponsoring renewable energy research in Africa by governments of African countries remains a great challenge. Generally, in Africa, R&D investment as a proportion of GDP is very low. Majority of countries fail to invest at all and the few that do also invest less than 1% of their GDP (IRENA and AfDB 2022). Table 8 shows the top 20 funding agencies that are responsible for about 14% of documents related to renewable energy research in Africa within the last two decades. It is interesting to note that only three agencies were affiliated to African countries namely the National Research Foundation in South Africa (41), the Science and Technology Development Fund in Egypt (16), and the Ministry of Higher Education Scientific Research (14). The remaining 17 are from Europe, the USA, China, and India. This shows that the commitment of African governments to fund basic and strategic research in the clean energy field is very low. Africa's governments can no longer rely solely on outside investors to support fundamental and strategic research. It is necessary for governments and policymakers, as well as the private sector to form a solid plan to invest in renewable energy research and innovation, especially if the continent is to play a significant role in the global knowledge economy. This includes the establishment of energy research institutions, especially in less contributing countries to address issues related to renewable energy development.

Finally, a very low level of intra-regional collaborations was found among African countries in this field. Presently, Africa's scientific output in this field is heavily reliant on international collaborations and overseas scholars. While there is an immense need to support collaborations between developed and developing countries in order to encourage the transfer and dissemination of knowledge on this subject, there is also a great need to foster intra-regional collaborations due to similarities in demographics, natural resources, and purpose. High contributing African countries can help push the research output of less contributing countries through intra-regional collaborations. Although research papers play an important role in the growth of renewable energy markets and policies, most research efforts in Africa conclude with the publication of a scholarly article. In order to convert knowledge into practical and marketable solutions that help industries and communities while also boosting the economic sustainability of research institutions, academic

Table 8 Top 20 funding agencies

Funding agencies	Number of documents
European Commission	121
UK Research Innovation	111
National Natural Science Foundation of China	72
Engineering Physical Sciences Research Council	59
Federal Ministry of Education Research BMBF	41
National Research Foundation South Africa	41
Economic Social Research Council	35
European Commission Joint Research Centre	31
National Science Foundation	31
Portuguese Foundation for Science and Technology	28
Consortium of International Agricultural Research Centres CGIAR	26
Natural Environment Research Council	21
Swedish International Development Cooperation Agency	20
Department of Science Technology India	19
Council of Scientific Industrial Research India	17
United States Department of Energy	17
Science and Technology Development Fund	16
Ministry of Education China	15
Ministry of Higher Education Scientific Research	14
Spanish Government	14

institutions and authors must establish extensive collaborations with the private sector. The private sector participants must also be included at all phases of the study to guarantee that the study meets real market needs.

Conclusions, recommendations, and limitations

In this study, we analyzed data collected from the Web of Science Core Collection using quantitative and qualitative research tools to map characteristics of research output on renewable energy in Africa from 1999 to 2021. The results revealed that growth in the number of publications was very slow and unsteady in the first decade but started to rise sharply from 2011. The three core journals related to this field were *Renewable & Sustainable Energy Reviews*, *Renewable Energy*, and *Energy Policy*. Our analysis of the performance countries showed that South Africa has contributed the most in terms of research output, accounting for 14.4% of the total publications, followed by the USA and Algeria, even though the USA, Germany, and Algeria were the most academically influential countries in terms of total citations and h-index. CDER, a research institute in Algeria was the leading institution in Africa's renewable energy research in terms of quantity and quality of documents. The three most prolific authors in this field in terms of the number of documents were Chowdhury S.P., Brent A.C., and Kusakana K, while Sarkodie S.A. emerged as the most influential author in terms of total citations. Co-authorship network analysis of authors, institutions, and countries indicated that most collaborative links exist between the most contributing countries and institutions, and the strongest links were found between authors of the same institution and institutions in the same country. We also observed that African countries have rather less intra-regional collaborations and tend to collaborate more with countries outside the continent.

It is interesting to note that the most cited document in this field was related to geothermal energy, despite the limited number of documents on this topic. Two dominant themes were found in the ten most cited documents: (1) bioenergy potential and production (2) establishing the relationship among economic growth, CO_2 emissions, and renewable energy. The co-citation analysis of cited references revealed four main clusters of co-citing networks, two of which focused on the panel unit root test in the power parity hypothesis. Our author keyword analysis identified solar energy as the most studied renewable energy resource in Africa along with related technologies, solar photovoltaic, and solar desalination. Other hot topics in this field include wind energy, rural electrification, and the role of renewable energy in climate change. Based on the keyword evolution analysis, we found that more research is being directed towards the relationship between renewable energy, economic growth, and CO_2 emissions in recent years due to their associated policy implications. Also, in terms of biofuels, bioethanol has started to receive more attention than biodiesel in the past 5 years perhaps due to its relative affordability. Finally, we see opportunities for more research focused on exploring green hydrogen production alternatives, especially in studies from some countries in North Africa. North African countries such as Algeria, Egypt, Morocco, and Tunisia are considering using their proximity to Europe to supply green hydrogen to a bigger market.

It is recommended that most renewable energy research initiatives in Africa have a people-centered perspective. This is because clean energy access does not only entail the physical availability of energy sources but also the capacity of individuals and industries to pay for them. Several rural communities in African countries reside within feet of national grid networks yet do not have access to the power that passes so near to their houses. Therefore, more studies are needed to focus on low-cost, off-grid alternatives for households, as well as recognition of the importance of women in energy usage, business, policymaking, and research. Methods for assessing sustainability, such as LCA and cost–benefit analysis should be used early on in the design process of renewable energy research projects. LCA is quickly becoming one of the most essential tools for determining the relationship and impact of energy use on the environment and this tool is much needed in Africa's renewable energy research, especially in biomass energy utilization. In biomass energy technology, for instance, the reuse of by-products not only has an impact on the ongoing operation of the said project but also creates substantial secondary pollution. There is also an issue with the massive cost of recycling and transportation. Therefore, these sustainability assessment tools are very crucial in analyzing and tackling these challenges in a more complete and detailed manner.

There is an intrinsic drawback of bibliometric techniques like these, which focus primarily on research outputs rather than content and this study is not without such limitations. The strength of the bibliometric method which is its ability to explore a wide scope of a research domain also happens to be its shortcoming in terms of evaluating research content in depth. So even though we were able to identify publication patterns and major topics related to Africa's renewable energy research over the last two decades, it was quite difficult to critically explore particular techniques and frameworks in order to conduct a more detailed analytical study of the research material. Furthermore, because the research documents were primarily based on the Web of Science Core Collection, there is a risk of selection bias. Even though the Web of Science is extensive and credible, incorporating more sources like Scopus and Google Scholar could present a more comprehensive picture. Nonetheless, if these constraints are resolved, we do not expect a considerable variation from the results of the current review.

Acknowledgements The authors would like to thank Prof. Mao Guozhu and Prof. Haifeng Liu from Tianjin University for their enormous supervision and guidance towards successfully completing the current study.

Author contribution Sandylove Afrane: investigation, writing original draft preparation, formal analysis, software; Jeffrey Dankwa Ampah: writing—original draft, formal analysis, methodology; Emmanuel Aboagye Mensah: writing—reviewing and editing.

Availability of data and materials The datasets generated and analyzed throughout the current study are available in the Web of Science Core Collection.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Abbasi K, Jiao Z, Shahbaz M, Khan A (2020) Asymmetric impact of renewable and non-renewable energy on economic growth in Pakistan: new evidence from a nonlinear analysis. Energy Explor Exploit 38:1946–1967

Abbasi K, Hussain K, Abbas J, Adedoyin F, Shaikh P, Yousaf H, Muhammad F (2021a) Analyzing the role of industrial sector's electricity consumption, prices, and GDP: a modified empirical evidence from Pakistan. AIMS Energy 9:29–49

Abbasi KR, Abbas J, Tufail M (2021b) Revisiting electricity consumption, price, and real GDP: a modified sectoral level analysis from Pakistan. Energy Policy 149:112087

Abbasi KR, Adedoyin FF (2021) Do energy use and economic policy uncertainty affect CO2 emissions in China? Empirical evidence from the dynamic ARDL simulation approach. Environ Sci Pollut Res 28:23323–23335

Abbasi KR, Adedoyin FF, Abbas J, Hussain K (2021c) The impact of energy depletion and renewable energy on CO2 emissions in Thailand: fresh evidence from the novel dynamic ARDL simulation. Renewable Energy 180:1439–1450

Abbasi KR, Adedoyin FF, Radulescu M, Hussain K, Salem S (2021d) The role of forest and agriculture towards environmental fortification: designing a sustainable policy framework for top forested countries. Environment, Development and Sustainability

Abbasi KR, Hussain K, Redulescu M, Ozturk I (2021e) Does natural resources depletion and economic growth achieve the carbon neutrality target of the UK? A way forward towards sustainable development. Resources Policy 74:102341

Abbasi KR, Lv K, Radulescu M, Shaikh PA (2021f) Economic complexity, tourism, energy prices, and environmental degradation in the top economic complexity countries: fresh panel evidence. Environ Sci Pollut Res 28:68717–68731

Abbasi KR, Shahbaz M, Jiao Z, Tufail M (2021g) How energy consumption, industrial growth, urbanization, and CO2 emissions affect economic growth in Pakistan? A novel dynamic ARDL simulations approach. Energy 221:119793

Abbasi KR, Hussain K, Haddad AM, Salman A, Ozturk I (2022) The role of Financial Development and Technological Innovation towards Sustainable Development in Pakistan: fresh insights

from consumption and territory-based emissions. Technological Forecasting and Social Change 176:121444
Aboagye B, Gyamfi S, Ofosu EA, Djordjevic S (2021) Status of renewable energy resources for electricity supply in Ghana. Scientific African 11:e00660
Adams S, Klobodu EKM, Opoku EEO (2016) Energy consumption, political regime and economic growth in sub-Saharan Africa. Energy Policy 96:36–44
Adedayo HB, Adio SA, Oboirien BO (2021) Energy research in Nigeria: a bibliometric analysis. Energy Strategy Reviews 34:100629
Adewuyi AO, Awodumi OB (2017) Biomass energy consumption, economic growth and carbon emissions: fresh evidence from West Africa using a simultaneous equation model. Energy 119:453–471
Afrane S, Ampah JD, Mensah EA (2021) Visualization and analysis of mapping knowledge domains for the global transition towards clean cooking: a bibliometric review of research output from 1990 to 2020. Environmental Science and Pollution Research
AFREPREN (2001) African Energy Data Reference Handbook: AFREPREN Trimestrial Report, Nairobi, Kenya
African Development Bank (2014): Ouarzazate Solar Complex Project – Phase II (NOORo II and NOORo III Power Plants). Abidjan: African Development Bank
African Development Bank (2018) The new deal on energy for Africa. A transformative partnership to light up and power Africa by 2025. Update of implementation.
Akella AK, Saini RP, Sharma MP (2009) Social, economical and environmental impacts of renewable energy systems. Renewable Energy 34:390–396
Akinbami OM, Oke SR, Bodunrin MO (2021) The state of renewable energy development in South Africa: an overview. Alex Eng J 60:5077–5093
Al-Kharabsheh S (2003) Theoretical and experimental analysis of water desalination system using low grade solar heat, University of Florida, ProQuest Dissertations Publishing
Aliyu AK, Modu B, Tan CW (2018) A review of renewable energy development in Africa: a focus in South Africa, Egypt and Nigeria. Renew Sustain Energy Rev 81:2502–2518
Amin M, Mabe M (2004) Impact Factors Use and Abuse. International Journal of Environmental Science and Technology (IJEST) 1:1–6
Ampah JD, Yusuf AA, Afrane S, Jin C, Liu H (2021) Reviewing two decades of cleaner alternative marine fuels: towards IMO's decarbonization of the maritime transport sector. J Clean Prod 320:128871
Amuzu-Sefordzi B, Martinus K, Tschakert P, Wills R (2018) Disruptive innovations and decentralized renewable energy systems in Africa: a socio-technical review. Energy Res Soc Sci 46:140–154
Baker HK, Kumar S, Pandey N (2021) Forty years of the Journal of Futures Markets: A bibliometric overview. J Futur Mark 41:1027–1054
Bamisile O, Dagbasi M, Babatunde A, Ayodele O (2017) A review of renewable energy potential in Nigeria; solar power development over the years. Eng Appl Sci Res 44:242–248
Bamisile O, Obiora S, Huang Q, Yimen N, Abdelkhalikh Idriss I, Cai D, Dagbasi M (2021) Impact of economic development on CO2 emission in Africa; the role of BEVs and hydrogen production in renewable energy integration. Int J Hydrogen Energy 46:2755–2773
Barbier E (2002) Geothermal energy technology and current status: an overview. Renew Sustain Energy Rev 6:3–65
Bekele G, Tadesse G (2012) Feasibility study of small Hydro/PV/Wind hybrid system for off-grid rural electrification in Ethiopia. Appl Energy 97:5–15
Bellini E (2021) South Africa installed 1.3 GW of PV last year, pv magazine - Photovoltaics Markets and Technology
BGR (2016) Regional Project: Geothermal Energy – East Africa. Bundesanstalt fur Geowissenschaften und Rohstoffe (BGR)
Boudries R, Dizene R (2008) Potentialities of hydrogen production in Algeria. Int J Hydrogen Energy 33:4476–4487
Bouznit M, Pablo-Romero MdP, Sánchez-Braza A (2020) Measures to promote renewable energy for electricity generation in Algeria. Sustainability 12
BP (2021) Statistical Review of World Energy – all data 1965–2019
Braun T, Glänzel W, Schubert A (2006) A Hirsch-Type Index for Journals Scientometrics 69:169–173
Bugaje IM (2006) Renewable energy for sustainable development in Africa: a review. Renew Sustain Energy Rev 10:603–612
Cai X, Zhang X, Wang D (2011) Land Availability for Biofuel Production. Environ Sci Technol 45:334–339
Campbell JE, Lobell DB, Genova RC, Field CB (2008) The global potential of bioenergy on abandoned agriculture lands. Environ Sci Technol 42:5791–5794
Chen D, Liu Z, Luo Z, Webber M, Chen J (2016) Bibliometric and visualized analysis of emergy research. Ecol Eng 90:285–293
Cobo MJ, López-Herrera AG, Herrera-Viedma E, Herrera F (2011) An approach for detecting, quantifying, and visualizing the evolution of a research field: a practical application to the Fuzzy Sets Theory field. J Informet 5:146–166
Come Zebra EI, van der Windt HJ, Nhumaio G, Faaij APC (2021): A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. Renewable and Sustainable Energy Reviews 144, 111036
Dahunsi SO, Fagbiele OO, Yusuf EO (2020): Bioenergy technologies adoption in Africa: a review of past and current status. Journal of Cleaner Production 264, 121683
De Angelis P, Tuninetti M, Bergamasco L, Calianno L, Asinari P, Laio F, Fasano M (2021): Data-driven appraisal of renewable energy potentials for sustainable freshwater production in Africa. Renewable and Sustainable Energy Reviews 149, 111414
de Vries BJM, van Vuuren DP, Hoogwijk MM (2007) Renewable energy sources: their global potential for the first-half of the 21st century at a global level: an integrated approach. Energy Policy 35:2590–2610
Demirbas A (2009) Global Renewable Energy Projections. Energy Sources Part B 4:212–224
Demirbaş A (2006) Global Renewable Energy Resources. Energy Sources, Part a: Recovery, Utilization, and Environmental Effects 28:779–792
Department of Energy (2019) The South African Energy Sector Report 2019, Department of Energy, Pretoria, South Africa
Donthu N, Kumar S, Mukherjee D, Pandey N, Lim WM (2021) How to conduct a bibliometric analysis: an overview and guidelines. J Bus Res 133:285–296
Du H, Li N, Brown MA, Peng Y, Shuai Y (2014) A bibliographic analysis of recent solar energy literatures: the expansion and evolution of a research field. Renewable Energy 66:696–706
du Plessis W (2015) Energy efficiency and the law: a multidisciplinary approach. S Afr J Sci 111:01–08
Eltawil MA, Zhengming Z, Yuan L (2009) A review of renewable energy technologies integrated with desalination systems. Renew Sustain Energy Rev 13:2245–2262
Esso LJ, Keho Y (2016) Energy consumption, economic growth and carbon emissions: cointegration and causality evidence from selected African countries. Energy 114:492–497
European Commission, Directorate-General for Research and Innovation (2017): Accelerating clean energy innovation : clean energy for all Europeans. Publications Office
Fadare D, Irimisose I (2010) Modeling of solar energy potential in Africa using an artificial neural network. American Journal of Scientific and Industrial Research 1:144–157

Federal Republic of Nigeria (2015) National Renewable Energy and Energy Efficiency Policy (NREEEP). Federal Republic of Nigeria, Abuja, Nigeria

Gao C, Lu Y, Shi H, Yang Y, Han X, Ma S, Xiao Y, Ma C (2020) China National Energy Strategy and Policy 2020 Subtitle 10: Policy Research on Energy Research & Development, National Research Center for Science and Technology for Development

Garfield E (1955) Citation indexes for science: a new dimension in documentation through association of ideas. Science 122:108–111

Garfield E (2006) The History and Meaning of the Journal Impact Factor. JAMA 295:90–93

Gerbens-Leenes PW, Hoekstra AY, van der Meer T (2009) The water footprint of energy from biomass: a quantitative assessment and consequences of an increasing share of bio-energy in energy supply. Ecol Econ 68:1052–1060

Gope G, Aghdasi F, Dlamini MD (1997) A review of the photovoltaic industry and its development in Africa. Sol Energy 59:217–225

Góralczyk M (2003) Life-cycle assessment in the renewable energy sector. Appl Energy 75:205–211

Goyal S, Chauhan S, Mishra P (2021) Circular economy research: a bibliometric analysis (2000–2019) and future research insights. Journal of Cleaner Production 287:125011

Gyamfi S, Derkyi NSA, Asuamah EY, Aduako IJA (2018) Chapter 6 - Renewable energy and sustainable development. In: Kabo-Bah A, Diji CJ (eds) Sustainable Hydropower in West Africa. Academic Press, pp 75–94

Gyimah J, Yao X, Tachega MA, Sam Hayford I, Opoku-Mensah E (2022) Renewable energy consumption and economic growth: new evidence from Ghana. Energy 248:123559

Hafner M, Tagliapietra S, de Strasser L (2018) Prospects for renewable energy in Africa. In: Hafner M, Tagliapietra S, de Strasser L (eds) Energy in Africa: challenges and opportunities. Springer International Publishing, Cham, pp 47–75

Hailu AD, Kumsa DK (2021) Ethiopia renewable energy potentials and current state. AIMS Energy 9:1–14

Hameer S, Ejigu N (2020) A prospective review of renewable energy developments in Ethiopia. AAS Open Research 3

Hayek N, Ferrini L (2016) Editorial to the Proceedings of RERIS 2016: Africa-EU Renewable Energy and Innovation Symposium. Energy Procedia 93:1–2

He Z-X, Xu S-C, Li Q-B, Zhao B (2018) Factors that influence renewable energy technological innovation in China: A Dynamic Panel Approach. Sustainability 10

Himri Y, Malik AS, Boudghene Stambouli A, Himri S, Draoui B (2009) Review and use of the Algerian renewable energy for sustainable development. Renew Sustain Energy Rev 13:1584–1591

Hirsch JE (2005) An index to quantify an individual's scientific research output. Proc Natl Acad Sci 102:16569–16572

Hjørland B (2013) Facet analysis: the logical approach to knowledge organization. Inf Process Manage 49:545–557

Ibrahim ID, Hamam Y, Alayli Y, Jamiru T, Sadiku ER, Kupolati WK, Ndambuki JM, Eze AA (2021) A review on Africa energy supply through renewable energy production: Nigeria, Cameroon, Ghana and South Africa as a case study. Energy Strategy Rev 38:100740

Idris N, Lamin H, Ladan M, Yusuf B (2012) Nigeria's wind energy potentials: the path to a diversified electricity generation-mix. International Journal of Modern Engineering Research 2:2434–2437

IEA (2018) 2018 Global Status Report. IEA, Paris

IEA (2019) Africa Energy Outlook 2019. IEA, Paris

IEA (2020) SDG7: Data and Projections IEA, Paris

Im KS, Pesaran MH (2003) On the panel unit root tests using nonlinear instrumental variables. Available at SSRN: https://ssrn.com/abstract=482463

IMF (2019) Regional economic outlook. Sub-Saharan Africa : recovery amid elevated uncertainty, International Monetary Fund Washington, DC

İnal V, Addi HM, Çakmak EE, Torusdağ M, Çalışkan M (2022) The nexus between renewable energy, CO2 emissions, and economic growth: empirical evidence from African oil-producing countries. Energy Rep 8:1634–1643

IPCC (2007) The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Iqbal N, Abbasi KR, Shinwari R, Guangcai W, Ahmad M, Tang K (2021) Does exports diversification and environmental innovation achieve carbon neutrality target of OECD economies? J Environ Manag 291:112648

IRENA (2011) Abu Dhabi Communiqué on Renewable Energy for Accelerating Africa's Development, IRENA Secretariat Abu Dhabi, United Arab Emirates

IRENA (2012) Prospects for the African Power Sector–Scenarios and Strategies for Africa Project. IRENA Abu Dhabi, pp. 1–60

IRENA (2015) Africa 2030: Roadmap for a Renewable Energy Future, IRENA, Abu Dhabi

IRENA (2021) The Renewable Energy Transition in Africa, IRENA, Abu Dhabi

IRENA, AfDB (2022) Renewable Energy market analysis: Africa and its regions, International Renewable Energy Agency and African Development Bank, Abu Dhabi and Abidjan

Jeenah M, Pouris A (2008) South African research in the context of Africa and globally. S Afr J Sci 104:351–354

Jin C, Ampah JD, Afrane S, Yin Z, Liu X, Sun T, Geng Z, Ikram M, Liu H (2021) Low-carbon alcohol fuels for decarbonizing the road transportation industry: a bibliometric analysis 2000–2021. Environ Sci Pollut Res 29:5577–5604

Justus CG, Hargraves WR, Mikhail A, Graber D (1978) Methods for estimating wind speed frequency distributions. J Appl Meteorol 1962–1982(17):350–353

Karekezi S (2002) Renewables in Africa—meeting the energy needs of the poor. Energy Policy 30:1059–1069

Karekezi S, Kithyoma W (2003): Renewable energy in Africa: prospects and limits, The workshop for African energy experts on operationalizing the NEPAD energy initiative, pp. 2–3

Kaygusuz K (2012) Energy for sustainable development: a case of developing countries. Renew Sustain Energy Rev 16:1116–1126

Kemausuor F, Adaramola MS, Morken J (2018): A review of commercial biogas systems and lessons for Africa. Energies 11

KenGen (2021): KenGen launches state-of-the-art research and development centre. In: Ochieng FD (Hrsg.). KenGen, KenGen Pension Plaza II, Nairobi

Levin A, Lin C-F, James Chu C-S (2002) Unit root tests in panel data: asymptotic and finite-sample properties. Journal of Econometrics 108:1–24

Lewis NS, Nocera DG (2006) Powering the planet: chemical challenges in solar energy utilization. Proc Natl Acad Sci 103:15729–15735

Linklaters (2021): African renewables in flurry of investments, African Law & Business. Sandy Bhadare, Global Legal Group London, UK

MacCoun RJ (1998) Biases in the interpretation and use of research results. Annu Rev Psychol 49:259–287

Maji IK, Sulaiman C, Abdul-Rahim AS (2019) Renewable energy consumption and economic growth nexus: a fresh evidence from West Africa. Energy Rep 5:384–392

Mao G, Liu X, Du H, Zuo J, Wang L (2015a) Way forward for alternative energy research: a bibliometric analysis during 1994–2013. Renew Sustain Energy Rev 48:276–286

Mao G, Zou H, Chen G, Du H, Zuo J (2015b) Past, current and future of biomass energy research: a bibliometric analysis. Renew Sustain Energy Rev 52:1823–1833

Mao G, Huang N, Chen L, Wang H (2018) Research on biomass energy and environment from the past to the future: a bibliometric analysis. Sci Total Environ 635:1081–1090

Mensour ON, El Ghazzani B, Hlimi B, Ihlal A (2017) Modeling of solar energy potential in Souss-Massa area-Morocco, using intelligence Artificial Neural Networks (ANNs). Energy Procedia 139:778–784

Menyah K, Wolde-Rufael Y (2010) Energy consumption, pollutant emissions and economic growth in South Africa. Energy Economics 32:1374–1382

Meo SA, Al Masri AA, Usmani AM, Memon AN, Zaidi SZ (2013) Impact of GDP, Spending on R&D, Number of Universities and Scientific Journals on Research Publications among Asian Countries. PLOS ONE 8:e66449

Meyer T (2020): Decarbonizing road freight transportation – a bibliometric and network analysis. Transportation Research Part D: Transport and Environment 89, 102619

Mission Innovation (2021) Morocco; Plans and Priorities

Mohammed YS, Mustafa MW, Bashir N (2013) Status of renewable energy consumption and developmental challenges in Sub-Sahara Africa. Renew Sustain Energy Rev 27:453–463

Motjoadi V, Bokoro PN, Onibonoje MO (2020) A review of microgrid-based approach to rural electrification in South Africa: architecture and policy framework. Energies 13

Niang I, Osman-Elasha B, Githeko A, Yanda PZ, Medany M, Vogel A, Boko M, Tabo R, Nyong A (2008) Africa climate change 2007: Impacts, adaptation and vulnerability: contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge UK, pp 433–467

Nouni MR, Mullick SC, Kandpal TC (2008) Providing electricity access to remote areas in India: An approach towards identifying potential areas for decentralized electricity supply. Renew Sustain Energy Rev 12:1187–1220

Ntombela SM, Bohlmann HR, Kalaba MW (2019) Greening the South Africa's economy could benefit the food sector: evidence from a Carbon Tax Policy Assessment. Environ Resource Econ 74:891–910

Oluoch S, Lal P, Susaeta A (2021) Investigating factors affecting renewable energy consumption: a panel data analysis in Sub Saharan Africa. Environmental Challenges 4, 100092

Ouedraogo NS (2019) Opportunities, barriers and issues with renewable energy development in Africa: a comprehensible review. Current Sustainable/renewable Energy Reports 6:52–60

Pegels A (2010) Renewable energy in South Africa: potentials, barriers and options for support. Energy Policy 38:4945–4954

Pesaran MH, Shin Y, Smith RJ (2001) Bounds testing approaches to the analysis of level relationships. J Appl Economet 16:289–326

Pouris A (2016) A bibliometric assessment of energy research in South Africa. S Afr J Sci 112:8

Qudrat-Ullah H, Nevo CM (2021) The impact of renewable energy consumption and environmental sustainability on economic growth in Africa. Energy Rep 7:3877–3886

Ramos-Rodríguez A-R, Ruíz-Navarro J (2004) Changes in the intellectual structure of strategic management research: a bibliometric study of the Strategic Management Journal, 1980–2000. Strateg Manag J 25:981–1004

REN21 2017: Renewables 2017 Global Status Report, Paris: REN21 Secretariat

Riti JS, Riti M-KJ, Oji-Okoro I (2022) Renewable energy consumption in sub-Saharan Africa (SSA): Implications on economic and environmental sustainability. Current Research in Environmental Sustainability 4, 100129

Roelf W (2021) South Africa proposes reduced 2030 greenhouse gas emission targets. In: Evans D (Hrsg.). Reuters

Sarkodie SA, Strezov V (2019) Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries. Sci Total Environ 646:862–871

Sayigh A (1999) Renewable energy — the way forward. Appl Energy 64:15–30

Schwartz FW, Fang YC, Parthasarathy S (2005) Patterns of evolution of research strands in the hydrologic sciences. Hydrogeol J 13:25–36

Shaaban M, Petinrin JO (2014) Renewable energy potentials in Nigeria: meeting rural energy needs. Renew Sustain Energy Rev 29:72–84

Small H (1973) Co-citation in the scientific literature: a new measure of the relationship between two documents. J Am Soc Inf Sci 24:265–269

Smeets EMW, Faaij APC, Lewandowski IM, Turkenburg WC (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. Prog Energy Combust Sci 33:56–106

Snyder H (2019) Literature review as a research methodology: an overview and guidelines. J Bus Res 104:333–339

Soetaert W, Vandamme E (2009) Biofuels in Perspective, pp. 1–8

Sokan-Adeaga AA, Ana GR (2015) A comprehensive review of biomass resources and biofuel production in Nigeria: potential and prospects. Rev Environ Health 30:143–162

Soumonni O, Ojah K (2022) Innovative and mission-oriented financing of renewable energy in Sub-Saharan Africa: a review and conceptual framework. Wiley Interdisciplinary Reviews: Energy Environment Protection Engineering, e416

Stambouli AB, Khiat Z, Flazi S, Kitamura Y (2012) A review on the renewable energy development in Algeria: current perspective, energy scenario and sustainability issues. Renew Sustain Energy Rev 16:4445–4460

Suberu MY, Mustafa MW, Bashir N, Muhamad NA, Mokhtar AS (2013) Power sector renewable energy integration for expanding access to electricity in sub-Saharan Africa. Renew Sustain Energy Rev 25:630–642

Tiruye GA, Besha AT, Mekonnen YS, Benti NE, Gebreslase GA, Tufa RA (2021) Opportunities and challenges of renewable energy production in Ethiopia. Sustainability 13

Tucho GT, Weesie PDM, Nonhebel S (2014) Assessment of renewable energy resources potential for large scale and standalone applications in Ethiopia. Renew Sustain Energy Rev 40:422–431

USAID (2019) Center of Excellence for Energy. USAIDEgypt

van der Linde HA (1996) Wind energy in South Africa. Renewable Energy 9:880–883

van Eck NJ, Waltman L (2010) Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84:523–538

Varun, Prakash R, Bhat IK (2010) A figure of merit for evaluating sustainability of renewable energy systems. Renewable and Sustainable Energy Reviews 14, 1640-1643

Wei Y, McGrath PJ, Hayden J, Kutcher S (2015) Mental health literacy measures evaluating knowledge, attitudes and help-seeking: a scoping review. BMC Psychiatry 15:291

Whitesides GM, Crabtree GW (2007) Don't forget long-term fundamental research in energy. Science 315:796–798

Winkler H (2005) Renewable energy policy in South Africa: policy options for renewable electricity. Energy Policy 33:27–38

World Bank (2015) World Development Indicators. World Bank, Washington, DC

World Resources Institute (2009) Climate analysis indicators tool. World Resources Institute, Washington, DC

Xu X, Wei Z, Ji Q, Wang C, Gao G (2019) Global renewable energy development: influencing factors, trend predictions and countermeasures. Resour Policy 63:101470

Yuqin L, Xuefeng W, Xiaoping L (2015) Design and implementation of academic relation and visualization system. Library and Information Service 59:103

Zahraoui Y, Basir Khan MR, AlHamrouni I, Mekhilef S, Ahmed M (2021) Current status, scenario, and prospective of renewable energy in Algeria: a review. Energies 14

Zeng J, Qu J, Ma H, Gou X (2021) Characteristics and trends of household carbon emissions research from 1993 to 2019: a bibliometric analysis and its implications. Journal of Cleaner Production 295, 126468

Zhang M, Gao Z, Zheng T, Ma Y, Wang Q, Gao M, Sun XJJoMC, Management W (2018) A bibliometric analysis of biodiesel research during 1991–2015. 20, 10–18

Zhou F, Guo H-C, Ho Y-S, Wu C-Z (2007) Scientometric analysis of geostatistics using multivariate methods. Scientometrics 73:265–279

Ziuku S, Meyer EL (2012) Mitigating climate change through renewable energy and energy efficiency in the residential sector in South Africa. Int J Renew Energy Technol Res 2:33–43

Zoundi Z (2017) CO2 emissions, renewable energy and the Environmental Kuznets Curve, a panel cointegration approach. Renew Sustain Energy Rev 72:1067–1075