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Review

A Bibliometric Analysis of Solar Energy Forecasting Studies in Africa

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Abstract: Solar energy forecasting is considered an essential scientific aspect in supporting efforts to integrate solar energy into power grids. Moreover, solar energy forecasting plays an essential role in mitigating greenhouse gas emissions and conserving energy for future use. This study conducted a bibliometric analysis to assess solar energy forecasting research studies evolution at the continental (Africa) and southern Africa levels. Key aspects of analysis included (i) scientific research trends, (ii) nature of collaboration networks, (iii) co-occurrence of keywords and (iv) emerging themes in solar energy forecasting over the last two decades, between the years 2000–2021. The results indicate that solar energy forecasting research has, on average, expanded by 6.4% and 3.3% in Africa and southern Africa, respectively. Based on the study context, solar energy forecasting research only gained momentum in 2015, peaking in 2019, but it is generally still subtle. The scientific mapping illustrated that only South Africa ranks among the leading countries that have produced high numbers of published documents and also leads in contributions to the research area in both Africa and southern Africa. Three emerging topics were identified from the thematic map analysis—namely, "solar irradiance", "artificial intelligence" and "clear sky", which implies that researchers are paying attention to solar irradiance, using modelling techniques that incorporate machine learning techniques. Overall, this study contributes to scientific information on the potential bankability of renewable energy projects that could assist power utilities, governments and policymakers in Africa to enforce the green economy through accelerated decarbonisation of the energy systems and building relationships with developed countries for support and better transitioning to solar energy. From a Water–Energy–Food nexus perspective, the results of this work could assist the scientific community in Africa to take advantage of the inherent interconnectedness of water, energy and food resources, whilst also advancing the use of integrated solutions to shape the focus of solar energy research into a more systems thinking and transdisciplinary approach involving the interconnected primary resources and stakeholders pursuit of the Sustainable Development Goals.

Keywords: bibliometric review; emerging topics; current trends; low-carbon economy; thematic map analysis

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1. Introduction

The shortage of energy resources is one of the critical challenges affecting sustainable economic growth and development at the national, regional and global spatial levels [1]. In particular, reduced energy resources affect the productivity of key economic sectors such as agriculture, manufacturing, construction and households, among others. Generally, energy resources are not uniformly distributed around the world. Such uneven distribution can be attributed to the geography, geology, and accessibility of resources such as oil and the influences of climate change and variability [1]. There is no doubt that global energy demand is expected to increase faster than population growth [2] due to increasing industrial activities and technological advances in developed and developing countries. According to the International Energy Agency (IEA) [3], global energy consumption will likely increase by 53% by 2030, making energy security critical. Internationally, various government institutions such as the World Energy Council (WEC), the Organization of Petroleum Exporting Countries (OPEC), and world mega-oil organizations have investigated future global energy forecasting [4]. These studies have highlighted that the world is heading toward an increased uptake of renewable energy and a new energy economy that promotes clean energy technologies and energy efficiency [5]. The current crisis in Europe, particularly in the Ukraine, has given impetus to the need to diversify the energy mix globally. Furthermore, one of the fundamental pillars of every policy is energy efficiency to ensure inclusive and sustainable economic growth across the globe [4].

The world's dependence on fossil fuels has had a huge impact on the environment, increasing heat-trapping greenhouse gas (GHGs) concentrations such as carbon dioxide in the earth's atmosphere, resulting in a long-term shift in temperatures and weather patterns. These climate changes pose a significant threat to Sustainable Development Goals (SDGs) and can exacerbate poverty and inequality among populations [6]. In response to global warming, the Paris Agreement is one of the climate change treaties signed by different countries to serve as a global framework to ensure that the rise in global average temperature is kept below 2 degrees Celsius above the pre-industrial levels within this century [7]. It also seeks to strengthen and support countries' responses to the impacts of climate change. The agreement is all-inclusive in that it addresses the mitigation, adaptation and finance aspects whilst also encouraging countries to set and track their Nationally Determined Contributions (NDCs). As part of climate change mitigation, the global response has been to increase the consumption of renewable energies such as solar energy [8].

While efforts are being made to include or increase the share of renewable energy in the energy mix, a radical shift to clean energy sources is required for Africa to align with the 2015 Paris Agreement and to work towards achieving SDGs, particularly goal number seven. This goal specifically aspires to "ensure access to affordable, reliable and sustainable energy", which is intrinsically linked to other SDGs, including poverty eradication (goal one), advancements in health (goal three), quality education (goal 4), clean water and sanitation (goal six), industrialization (goal 9) and mitigating climate change (goal 13). In Africa, the current energy mix mainly includes burning coal, oil, and biomass [9]. Consequently, Africa needs to move toward an economically and environmentally viable energy mix. This will require addressing the high costs of installing and building renewable energy systems. Schwerhoff et al. [9] show that renewable energy's suitability is unique in different African countries. For example, geothermal energy is most suitable in Kenya and hydropower in most West African countries and the Democratic Republic of Congo, Ethiopia, Zambia, Zimbabwe, and South Africa, even though dam levels frequently affect full capacity operation due to droughts in these countries. Solar and wind resources are abundant in most African countries and coastal areas. According to Mutavhatsidi et al. [10], solar energy is one of Africa's most important renewable energy sources.

Several studies [8,11,12] have pointed out Africa's high solar resource potential. This is especially true given that most countries in the continent have a landmass exposed to an average of 325 days per year of bright sunlight [11]. South Africa, for example, already boasts several solar power plants with a capacity of more than 100 megawatts [9].

Most of the solar plants in South Africa are based in the Northern Cape Province and were developed through the 2010 Integrated Resource Plan (IRP), which promoted that 5.7 GW of solar power should be added to the grid by 2030 [12]. These solar power plants assist South Africa's primary energy supplier, Eskom, in meeting the energy demand whilst generating income from exporting electricity to seven countries in southern Africa. Currently, South Africa is facing energy supply challenges and is struggling to meet the demand due to the constrained power system. The relevant authorities had to frequently implement load shedding, a strategic mechanism to schedule and divide the electricity supply in the country to protect the power system from total blackout [7]. Loadshedding has also been implemented in several other African countries, such as Kenya, Zimbabwe and Zambia, where energy generation struggles to meet the increasing energy demands with huge impacts on social and economic sectors [13]. Overall, these omnipresent blackouts in the African countries have crippled the economies, whose impacts are mostly felt by poor households [13]. A reliable and efficient energy supply is critical for meeting current and future development goals in each of the respective African countries; hence, there is a need to understand energy forecasts and plan for future energy demand [12].

Solar irradiance forecasts are generally derived from Numerical Weather Prediction (NWP) models, but statistical and machine learning techniques are increasingly being used with the NWP models to produce more accurate forecasts [14]. The significance of solar energy forecasting is to ensure the sustainable operation of the national grid and its stability [14]. Providing the full predictive density or prediction intervals of the forecast assists decision-making within power utilities by assessing the future uncertainty of the power supply [14,15]. For Africa to successfully uptake solar energy and the development thereof, there is a need to understand current developments and activities conducted within the solar energy and solar energy forecasting research fields. Awareness of previous research and gaps in the published literature will pave the way for strategic research and mainstreaming efforts in Africa's solar energy forecasting research and development.

The present study undertook a scientific mapping of solar energy forecasting scholarship through an analysis of the evolution of research over the years to understand the developmental growth pattern of solar energy forecasting in Africa, thematic trends, the inherent intellectual and social structures, the nature of collaboration, as well as the general narrative in the field. The study has an important scientific contribution by elucidating the evolution of solar energy forecasting research themes and methodology in Africa. Its findings guide researchers on the current "hot topics" and the future direction of "emerging topics" of solar energy and solar energy forecasting research in support of policy and decision-making and the development of relevant renewable energy interventions and electrical grid management. The paper proceeds as follows: Section 1 is the introduction, followed by Section 2, which presents the materials and methods used in the study. The results are presented in Section 3, and the discussion and conclusion are presented in Sections 4 and 5.

2. Materials and Methods

The current study used the Web of Science (WoS) and Scopus databases to retrieve relevant documents on solar energy forecasting research. Solar energy forecasting is the process of obtaining and evaluating data to forecast solar power generation over a range of periods to reduce the impact of solar intermittency. Solar energy forecasts are used to predict power generation and consumption for efficient electric grid management [14,15]. The main purpose of this study is to conduct a scientific mapping and analysis of solar energy forecasting studies in Africa to understand thematic trends, developments, the nature of collaboration networks and general narrative within solar energy forecasting in Africa. Solar energy forecast approaches can be classified into planning methodologies used for strategic or tactical purposes, such as energy planning based on the availability of solar energy forecasting [16], as well as control techniques used for operational purposes, such as short-term prediction used in the energy management and control systems of grids and microgrids equipped with renewable systems [17]. The WoS and Scopus are considered the main and largest core collection databases, housing peer-reviewed scientific data, including articles, book chapters, and conference proceedings. In this regard, the two selected database sources of scientific documents have been extensively used in bibliometric review studies, covering a wide range of scientific disciplines and subdisciplines, such as health [18], water–energy–food nexus [19], drought [20], flood risk assessment [21], climate–smart agriculture [22], and environmental risk and impacts [23], among others. The current paper scaled up the methodology to solar energy forecasting research. This study defined comprehensive search topics to retrieve all feasible scientific documents in solar energy forecasting to conduct a scientific mapping and analysis. Bibliometric analysis is commonly used to investigate structural and dynamic elements of research topics using scientific mapping [22].

Consequently, the scientific mapping undertaken in the present study assessed (1) publication growth and trends, (2) leading countries contributing to solar energy forecasting research, (3) collaboration networks, (4) keyword occurrences, and (5) emerging themes. A summary of these search topics is given in Table 1. An example of document searches in both Scopus and WoS was set as follows: "solar energy forecasting" on the first row of the web portal; [AND] "prediction" on the second row; in conjunction with [AND] "Africa" on the third row, for a real restriction. A similar search was conducted, restricting the area to southern Africa. The document search was restricted to only those written in English but covered all types of published documents from 2000 to 2021.

Table 1. The search topics used to retrieve energy-related documents published in Africa and southern Africa.

Search Topics in Both Scopus and WoS Databases
"Solar energy forecasting" AND "prediction" AND "Africa" OR "southern Africa"
"Solar power forecasting" AND "prediction" AND "Africa" OR "southern Africa"
"Solar radiation forecasting" AND "prediction" AND "Africa" OR "southern Africa"
"Solar thermal forecasting" AND "prediction" AND "Africa" OR "southern Africa"
"Solar photovoltaic forecasting" AND "prediction" AND "Africa" OR "southern Africa"

Table 2 summarises the retrieved documents covering both continental (Africa) and regional (southern Africa) after the pre-processing and filtering of duplicated data. Most of the retrieved documents are scientific articles, followed by conference papers. The search resulted in 242 in Africa and only 34 in southern Africa. Appendix A shows the list of documents retrieved and assessed in southern Africa. The documents were analysed using a bibliometric mapping approach [24] and visualized in VOSviewer software [25]. Different subgroups were analysed to evaluate the current state of solar energy forecasting in both Africa and southern Africa. These subfields include evolution trends, the most active countries in researching within the field, citations per country, partnerships within countries, frequent keywords, and emerging thematic topics.

Table 2. A summary of retrieved documents.

Document Type	Document(s)—Africa	Document(s)—Southern Africa
Article	193	26
Proceedings	8	1
Conference paper	22	4
Conference review	6	3
Review	12	
Total	242	34

3. Results

3.1. Scientific Mapping of Solar Energy Forecasting

3.1.1. Evolution in Scientific Production

Figure 1 depicts the evolution of scientific documents published in the field of solar energy forecasting research in Africa (blue bars) and the southern African region (orange bars) between 2000 and 2021. Despite the small numbers, continental and regional research output has a noticeable growing trend. The average annual growth rates increase in annual scientific publications amounted to 6.4 and 3.3% in Africa and southern Africa, respectively. Significant growth is observed from 2015 to 2021, with 2019 being the most productive year showing the growing importance of solar energy forecasting research in Africa and the southern African region. The main drivers include, among others, the increased advocacy toward a transition to a low-carbon economy, thereby mitigating the impacts of climate change, supportive government policies, a reduction in the solar technology prices, increasing energy prices and the need to improve energy security and access, as well as working toward the achievement of linked sustainable development goals.

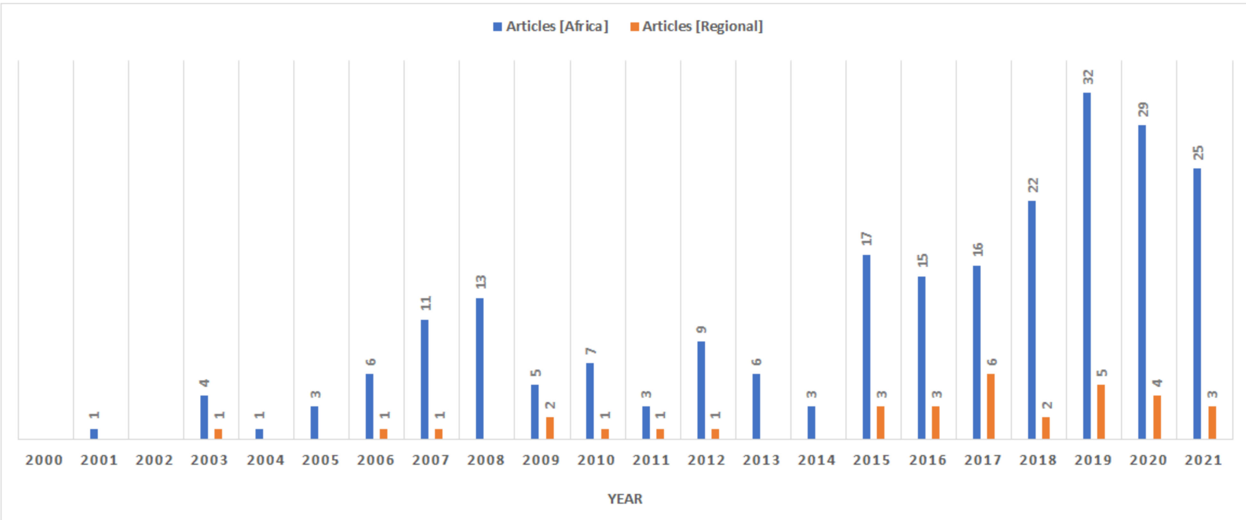

Figure 1. Annual publications from 2000–2021.

3.1.2. Countries with the Most Published Articles

Several countries have contributed to the solar energy forecasting research output. Figure 2 shows leading countries in the solar energy forecasting research. Figure 2a,b depict the top 10 and the top 5 countries that have produced high numbers of published documents in Africa and southern Africa, respectively. The countries are ranked based on the corresponding author's affiliated country. Figure 2 reflects that some articles were published under Single Country Publications (SCP), while others were under Multiple Country Publications (MCP). South Africa, the United States of America (USA), Germany, Nigeria, France, Algeria, and China are among the top ten countries, with South Africa leading in terms of contributions to the research area. It is also clear from the analysis that most of the publications were outcomes of collaborations with countries outside Africa. An analysis of results points to the paucity of renewable energy research scholarship that African scientists lead. In southern Africa, only South Africa had a fair share of contributions. The absence of African lead authors in the subject matter could be attributed to a lack of capacity to undertake the research or the need for funding to support such research activities and outputs. Also significantly noted in Figure 2a was the ratio between the SCP and the MCP; a huge gap between SCP (37) and MCP (2) is observed in output from South Africa compared to other regions. Publications in South Africa were mostly SCP, which demonstrates the need for countries in Africa to explore collaborations with other countries outside Africa to improve their network, lead innovation, learn more and encourage unified problem-solving.

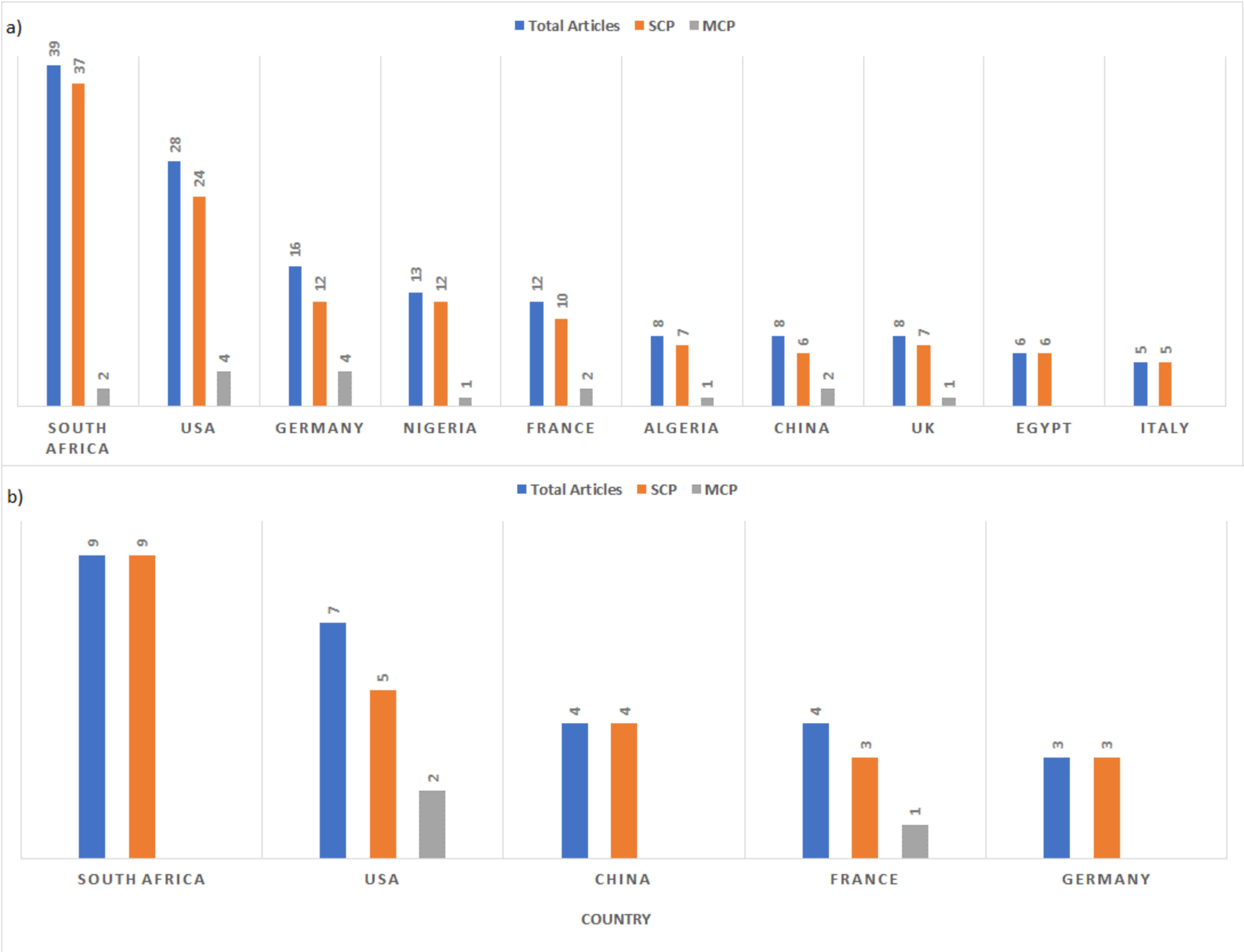

Figure 2. The top (**a**) ten (10) and (**b**) five (5) countries with a high number of published documents in Africa and southern Africa, respectively. The countries are ranked based on the corresponding author's affiliated country. SCP—Single-Country Publication and MCP—Multi-Country Publication.

Table 3 shows the number of citations the published articles have received per country during the study period. Germany received the highest number of citations (1645) based on the African content, followed by the USA with 1035. South Africa, Nigeria and Uganda have also topped the list with 391, 335 and 246 citations, respectively. Similarly, Germany ranks first in southern Africa, followed by Nigeria, the USA and South Africa with 1242, 184, 157 and 111 citations. A higher number of citations can be attributed to various factors, including authors following a similar methodology [26] and the merit and content (quality, significance, impact) of a research paper [27], as well as the relevance and active interest in the cited work [28].

Table 3. The total citations per country.

Africa		Southern Africa Data	
Country	**Total Citations**	**Country**	**Total Citations**
Germany	1645	Germany	1242
USA	1035	Nigeria	184
Algeria	475	USA	157
South Africa	391	South Africa	111
Switzerland	343	Spain	55
Nigeria	335	United Kingdom	30
France	332	China	22
Belgium	251	Cyprus	18
Uganda	246	France	18
United Kingdom	201		

According to Garfield [29], closely linked to citations are the journals in which the relevant sources are published. The information on the most relevant sources in the present review study is shown in Table 4. For Africa, some articles were published in high impact journals such as Applied Energy, Renewable Energy, Atmospheric Chemistry and Physics and Solar Energy, all with the latest impact factors above 5. For southern Africa, most of the journals have the latest impact factors, which are less than 5, except for Applied Energy and Atmospheric Chemistry and Physics journals. Nader et al. [30] proposed 33 ways for increasing citations. The lack of such strategies could be a factor in the high and low citations for some of the publications included in the analysis in this paper. The strategies include publishing in high impact factor journals, publishing in open access journals, publishing with international authors, publishing in discipline journals—specific journals and exposing the research articles to a large audience.

Table 4. The most relevant sources/journal.

Sources (Impact Factor)—Africa	Sources (Impact Factor)—Southern Africa
Energies (3.004)	Space Weather (3.584)
Advances in Space Research (2.152)	Climate Dynamics (4.375)
Renewable Energy (8.001)	International Journal of Climatology (4.069)
Journal of Geophysical Research Atmospheres (3.821)	Advances in Space Research (2.152)
Solar Energy (5.742)	African Journal of Ecology (1.426)
Journal of Energy in Southern Africa (0.661)	African Zoology (1.436)
Atmospheric Chemistry and Physics	Applied Energy (9.746)
Energy (6.133)	Atmosphere (2.682)
International Journal of Sustainable Energy (2.017)	Atmospheric Chemistry and Physics (6.12)
Applied Energy (9.746)	Climatic Change (4.743)

3.1.3. Country Collaborations

Figures 3 and 4 illustrate the country collaboration network derived from African and southern African published scientific documents in solar energy forecasting research, respectively. In Figure 3, the countries are separated into five clusters, with the cluster size depicting the strong collaboration of a particular country with others. The USA in the red cluster shows strong collaboration with at least six countries, including Namibia from Africa. Similarly, China, assigned to the green cluster, depicts a strong collaboration with six countries, three of which are in Africa (Cameroon, Nigeria and Rwanda). Meanwhile, Germany depicts a strong collaboration with five countries, including South Africa and Ethiopia in Africa. The yellow cluster only has three countries collaborating, one out of the three from Africa (Algeria), with France showing strong collaboration among the other two countries in this yellow cluster. Lastly, the purple cluster is the only cluster that shows no collaboration with Africa. Only two clusters are shown in the Southern African country collaboration network (Figure 4). The USA leads in the red cluster with three collaborations. Meanwhile, countries in the green cluster had equal efforts.

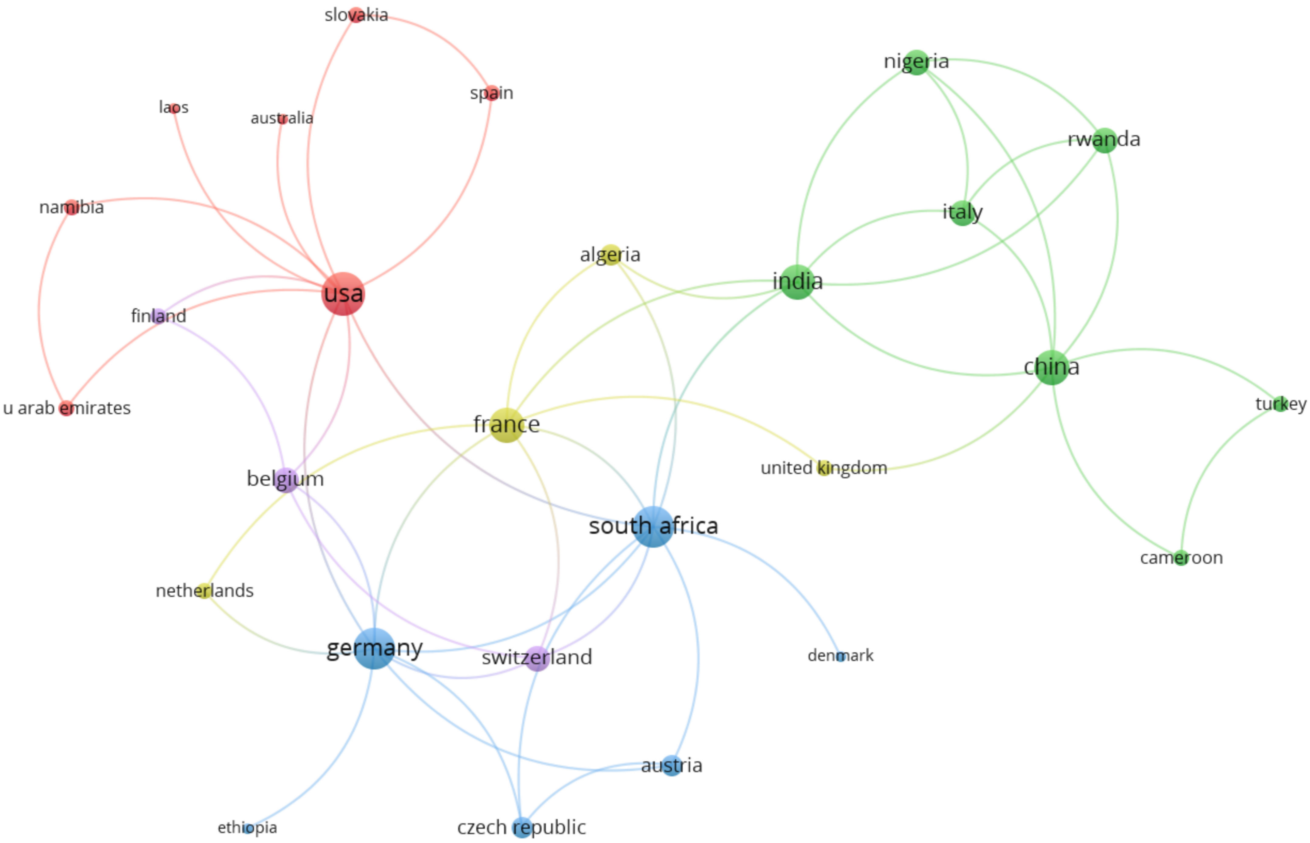

Figure 3. The country collaboration network derived from African published documents.

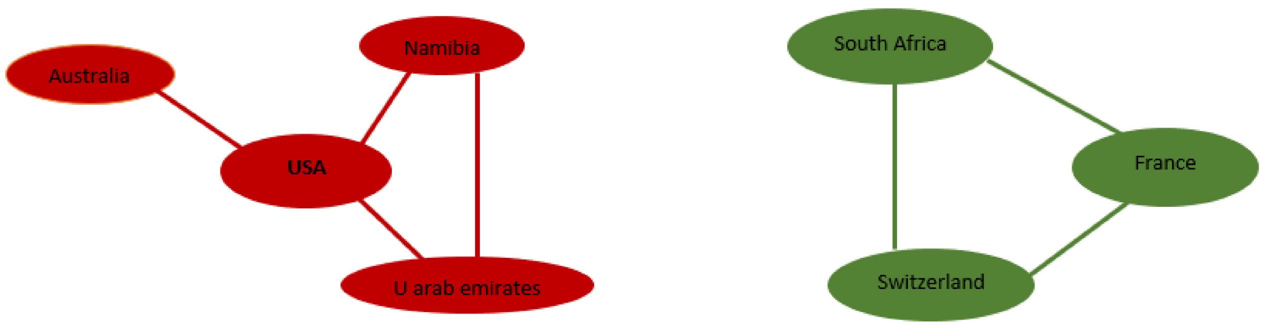

Figure 4. The country collaboration network derived from southern African published documents.

3.1.4. Keywords Analysis

The analysis of keywords, which depicts the frequency of co-occurrences of keywords in the articles, yielded five clusters, as shown in Figure 5 for Africa and Figure 6 for southern Africa. Table 5 shows detailed information on keywords in each cluster. The red cluster has dominant keywords for both Africa and southern Africa, with a total number of words at thirty-one and twenty-one, respectively, as shown in Table 5. This cluster reflects on different themes that address important aspects of forecasting. The most frequently occurring keywords in the red cluster are "weather forecasting" appearing in 71 articles, "numerical models" (56), "satellite imagery" (41), "computer simulations" (40), and "parameterization" (35) for Africa. Meanwhile, much attention in southern Africa was given to words such as "evapotranspiration", "regional climate", "global warming", "satellite imagery", "machine learning", and remote sensing"; these appeared in 43, 38, 36, 29, 25 and 24 articles, respectively.

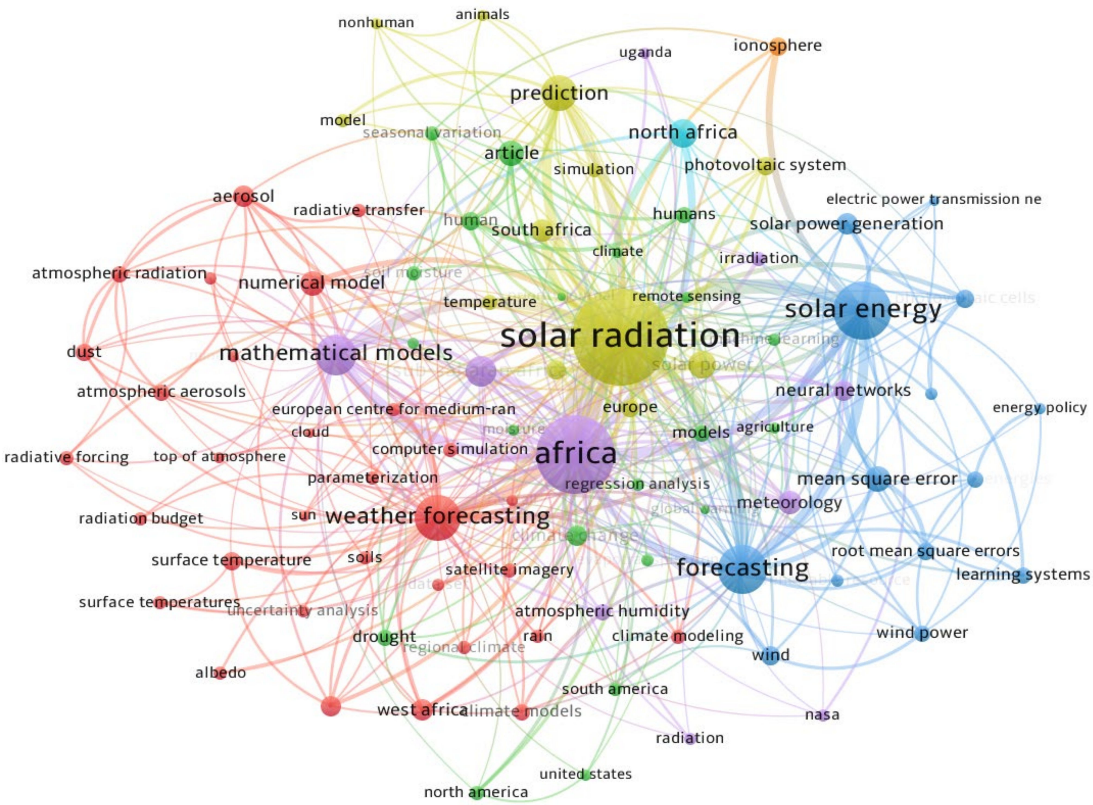

Figure 5. Keyword co-occurrences based on published documents in Africa.

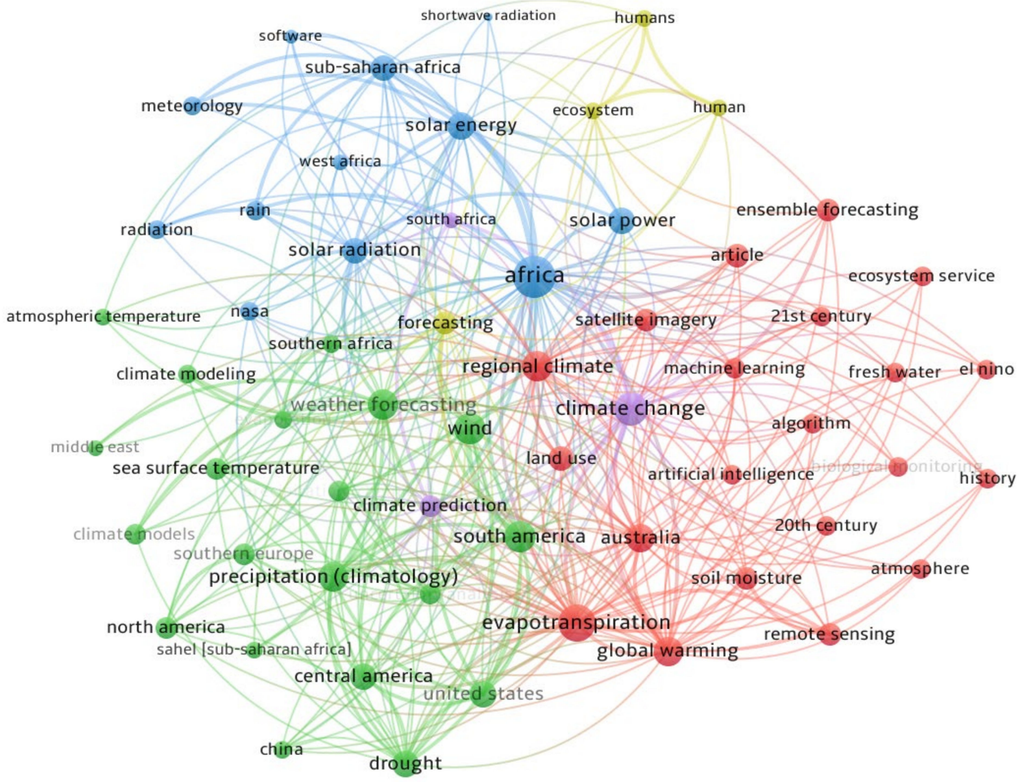

Figure 6. Keyword co-occurrences based on published documents covering the southern Africa region.

Table 5. A summary of the most frequent keywords.

Africa		Southern Africa	
Cluster (Number of Words)	**Dominant Words**	**Cluster (Number of Words)**	**Dominant Words**
Red (31)	Weather forecasting (71); numerical models (56); satellite imagery (41); computer simulations (40); parameterization (35)	Red (21)	Evapotranspiration (43); Regional climate (38); global warming (36); satellite imagery (29); machine learning (25); remote sensing (24)
Green (21)	Climate change (52); drought (43); remote sensing (33); agriculture (27)	Green (20)	Weather forecasting (33); precipitation (29); wind (29); drought (24); sea surface temperature (22)
Blue (14)	Forecasting (71); Solar energy (62); solar power generation (30); wind power (24); energy policy (15)	Blue (12)	Africa (53); solar radiation (24); solar energy (22); radiation (18)
Yellow (12)	Solar radiation (88); prediction (44); temperature (39); Simulation (32)	Yellow (4)	Forecasting (21); ecosystem (11)
Purple (10)	Africa (88); mathematical models (55); atmospheric humidity (34); radiation (32);	Purple (3)	Climate change (43); climate prediction (23); South Africa (10)

Keywords with a high frequency of occurrence in the green cluster are ”climate change”, followed by “drought” in Africa and “weather forecasting” in southern Africa. Most researchers had an interest in “forecasting”, “solar energy”, solar power generation”, “wind power” and “energy policy” in the blue cluster at the continental spatial scale. Regionally, researchers have shown an interest in “solar radiation and “solar energy”. Frequent keywords in the yellow cluster are “solar radiation”, “prediction” and “temperature” at continental and “forecasting” and ecosystem” at a regional spatial scale. The purple cluster contains the least keywords, with the most dominant being “mathematical models” and “atmospheric humidity” in the African context and “climate change” and “climate prediction” in southern Africa. Overall, the red cluster attracted the most attention in the solar energy forecasting research in Africa and southern Africa, and the purple cluster attracted minimal attention.

3.1.5. Thematic Network Analysis

A thematic map was used to assess the evolution of solar energy forecasting research topics in Africa and southern Africa. The thematic graphs in Figures 7 and 8 are subdivided into four quadrants. The themes seen on the quadrant’s upper right corner are motor themes (hot topics), i.e., these are well-developed themes with strong external ties with other subfields. Themes appearing in the upper left quadrant are known as niche themes, i.e., these are well-established themes and are very important in the solar energy forecasting research field. Meanwhile, themes in the lower left quadrant are referred to as emerging or declining, i.e., these themes are considered weakly developed due to low density and low centrality. Lastly, themes in the lower right quadrant are basic but specialized and still being developed in the field. Clearly illustrated in Figure 7, the hot topics in Africa are the artificial neural network, surface solar radiation and cloud cover, and the emerging topic is solar irradiance, artificial intelligence and clear sky. A study by Dogaru et al. [5] suggested that the fourth industrial revolution will be driven by renewable energy. In southern Africa, a stable topic is renewable energy; the hot topic is surface solar radiation. The emerging or declining topic is precipitation, African savanna drought, and lastly, the basic themes are climate change and remote sensing.

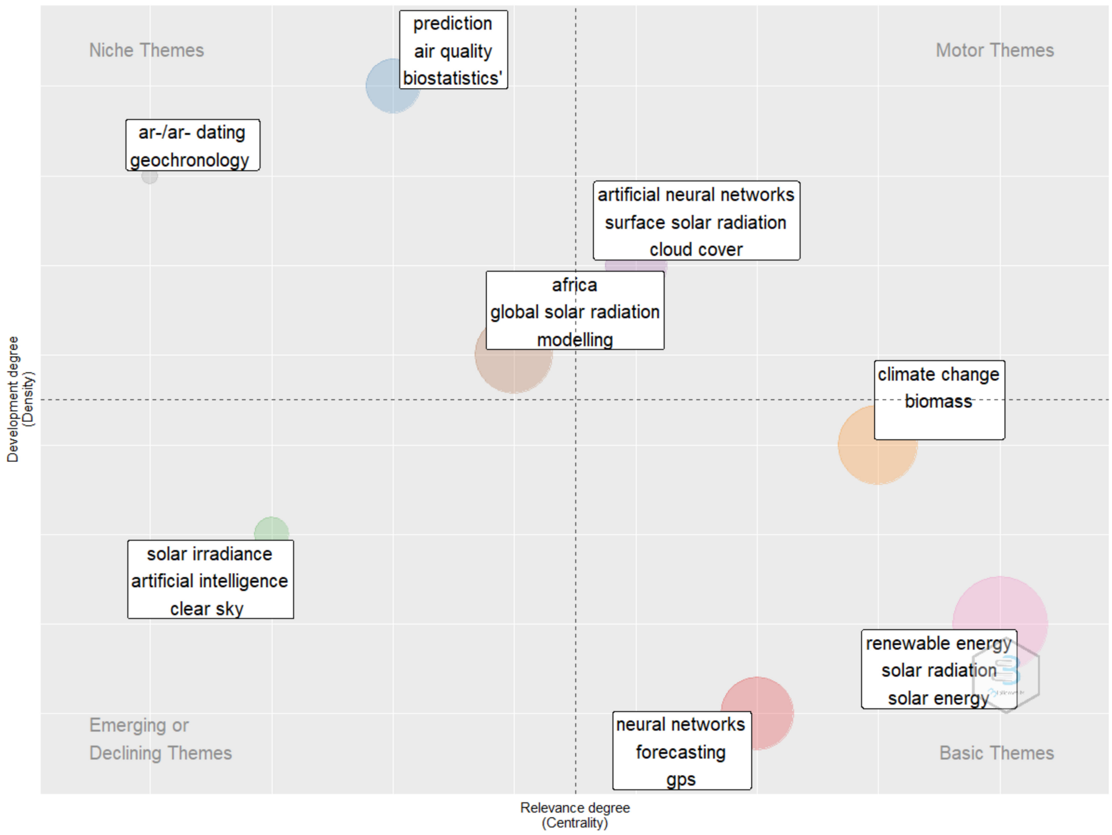

Figure 7. A thematic network of themes from African data.

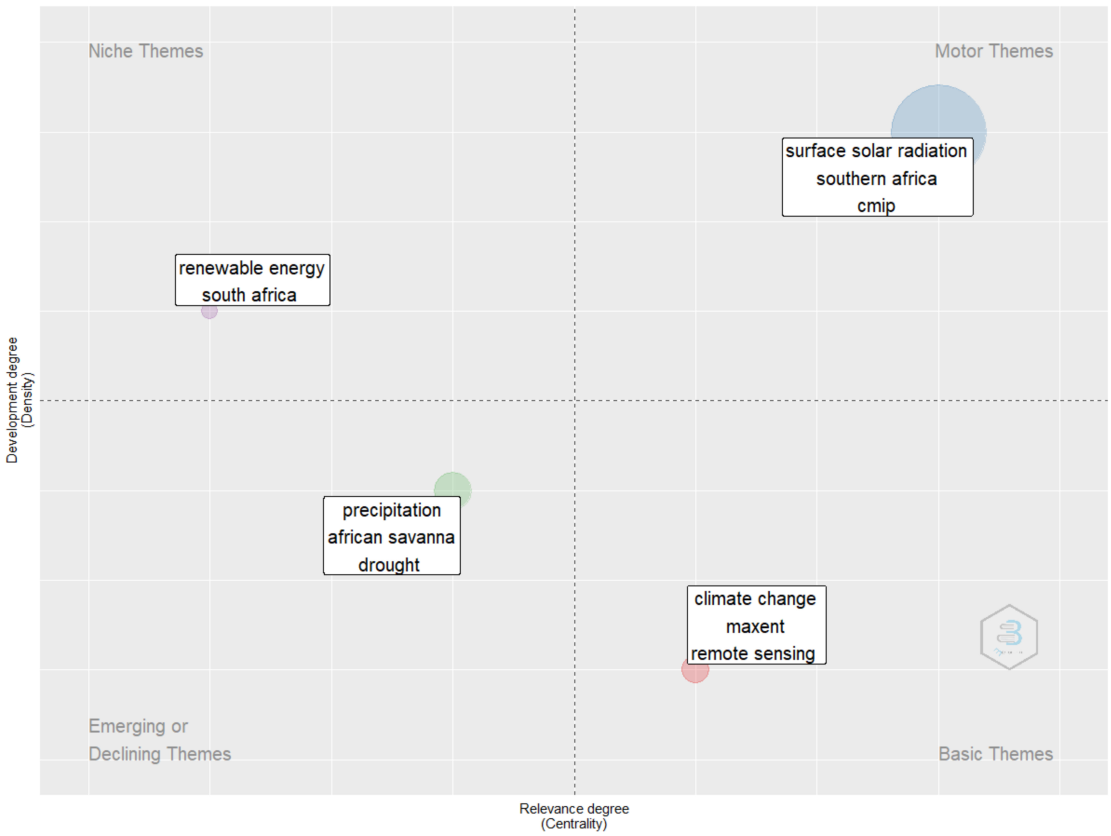

Figure 8. A thematic network of themes from southern African data.

4. Discussion

The current study is one of a kind in the solar energy research field that captured the evolution of solar energy forecasting research in Africa, considering research outputs from 2000 to 2021. In this study, it was revealed that there is a growing trend in solar energy forecasting research, and the significant growth was seen from 2015, peaking in the year 2019, which was observed to be the most productive year in the field to date (Figure 1). The observed great progression implies that the African scientific community is paying greater attention and are exploring all avenues to enhance solar energy forecasting research for better implementation and operationalization thereafter.

Results for the leading country in solar energy forecasting research paint a worrisome picture. As shown in Figure 2a,b, a few African countries feature in the top ten list of the most productive countries in solar energy forecasting research. This is attributed to a lack of capacity to undertake the research or the need for funding to support such research activities and outputs. Only a few countries, such as South Africa, Nigeria, Algeria and Egypt seem to have capacity and research support systems in place [31]. Ngongalah et al. [32] highlighted that strengthening research capacity in Africa has been recognised as a need. This involves efforts to increase the ability of institutions and individuals to undertake high-quality research efficiently and sustainably. The outcomes of this work agree with observations by Chu et al. [33] that efforts to strengthen research capacity in Africa have been led mostly by institutions from high-income countries. The authors further pointed out that while African organisations support the strengthening of research capacity in some African countries, most African countries mostly depend on foreign research support.

Analysis in this study has further shown that Africa has limited international collaborations (Figure 3), and the few that are there (namely, South Africa, Namibia, Cameroon, Nigeria, Rwanda, Ethiopia and Algeria) are rated among the most developed countries in Africa by the United Nations Human Development Index [34]. Collaborations in Africa have advanced by countries such as the USA, China, Germany and France. While the mentioned collaborations are appreciated, there is a need to widen the scope between (and within) African countries and the international community, including under-developed countries. Moreso, Africa's financial and capacity challenges require collaborations to support African countries to meet development goals whilst also mitigating the impacts of climate change by providing financial and technical support for the enhanced uptake of renewable energy and smart grid technologies on the continent.

According to the analysis of the keywords in Figure 5, the red cluster had dominant keywords indicating the high frequency of occurrence, implying that most researchers in solar energy forecasting in Africa were interested in "weather forecasting" appearing in 71 articles, "numerical models" (56), "satellite imagery" (41), "computer simulations" (40) and "parameterization" (35). This is not surprising because some of the recent studies [15,29,35] conducted in Africa have developed different methods for solar irradiance forecasting such as statistical approaches using historical data, the use of NWP models, tracking cloud movement from satellite images and tracking cloud movements from direct ground observations using sky cameras (more notable methods and reviews on solar energy forecasting models are discussed in Mpfumali et al. [14]).

From a thematic map in Figure 7 for Africa, three topics ("solar irradiance", "artificial intelligence", and "clear sky") were identified as emerging or declining. The three topics are emerging in Africa, judging from the limited literature in solar energy forecasting research in the region. In the past, renewable energy was considered unpredictable because of its dependence on varying weather conditions [36]. However, recently, due to their increasing penetration in some power systems globally, renewable energy is becoming significant and reliable, as researchers are now paying attention to solar irradiance, using modelling techniques (i.e., Genetic Algorithms, quantile regression models, etc.) and machine learning techniques such as artificial neural networks [15].

Based on the literature, it is clear that solar energy forecasting research is not popular in Africa. Studies by Mabasa et al. [37] illustrated solar irradiance prediction using physical clear-sky models that estimate solar irradiance in the absence of clouds in South Africa, employing a hybrid of radiometric and satellite data. Other studies, such as Danso et al. [8], used the European Centre for Medium-range Weather Forecasts reanalysis data to examine the occurrence and persistence of cloudy and clear-sky conditions in west Africa. Recent studies [10] have considered forecasting solar irradiance in South Africa using machine learning models. [38] used cluster analysis and Numerical Prediction Models to forecast hourly cloud cover percentage and use it to predict the irradiance for that day. Further, Fadare [11] investigated the modelling of solar energy potential in Africa using an artificial neural network. Lastly, work by Sawadogo [39] assessed the impact of climate change on solar and wind energy potential over Africa under two (high end and low end) different emission scenarios using high-resolution simulations with Regional Climate Model version 4, produced as part of the CORDEX-CORE initiatives for a period of the near future, 2021–2040, and the mid-century future, 2041–2060.

In general, the above studies have a common goal: to forecast solar power for the efficient management of the electric grid and power trading in Africa, and to identify the barriers to solar power integration into the energy mix. One of the major barriers to renewable energy research in Africa is the lack of solar radiation data due to the inability to afford the measuring equipment and techniques required. The inaccessibility of data in many African countries has limited the development of energy applications on the continent. Thus, researchers need to focus on developing methods (such as empirical models) to estimate the solar radiation parameters (i.e., global horizontal irradiance, diffuse horizontal irradiance and direct normal irradiance) based on other climatological parameters that are easily measured with more affordable equipment; these include sunshine hours and duration, relative humidity and maximum temperatures, and the number of rainy days. Additionally, there is a need to foster collaborative research and jointly establish solar energy monitoring networks across the African countries through public–private partnerships to lessen the huge costs associated with installing and maintaining the solar radiation network.

Globally, renewable energy forecasting is gaining more traction in the research field due to inherent socio-economic benefits for society and the environment. In addition to the role played by renewable energy in the mitigation of greenhouse gas emissions, renewable energy forecasting assists in conserving energy for future use, particularly where storage systems are incorporated into the energy systems [40]. In Africa, the growth in energy demand has been noted and is currently fulfilled via centralized and conventional power generators and fossil fuel-based generations [31]. The excessive dependence on conventional and fossil fuel-based generation is problematic and generally unsustainable due to the various environmental impacts and their supply and variability in their prices [41]. According to Pan and Dinter [31], the future of modern power systems and developments is going to be different, expressed in the World Energy Congress Report [42] as "The Grand Transition". Worldwide, Africa is responsible for minimal contribution to greenhouse gas emissions; yet, they are most susceptible to variations in climatic conditions [43]. As a result, there is a growing need for African governments to enforce and develop low-fuel, low-carbon systems for power generation. Access to energy can be alleviated using renewable energy (such as solar), especially in under-developed remote areas of Africa where the transportation cost of conventional resources to large-scale power plants is high [44].

Furthermore, African governments can forge collaborations with funding and technical expertise with countries such as the United Kingdom (UK), which have been able to provide sufficient energy for their populations and are taking steps towards a green economy [45]. Researchers in African countries also need to establish more collaborations with the UK and draw lessons from their experience to support similar initiatives in Africa. Furthermore, the current war in Ukraine has undoubtedly brought to the fore the need for a faster transition to renewable energy across many countries. The Ukraine crisis demonstrates the risk of overreliance on, for example, fossil fuels. Overall, policies in Africa should emphasise the move to more sustainable and cost-effective energy sources to reduce greenhouse gas emissions and uphold the goals of the 2015 Paris Agreement. Furthermore, African countries need to develop or upgrade their renewable energy policies, put in place robust power sector master and development plans or integrated resource plans that articulate actions to support capacity expansion, transmission development and the integration of variable renewables into the grid in ways that do not compromise system operations and reliability.

From the perspective of the water, energy and food (WEF) nexus, a transformed energy system (which incorporates renewable energy) has the advantage of being less water-intensive compared to an energy system that is largely dependent on fossil fuels (see Sanchez et al. [46] and Masoud [47]). A study by the International Renewable Energy Agency (IRENA), reported in Ferroukhi et al. [48], shows that renewable energy technologies can boost water security by improving accessibility, affordability and safety. Additionally, Ferroukhi et al. [48] concluded that incorporating renewable energy in the agrifood supply chain could also contribute toward (a) buffering the sector from shocks of cost volatility prevalent in agro-products, (b) ensuring energy security, (c) lessening the impacts of greenhouse gas emissions and (d) contribute to long-term food sustainability. As a result, situating the solar energy scholarship in the WEF nexus framework would have important scientific and practical policy and decision-making applications with far-reaching contributions to SDGs.

5. Conclusions

The present study conducted a bibliometric analysis of 242 and 34 scientific documents to assess the current state of solar energy forecasting in Africa and southern Africa, respectively. The findings in this study indicated that the scientific community had conducted limited research on solar energy forecasting over the study regions. The literature synthesis reveals that South Africa appears among the leading countries that have produced high numbers of published documents and contributions to the renewable energy research domain. The research on solar energy forecasting in Africa only gained momentum in 2015, peaking in 2019. An analysis of results points to the paucity of renewable energy research scholarship that African scientists lead. The absence of African lead authors in the subject matter could be attributed to a lack of capacity to undertake the research or the need for funding to support such research activities and outputs.

Furthermore, an analysis in this review indicates that Africa has limited international collaborations. The few involved (e.g., South Africa, Namibia, Cameroon, Nigeria, Rwanda, Ethiopia and Algeria) are rated among the most developed countries in Africa. There is a gap in including under-developed countries in the subject matter. This will allow prospective researchers to conduct solar energy forecasting research in these areas and development. Moreso, a need for financial and technical support is considered an important aspect in support for the enhanced uptake of renewable energy and smart grid technologies on the continent. Overall, governments and policymakers in Africa must enforce the decarbonized economy through accelerated decarbonisation of the energy systems and build relationships with developed countries to secure support and funding. Therefore, this study provides a situational analysis of the renewable energy research social networks and vital research trends, including the uptake of renewable energy research outputs and the evolution of renewable energy research themes that contribute toward sustaining the energy sector and the African development goals. Energy insecurity remains one of the key challenges many households face on the continent. This work can be adapted to support energy planning and demand-side management work to reduce poverty and enhance community development through improved energy security in the study area. Future work will include a review of the scientific methods in solar energy forecasting, differences and peculiarities in approaches used by the various authors, and an assessment of different forecasting models to identify the most accurate model.

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Appendix A

Table 1. Summary of selected scientific publications on solar energy forecasting studies conducted in Africa.

Reference	Corresponding Author	Publication Year	Country Led	Theme of the Study
[8]	Danso, D.K.	2020	France Ivory Coast Niger	The study aimed to better understand the occurrence of cloud cover and the effect it has on surface solar radiation in West Africa. This understanding is important in developing plans to better manage future solar energy production in the region. [A spatial and temporal analysis was done using ERA5 data and grouped according to the different seasons and rainy seasons.]
[10]	Mutavhatsindi, T.	2020	South Africa	The forecasting of solar irradiance is essential within renewable energy grids for operational planning, backup programming and short-term power purchases. The study focused on using radiometric station data to forecast hourly solar irradiance. The study compared the predictive performance of three different forecasting models namely, support vector regression, feed forward neural networks and long short-term memory.
[11]	Fadare, D.	2009	Nigeria	The study developed an artificial neural network (ANN) model for predicting solar energy potential in Nigeria. The ANN model is a feed-forward, multi-layered, backward-propagation model using meteorological and geographical data. The model was trained and tested to use input data to produce solar radiation intensity as an output. The results show a correlation coefficient higher than 90% between the model predicted values and the observed mean monthly global solar radiation intensities used for training the model. The study results suggest a good reliability of the model for evaluating solar radiation in locations where data is not available.
[49]	Fuller, S.	2017	US	The author explores the central question: "Will the new technologies that have sustained globalization reinforce or undermine democracy?" The author examines and explores various cases and examples throughout North Africa. The relations between sustainable development and renewable energy are explored, together with anticipated patterns of future energy use, the consequent environmental impacts along with potential solutions.
[50]	Oakleaf, J.R.	2015	US	The increased demand for resources and the acceleration of habitat modification are being driven by a growing and more affluent human population. The study attempted to project how much and where these changes will take place. The study projected and aggregated global spatial patterns of expected agricultural and urban expansion, together with development in the mining, solar, wind, biofuels, coal, oil and gas sectors. The study estimates half of the world's biomes are at risk and land conversion in Africa to triple in the future. In order to curtail the further substantial loss of nature, stricter legal protection is needed for the environment and better estimation and mitigation of multi-sector development risk.

Table 1. *Cont.*

Reference	Corresponding Author	Publication Year	Country Led	Theme of the Study
[51]	Emhemed, A.	2011	UK	The study used parabolic trough solar collectors to evaluate, estimate and compare the on-stream renewable electricity generation in North Africa and South Europe by the year 2020. The study estimated the required generation capacity and developed forecasting scenarios for electricity production. Supply growth rate estimates using historical data were also considered in the study. The study suggested locations with favourable prospects for the export of green electricity, where the solar resource potential and the potential net electricity output are greater than the estimated consumption.
[52]	Stager, J.C.	2007	USUK	Over the last century, there have been many investigations and debates focussing on the association of high sunspot numbers with the water level rises of Lake Victoria. This study show Lake Victoria water level maxima were accompanied by peaks in the 11-year sunspot cycle due to the occurrence of positive rainfall anomalies 1 year before solar maxima. This pattern occurred in 5 other east African lakes and suggests that those sunspot-rainfall relationships were regional in scale. The study suggests that if these sun-rainfall relationships persist into the future, they can be used for the longer-term prediction of precipitation anomalies and the associated outbreaks of insect-borne diseases in East Africa.
[53]	Annandale, J.	2003	South Africa	The water and energy distribution in widely spaced, micro-irrigated, hedgerow crops are non-uniform, and more accurate water use predictions are critical. To try and address this issue, this study developed a two-dimensional, mechanistic and user-friendly soil water balance model. The model calculates crop water uptake as a function of soil water potential, root density, and evaporative demand. Results from a field trial show the model predictions compared generally well to soil water content measurements. From the study results, it is suggested that the model has the potential for improving irrigation efficiency and scheduling in hedgerow tree crops.
[54]	Chandiwana, E.	2021	South AfricaZimbabwe	Over the past decade, probabilistic solar power forecasting has become more critical in Southern Africa as a consequence of major power shortages resulting from climate change coupled with other factors. This study discussed forecasting hourly global horizontal irradiance (GHI) using a core vector coupled with regression Gaussian process regression (GPR). The proposed forecasting method was tested with two radiometric stations' real time data and the resulting percentage bias, root mean square, and mean absolute errors were calculated. The results were compared to other models and showed the GPR yields more accurate results, thus making the model a useful tool for system operators and decision-makers working in power utility companies.

Table 1. *Cont.*

Reference	Corresponding Author	Publication Year	Country Led	Theme of the Study
[55]	Schroedter-Homscheidt, M.	2016	Germany	Electricity production forecasts for 48 h are required for the successful integration of solar electricity into the existing electricity supply. The short-term nowcasting required for the optimized operation of a power plant is still a major field of development. This study reported on parts of the European Commission's solar production forecasting tool aimed at improving short-term nowcasting for solar power production. The paper focused on using a sectoral approach, rather than a motion vector approach, for distinguishing between different cloud types, heights and moving directions. This different approach has a significant impact on the calculation of direct normal irradiances (DNI). This paper presented the verification results of this scheme. The scheme had a positive impact on hourly DNI calculations 8 h ahead, depending on the time of day.
[56]	Lotz, S.I.	2017	South Africa	Grounded conductor networks, like power grids, can be affected by geomagnetically induced currents (GIC) which is an electrical field induced by solar activity or space weather. The study presents an empirical regression-based model for the quantitative prediction of induced electrical field components. The study made use of near-earth measurements of magnetic field parameters and solar wind plasma over a historical period. Testing the model over two years yielded a correlation between 0.68 and 0.75 for the predicted northward horizontal component of the induced electrical field. The study presented the testing results at various locations and latitudes.
[57]	Kotzé, P.B.	2015	South Africa	The primary objective of this paper was to discuss the role of the geomagnetic observation network in space weather monitoring and to describe the geomagnetic data sets used to characterize and monitor various solar-driven disturbances. The aim was to provide a better understanding of the different physics associated with the processes and to provide relevant space weather monitoring and prediction.
[58]	Chao Tang	2019	France, Switzerland, South Africa	The study evaluated the performance of five Regional Climate Models (RCM) namely: (CCLM4, HIRHAM5, RACMO22T, RCA4 and REMO2009) and 10 General Circulation Models (GCMs) in estimating global horizontal irradiance (GHI) over Southern Africa (SA). The reference data from ground-based measurements, satellite-derived products, and reanalyses over the period 1990–2005 were used to gauge the performance of the models. The authors found that GCMs overestimated GHI over SA in terms of their multi-model mean by about 1 W/m^2 and 7.5 W/m^2 in austral summer and winter respectively. RCMs underestimated the multi-model mean of GHI in both seasons with Mean Bias Errors (MBEs) of about -30 W/m^2 in austral summer and about -14 W/m^2. CCLM4 underestimated GHI the most with MBEs of -76 W/m^2 in summer and -32 W/m^2 in winter. The errors in the estimated GHI over SA were larger in the RCMs than in the GCMs. Over the period of 1990–2005, both GCMs and RCMs showed a GHI trend of less than 1 W/m^2 per decade, however, variations of GHI trend existed in the reference data. The information obtained study could be used in understanding future climate projections of GHI and for relevant impact studies.

Table 1. *Cont.*

Reference	Corresponding Author	Publication Year	Country Led	Theme of the Study
[59]	R Deshmukh	2018	United States of America	The study assessed the feasibility and cost-effectiveness of renewable energy alternatives to Inga 3, a 4.8-GW hydropower project on the Congo River, to serve the energy needs of the Democratic Republic of Congo (DRC), and South Africa. A spatially and temporally detailed power system investment model for South Africa was built to account for uncertainty in the literature. The authors found that a mix of wind, solar photovoltaics, and some natural gas is more cost-effective than Inga 3 to meet future demand. In the authors' scenarios, the effect of Inga 3 deployment on South African power system costs ranges from an increase of ZAR 4300 (US$ 330) million annually to savings of ZAR 1600 (US$ 120) million annually by 2035. Considering time and cost overruns and losses in transmission from DRC to South Africa makes Inga 3 a less attractive investment. For DRC, the authors found abundant renewable energy potential of 60 GW of solar photovoltaic and 0.6–2.3 GW of wind located close to transmission infrastructure have levelised costs less than US$ 0.07 per kWh (i.e., the anticipated cost of Inga 3 to residential consumers)
[60]	Grace C. Wu	2017	Namibia, USA, United Arab Emirates	The study assessed wind and solar energy potential for large regions of Africa. The assessment was done because the forecasts predicted that African countries must triple their current electricity generation by 2030. The assessment was done by creating the Multicriteria Analysis for Planning Renewable Energy (MapRE) framework to map and characterize solar and wind energy zones in 21 countries in the Southern African Power Pool (SAPP) and the Eastern Africa Power Pool (EAPP), this was done to find countries where the potential is several times greater than demand. The authors found that in many countries the potential was several times greater than the demand. The results further show that wind and solar energy are economically competitive and have a low environmental impact and as a result, they can significantly contribute to meeting the forecasted demand. However, the wind and solar energy potential were found to be spatially heterogeneous, meaning for the resources to be utilised there is a need for regional coordination and transmission infrastructure to enable resource sharing.
[61]	Lunche Wang	2019	China	The study analysed historical global horizontal irradiance (GHI) from (1850–2005) and future photovoltaic (PV) power output (2006–2100), the analysis was done to investigate the spatial distribution and long-term variation in global solar energy based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) models and the Global Energy Balance Archive (GEBA) database. The authors found that global mean GHI significantly decreased by 0.014 W m^{-2} $year^{-1}$ from 1850–2005. According to the Model for Interdisciplinary Research on Climate (MIROC5), GHI significantly decreased by 3.42 W m^{-2} $year^{-1}$ from 1951–1992 and increased by 4.75 W m^{-2} $year^{-1}$ from 1993–2005. Stations in Southeast Africa showed renewed decreasing trends after the 1990s. The direct and indirect effects of anthropogenic aerosols and cloudiness in different periods were suspected to be the main causes of the changes.

Table 1. *Cont.*

Reference	Corresponding Author	Publication Year	Country Led	Theme of the Study
[62]	Shukla, S.	2015	United States of America	This study provides a first skill evaluation of global seasonal ETo forecasts, for their potential use in food insecurity assessments by the FEWS NET. The primary objectives of this study are: (1) to develop ETo forecasts at a global scale; (2) to analyze their skill globally with particular emphasis on FEWS NET focus regions; (3) to illustrate how ETo forecasts can be used for early warning applications.
[63]	Zittis, G.	2017	Cyprus	The theme is to analyse and compare the model's output with surface and satellite observations and by applying statistical metrics for climatology, variability, and trends, considering also the different land types and sub-regions of the MENA-CORDEX domain. In addition to the modelling part of this study, we also touch on issues such as observed temperature trends and observational uncertainty over the poorly studied MENA region.
[64]	Tang, C	2019		Investigate SSR changes based on a multi-model ensemble (10 GCMs and 5 RCMs) in the region of Southern Africa (SA). The first part of this study evaluated the SSR patterns simulated by the RCMs and GCMs, showing that the GCM ensemble mean has a positive spatial mean SSR bias of about 1 W/m^2 over SA, while the RCM ensemble mean has a negative bias of about -20 W/m^2 for the past period. In terms of long-term changes, both GCMs and RCMs.

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