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Review article

Drivers and challenges of off-grid renewable energy-based projects in West Africa: A review

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ABSTRACT

Off-grid hybrid power systems with renewable energy as the primary resource remain the best option to electrify rural/remote areas in developing countries to help attain universal electricity access by 2030. However, deploying these systems in West Africa faces several challenges and regularly fail to transition from pilot, donor-sponsored projects to sustainable large-scale implementations. The study examined the drivers and challenges by conducting a review of previous studies done in the region and a short survey in Ghana. Using Political, Economic, Social, Technical, Legal and Environmental dimensions, the review and survey showed that economic challenges have the worst impacts on the sustainable development of off-grid renewable energy-based power systems in WA. Further, the analysis revealed patterns and linkages among the challenges that make it detrimental to focus solely on the most pressing challenges.

1. Introduction

Access to electricity stimulates social, economic, and environmental development, the three pillars of sustainable development [1,2]. According to the International Energy Agency (IEA), energy access is defined as "a household having reliable and affordable access to both clean cooking facilities and to electricity, which is enough to supply a basic bundle of energy services initially, and then an increasing level of electricity over time to reach the regional average [3]". The discussion on energy access received global attention after launching the Sustainable Development Goals (SDGs) in 2015 with SDG target 7.1 aiming at 'universal energy access for all' by 2030 [4].

Providing 'universal access to electricity for all' directly impacts achieving the global sustainable future agenda [5]. As Bukari et al. (2021) pointed out, access to sustainable electricity serves as a springboard for realizing all other SDG targets [6]. For instance, substituting wood fuel with electricity for cooking will reduce human health burdens (SDG 3) and deforestation (SDG 13) [7,8]. Access

Abbreviations: AHP, Analytic Hierarchy Process; CAPEX, Capital Expenditure; ECOWAS, Economic Community of West Africa States; ESMAP, Energy Sector Management Assistance Program; GEDAP, Ghana Energy Development and Access Project; GHGs, Green House Gases; HOMER, Hybrid Optimization of Multiple Energy Resources; IPCC, Intergovernmental Panel on Climate Change; IEA, International Energy Agency; $kgCO_2eq$, Kilogram carbon dioxide equivalent; LCOE, Levelized Cost of Electricity; OGPS, Off-grid Power Systems; PESTLE, Political, Economic, Social, Technological, Legal, and Environmental; PAOP, Power Africa Off-grid Project; PPP, Public Private Partnership; RE, Renewable Energy; ASER, Senegalese Rural Electrification Agency; SHS, Solar Home Systems; SSA, Sub-Saharan Africa; SDGs, Sustainable Development Goals; SE4ALL, Sustainable Energy for All; UNT, Uniform National Tariff; USAID, United States Agency for International Development; WA, West Africa.

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to electricity improves the quality of education (SDG 4) by providing light for learning at night and access to the internet for research [9]. Social science researchers have also discovered an interrelation between poverty and energy access [10–13].

Worldwide, as of 2019, the number of people without clean cooking and electricity access was 2.6 billion and 759 million, respectively, a record low in recent years [14]. The lack of clean energy access in rural areas is particularly distinct in Sub-Saharan Africa (SSA), which accounts for 75% of the global rural population and requires urgent attention to achieve SDGs by 2030 [1]. According to the report, 'Tracking SDG 7: The Energy Progress Report, 2021' by the World Bank, though the overall number of people without electricity access has steadily dropped worldwide, in 2019, the twenty countries that have the smallest share of the population with access to electricity were all located in SSA [15].

Access to electricity is most challenging in the western part of SSA. Data from the World Bank indicates that, as of 2019, more than half of the population of West Africa (51.1%) lacks access to electricity [16]. Further, rural areas, which are home to 49% of the total population of West Africa (WA), had an electrification rate of only 28% [17]. Moreover, the United Nations Development Programme asserts that 11 of the 15 member states in WA are classified under Least Developed Countries [18]. This socio-economic indicator is influenced mainly by access to electricity. Therefore, there is a need to drastically ramp up electrification efforts in rural areas in WA to stimulate sustainable growth to meet the SDG targets [19].

These rural settlers are commonly clustered in geographically dispersed locations and isolated from the utility grid [20,21]. As such, extending the centralized grid to these distant areas comes with several challenges [6,22]. Low energy demand, high cost of grid extension, low level of industrialization, rough terrain and low economic activities are some delimiting constraints that hamper this option [23]. Off-grid Power Systems (OGPS) with renewable energy (RE) sources offer an alternative pathway to achieving total electrification in such circumstances [24]. The IEA, in a 2011 study, attested that the expansion of the grid is effective for urban areas and 30% of unelectrified rural areas [1]. The remaining 70% is best suited for off-grid systems. Moreover, IEA estimates that 43% of unelectrified populations must be supplied with decentralized systems to meet the universal energy access goal by 2030 [6].

It is prudent to mention that rural settlers already use decentralized energy sources to meet their demand. Historically, standalone fossil-fuelled generators operating in off-grid mode power loads in rural areas [25]. However, the continuous use of these conventional energy sources contributes adversely to environmental impacts such as global warming and resource depletion. Subsequently, RE-based OGPS has the capacity to allow the smooth transition to low-carbon West African economies while increasing energy access.

Adapting RE-based OGPS is proving to be a cost-competitive option to fossil fuel-based generators. It is estimated that the levelized cost of electricity of RE-based OGPS in developing countries is between USD 0.39/kWh to USD 0.75/kWh, with the prospects of decreasing to USD 0.2/kWh by 2035 [26]. It is imperative to emphasize that off-grid systems come in two forms: standalone systems often referred to as Solar Home Systems (SHS) and isolated mini/micro-grids with single or hybrid energy sources [27]. A 2015 report by IRENA classified micro-grids and mini-grids according to generation capacity as 5–100 kW and 0–100,000 kW respectively [28]. In this study, OGPS refers to isolated micro-grids or mini-grids with a capacity less than 10 MW.

Several OGPS projects have been implemented across WA over the last two decades using RE solutions to supply modern energy to rural areas. Governments, developmental agencies, and private sector investors are all involved in taking the initiative. Through the joint Sustainable Energy for All (SE4ALL) program, the UN and the World Bank are leaders in promoting rural electrification in the region [29]. Despite this, large-scale replication of demonstration projects remains a mirage, as evident by the fact that targets set by governments across the region are often missed. To foster the successful implementation of affordable, scalable, and sustainable RE OGPS projects requires fully comprehending the challenges causing their premature failure.

The authors used the Political, Economic, Social, Technological, Legal, Environmental (PESTLE) approach to unravel the drivers and challenges to implementing RE-based OGPS in WA. Ghotge et al., in 2020 performed a global analysis focussing on the drivers and challenges for microgrids using the PESTLE framework [30]. However, the authors surveyed only scientific and non-scientific research conducted in 2019 and did not delve into systems located in rural communities. Other relevant studies that used the PESTLE approach include a study on the sustainable development of renewable energy in Malawi using PESTLE analysis [31] and a PESTLE analysis of solar home systems in refugee camps in Rwanda [32]. To the best of our knowledge, the PESTLE approach is yet to be used to assess the drivers and challenges of OGPS in WA. Through a detailed review and a short survey, this paper answers the following question:

> "What does the literature tell us about the drivers and challenges of RE-based OGPS implementation in WA and what factors are needed to implement a successful OGPS in the future?"

The novelty of this study is that the macro-environment challenges are addressed holistically. Moreover, we used the bibliometric analysis method to objectively analyse the research corpus from various aspects to provide a whole picture of OGPS-related research in WA, including discipline research trends, keyword clusters and content analysis of research topics involved in the field, which has rarely been examined in previous studies in this field.

The rest of the paper is organized as follows:

Section 2 elaborates on the electrification rates, resource potential and status of RE OGPS projects in WA. Section 3 explains the approach used to conduct the study while Section 4 presents the literature review and the short survey findings. Section 5 discusses the findings and analyses factors needed to improve the success rate of future OGPS projects. Finally, section 6 presents the conclusions and recommendations.

2. Current electrification rates, resource potential and status of RE-based OGPS projects in WA

With commodity prices soaring, leaders worldwide are worried about energy shortage and energy poverty. In WA, only three countries are on track to provide access to electricity for all by 2030 [33]. This section reviews the current electrification rates, resource potential and status of RE-based OGPS projects in WA.

2.1. WA current electrification rates and RE resource potential

The study focuses on rural electrification rates of the 15 members of the Economic Community of West Africa States (ECOWAS). Fig. 1 shows a plot of the rural population rate against the rural electrification rate for each ECOWAS member. The plot's skewness shows that most ECOWAS countries have high rural population rates but low electrification rates. Apart from Ghana (70%) and Cape Verde (95.9%), none of the countries have rural electrification rates above 50%. With 70% of its population living in rural areas, Burkina Faso has only a 4.7% rural electrification rate [17,34]. Another country of concern is Sierra Leone, where the rural electrification rate is 1.5% even though 58% of the population lives in rural areas.

The average WA electrification rate is well below the world average rate and leaves a deficit of 183.84 million people unserved [35]. Despite the region's enormous energy endowments, per capita consumption of final electricity is among the lowest in the world with approximately 160 kWh consumed per capita annually [36].

In the poorest WA countries, under 30% of the population have access to electricity (compared to 37% in Sub-Saharan Africa), with overall access rates below 12% in Guinea Bissau and Niger. Fig. 2 compares WA countries' urban and rural electrification rates and average urban and rural electrification rates. The graph shows that barring Cape Verde, which has relatively equal urban and rural electrification rates, all other countries have lower rural electrification rates than urban. This observation can be attributed to the fact that urban centres have accessibility to the central grid.

Extensive research and development have driven down the cost of RE technologies [6,40]. Volatile petroleum prices and the urgency to reduce Greenhouse Gas (GHG) emissions are two other reasons that give RE sources a competitive advantage over fossil fuels [41–43]. Despite the incentives in producing electricity from RE, these resources remain largely untapped in WA.

WA has a range of diverse RE resources capable of meeting its present and future energy needs and contributing significantly to the development of RE-based OGPS in rural communities [38,39]. An analysis by Ref. [44] estimates the resource potential for small hydro, concentrated solar power (CSP), solar photovoltaics (PV), biomass and wind in WA countries as 3113 MW, 323,805 MW, 1,453, 231 MW, 22,352 MW and 128,093 MW respectively.

On average, WA countries receive 6–8 kWh/m^2/day of solar irradiation, suitable for both PV and CSP applications [45]. Countries along the Sahel Savannah region (Mali, Niger, Burkina Faso and Nigeria) have the highest solar potential. Wind energy is the second highest RE resource available in WA, with the Sahel Savannah region having the highest potential. Though small hydro represents the least potential, it can still provide rural communities with enough electricity for basic needs. Geothermal energy is predominant in East and Southern Africa countries and is neither part of most WA countries' current nor future generation mix.

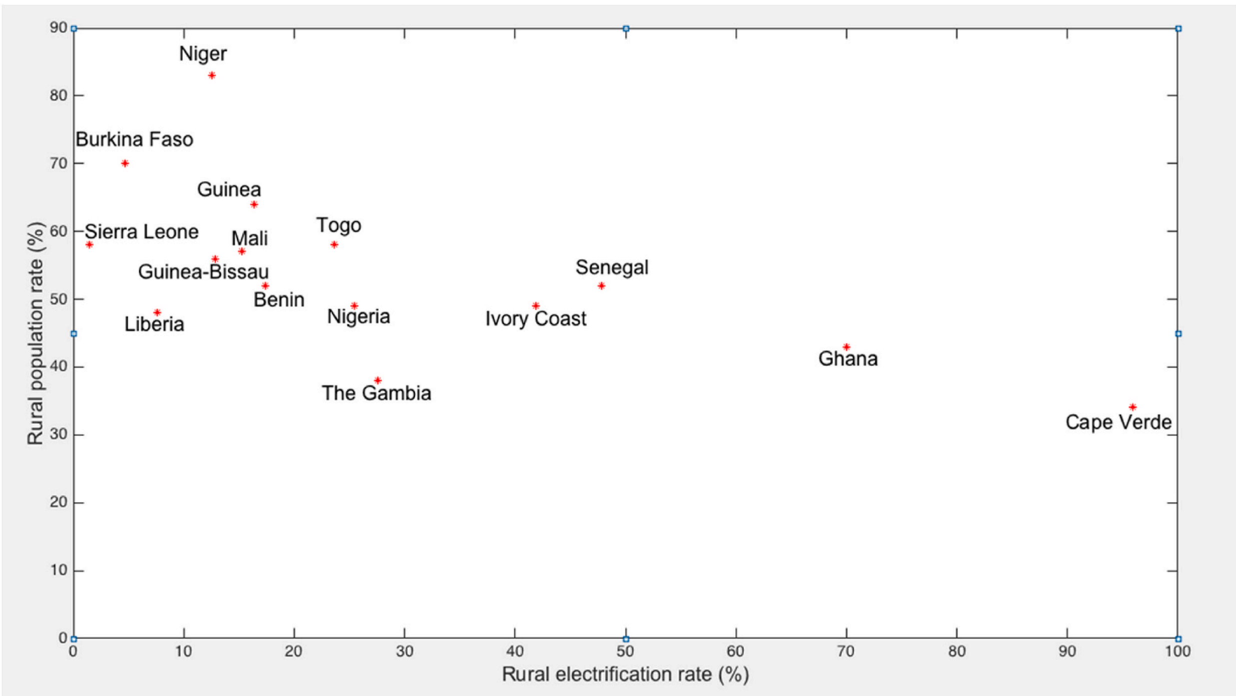

Fig. 1. Share of rural population against rural electrification rate. Source of data: Share of rural population [34], rural electrification rate [17].

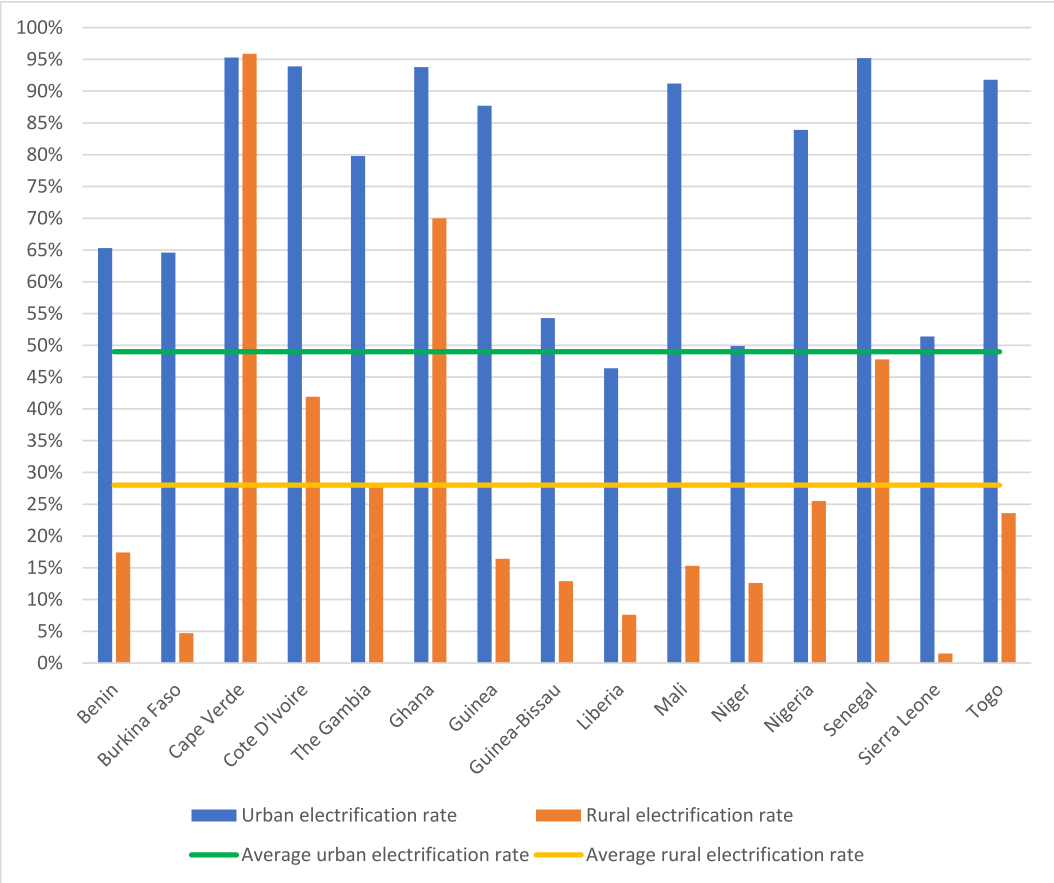

Fig. 2. Urban and rural electrification rates of WA countries. Source of data: Urban electrification rate [37], rural electrification rate [17].

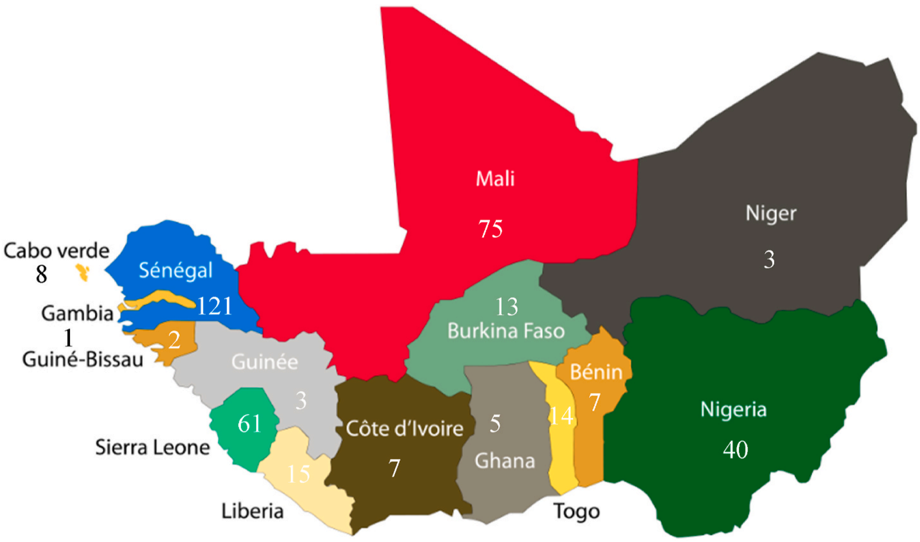

Fig. 3. *OGPS installed in WA countries* Source of data [50]:

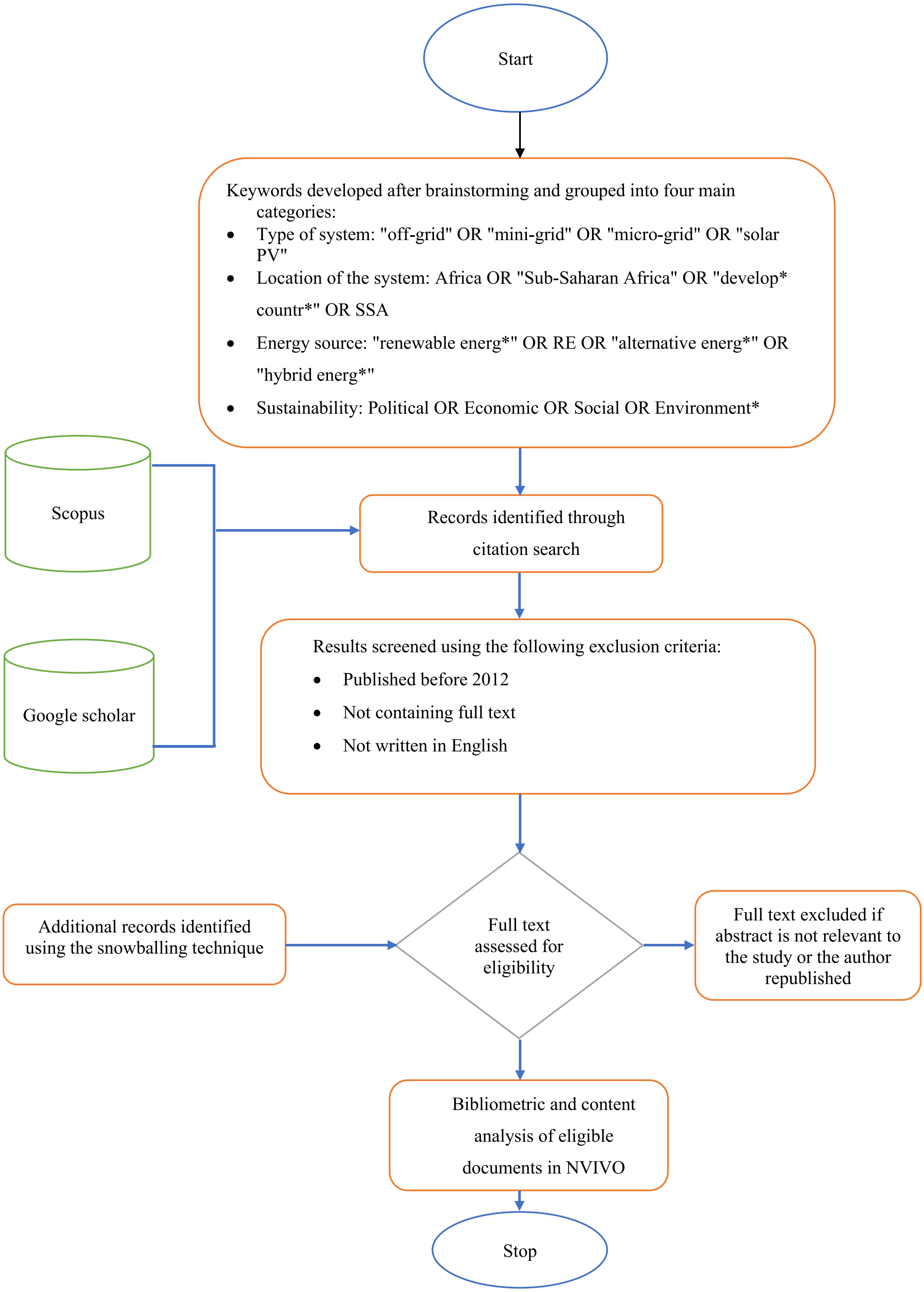

Fig. 4. Flowchart of the methodology adopted for the literature review.

2.2. Status of RE-based off-grid projects in WA

Using decentralized systems such as OGPS as a solution for remote area electrification has gained traction in developing countries in general and WA in particular [46]. A report by IRENA in 2019 showed that off-grid RE solutions expanded six-fold and positively impacted 133 million people globally during a six-year span (2011–2016) [47]. RE mini-grid deployment has accelerated since 2016, with the global market in 2018 exceeding US$ 200 billion annually [48]. According to a 2019 technical report by the World Bank's Energy Sector Management Assistance Program (ESMAP), at least 4000 mini-grids are installed across Africa. These mini-grids are either diesel-fuelled, hydro-powered, or solar photovoltaic-hybrid systems and were installed between 2014 and 2018 [49].

While East and South African countries have made significant strides in OGPS integration for rural electrification, WA nations lag in large-scale implementation. Fig. 3 shows the latest data on RE-based OGPS installed in WA by the end of 2020. There are 385 systems deployed in the region that produces a combined 36.6 MW of power using mainly PV (179) and hybrid PV-diesel (182) energy sources [50]. Further, the figure shows that over 50% of WA countries have less than 10 systems installed and only one country (Senegal) has more than 100 systems.

However, rural electrification initiatives are gradually changing the narrative and positively impacting RE development in WA. The government of Senegal established the Senegalese Rural Electrification Agency (ASER) to increase access to electricity in rural Senegal and reduce global GHGs. The government adopted a hybrid utility-private ownership model where the government owns the system and the private investor operates and maintains it [51]. Mali is another country in the region that has successfully implemented OGPS. A rural electrification fund was established in 2003 by the government to strengthen private sector involvement in the hybridization drive of diesel-based systems [51]. Installers who imported RE equipment were given tax breaks as a financial incentive.

International agencies have also sponsored off-grid mini-grid development in WA over the years. The Power Africa Off-grid Project (PAOP) was launched in November 2018 to accelerate off-grid electrification growth across SSA. Under the auspices of the United States Agency for International Development (USAID), this four-year project intends to provide support to private off-grid companies and create an enabling environment to boost investors' confidence in the SSA market [52]. The PAOP focuses on five countries in WA: Côte d'Ivoire, Ghana, Niger, Senegal and Liberia with varying degrees of support to the other ten countries [52]. Through the Ghana Energy Development and Access Project (GEDAP), part of the Lighting up Africa program, the World Bank sponsored a pilot project to install mini-grids in five communities along the Volta Lake in Ghana [6,53].

3. Methodology

This study adopted a qualitative method to conduct the literature review on OGPS implementation in WA and a quantitative approach to conduct a short survey of a specific community mini-grid in Ghana.

3.1. Literature review

Many articles have been published on the challenges of implementing RE-based OGPS in remote and rural areas of developing countries and the factors that drive the planning of such systems. The authors reviewed documents from relevant articles, conference proceedings, dissertations and books. These documents were identified and screened using the methodology shown in Fig. 4. Firstly, search terms (see Fig. 4) were identified by a brainstorming session with the research group. Since they have very high coverage, Scopus and Google Scholar were used as the primary sources of bibliometric data. Research sources included journal articles and

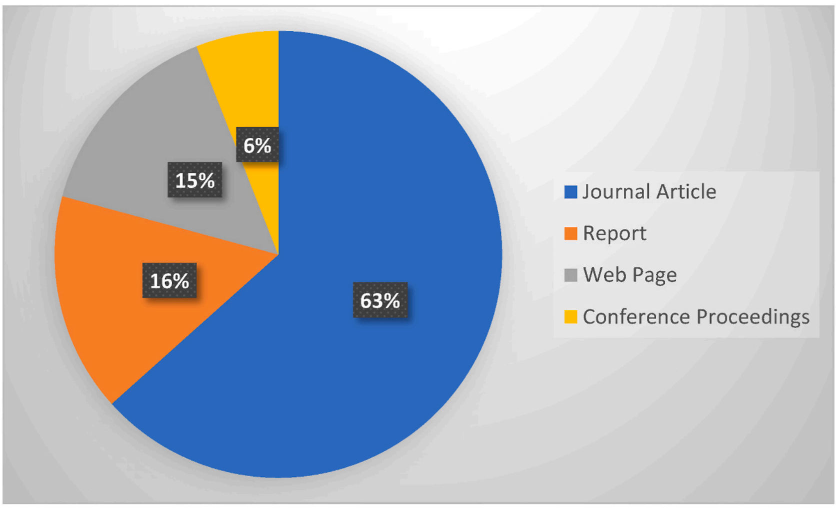

Fig. 5. Distribution of reference type included in the review.

reports from national and international organizations that have worked in this research field. Moreover, a snowballing technique was used to retrieve additional information.

Two levels of screening were performed to filter out unrelated documents. The first exclusion criteria limited the search to full text articles published in English from 2012 to 2022. Subsequently, once the articles were identified, the title and abstract were reviewed to include or exclude them in the study. Some studies have proven that keywords and abstracts can describe the content of the article but not in considerable detail; therefore, in some cases, the methods and conclusions were considered before including or excluding the articles.

The initial search retrieved 754 documents but applying the exclusion criteria and analysing the methods and conclusions in some instances reduced the number to 101 documents. As shown in Fig. 5, 63% of the 101 documents were journal articles, 16% were reports from national and international agencies, 15% were documents from web pages and 6% were conference papers. The NVIVO software was used to analyse the content of relevant documents into PESTLE themes related to the drivers and challenges of OGPS implementation in WA.

Fig. 6 shows the trend of publications in the last decade according to year and number. The figure shows that the total number of publications increased after 2019.

Using keyword clusters, the researchers also investigated common research trends in the data. The analysis depicted in Fig. 7 shows that most recent research centred on using the keyword 'renewable energy' for electricity generation. Rural development is also another area that is commonly researched. Among the RE sources, there were more studies into solar energy than wind energy and hybrid systems.

3.2. Survey

The authors were guided by the method used by Ref. [54] to conduct a short survey in Ghana. Using PESTLE challenges as indicators that hinder the growth of RE-based OGPS implementation in Ghana, key stakeholders conducted a pairwise comparison of the indicators. To ensure the objectivity of the results, fifty informants with diverse expertise (academia, government agency, RE consultant and private sector) were invited to evaluate the indicators by answering a questionnaire. Using Saaty's Analytical Hierarchy Process (AHP), comparison judgments of the respondents were converted to numerical values on a 1 to 9 scale (1 for equal hindrance and 9 for extremely strong hindrance) to reflect their strength of preferences.

Next, a pairwise comparison decision matrix was formulated using the geometric mean of the respondent's choices. Subsequently, the decision matrix was normalized to find the criteria weights. The final step involved calculating the consistency ratio (CR), the ratio between the consistency index (CI) and random index (RI), as shown in Equation (1).

$$CR = CI/RI \tag{1}$$

where $CI = (\lambda_{max} - n)/(n - 1)$, n = number of criteria, λ_{max} = maximum eigenvalue.

RI is a fixed value that depends on the number of criteria, n as shown in Table 1.

4. Results and analysis

This section presents the results of the literature review and survey. The results are presented according to the PESTLE framework. The drivers, challenges and success factors are analysed using the PESTLE criteria to help promote sustainable RE-based OGPS implementation in the future.

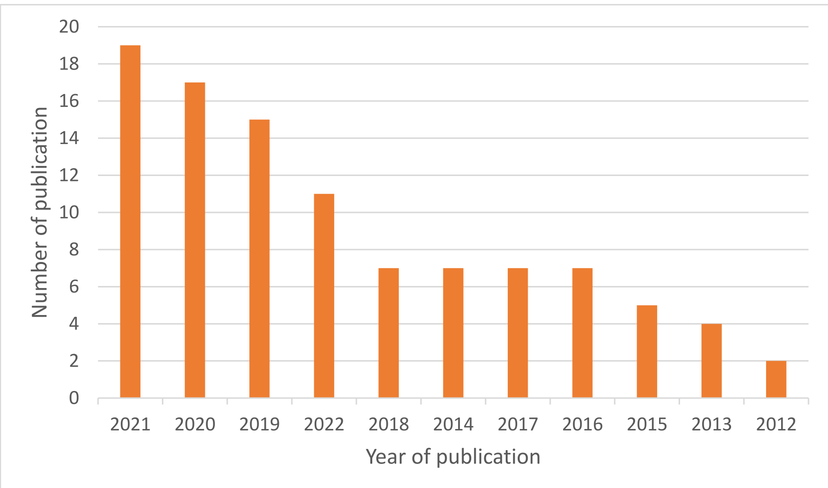

Fig. 6. Publication trends over the last decade

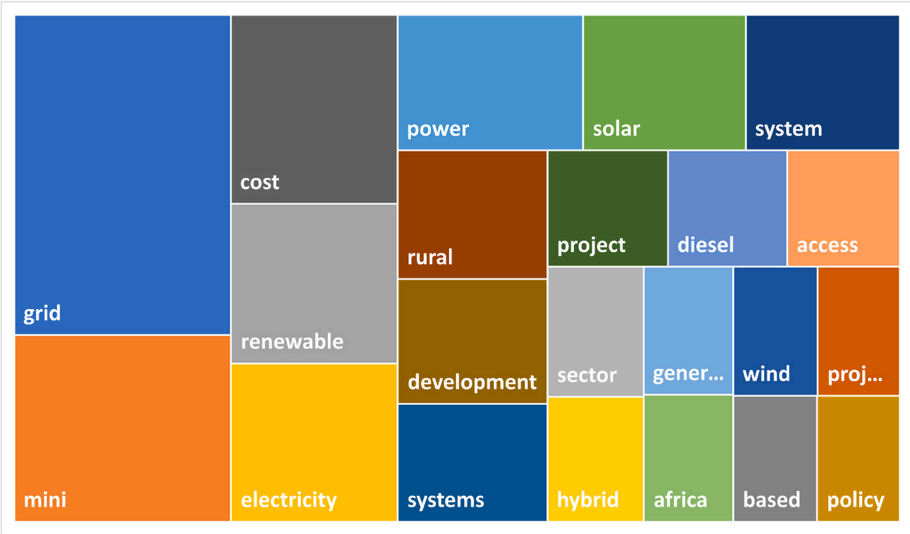

Fig. 7. Keyword cluster analysis

Table 1
Random index [55].

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.4

Country	Renewable energy targets	Feed-in-tariff	Electric utility quota obligation/RPS	Net metering	Tradable energy certificate
Benin	✓	✗	✗	✗	✗
Burkina Faso	✓	✗	✗	✗	✓
Cape Verde	✓	✗	✗	✓	✗
Cote d'Ivoire	✓	✗	✗	✗	✗
Gambia	✓	✗	✗	✗	✓
Ghana	✓	✓	✓	✗	✓
Guinea	✓	✗	✗	✗	✗
Guinea-Bissau	✓	✗	✗	✗	✗
Liberia	✓	✗	✗	✗	✗
Mali	✓	✗	✗	✗	✗
Niger	✓	✗	✗	✗	✗
Nigeria	✓	✓	✓	✗	✗
Senegal	✓	✓	✓	✓	✗
Sierra Leone	✓	✗	✗	✗	✗
Togo	✓	✗	✗	✗	✗

Fig. 8. Authors' own illustration of renewable energy targets and policies for WA countries, 2020. Source of data [58]:

4.1. Drivers and challenges of accelerating the deployment of RE-based OGPS projects in WA

Policy/Political.

When RE targets and policies are developed, they boost stakeholders' interest in investing in OGPS in rural communities. Decentralized mini-grids deployment took off in Liberia when the Renewable Energy Strategy and Master Plan was adopted. The Liberian government also adopted micro-utility regulations while in the process of finalizing tariff regulations [56]. These policy frameworks created an equal playing ground and attracted investors by applying cost-reflective tariffs and offering protection against grid creep.

Sierra Leone is another country in the region that has developed policies to promote the growth of RE for rural electrification. Financial institutions, donors and international organizations started showing confidence in investing in Sierra Leone after RE policies and regulations were aligned to create a conducive environment to invest in mini-grids [58]. The Sierra Leone Electricity and Water Regulatory Commission developed a comprehensive mini-grid regulation and enacted into law in 2019. The regulation simplified RE project requirements, reduced development costs and set principles for tariff determination [57].

As shown in Fig. 8, all fifteen WA states have RE targets, which is very laudable. The main challenge is the lack of targeted policies that create an enabling environment to invest in OGPS. From the figure, only Ghana, Senegal and Nigeria have feed-in-tariff policies, whilst net metering is adopted in only Cape Verde and Senegal. The importance of effective policies to foster the growth of the RE off-grid sector must be emphasized.

Akom et al. (2020) used the Long-range Energy Alternative Planning (LEAP) tool to develop an integrated energy planning framework for Ghana to address energy challenges, carbon dioxide reduction and RE sources utilization [59]. The study also analysed barriers to RE development in Ghana. The results showed that the barriers can be linked to the need for clearer policies in RE project implementation and regulation. They recommended a dedicated government agency solely responsible for RE development to streamline the various policies, create public awareness and propel RE development. Their conclusions were consistent with Atubuga and Tuokuu's study [60]. A case study conducted by Babatunde et al. (2019) revealed that it is essential to adopt an appropriate policy to ensure the successful implementation of off-grid hybrid RE systems in rural healthcare centres (RHC) in Nigeria [61]. They argued that though it is feasible to use RE sources to power RHC, adopting local policies that suit the ground's local conditions is key.

The political will to enforce existing policies and guidelines is another stumbling block identified in literature. Agyekum et al. (2021) used the PESTLE approach to examine the challenges and opportunities for developing RE in Ghana [55]. Using the AHP technique, experts ranked the various challenges that impact the growth of RE in the country. The results showed lack of enforcement of policies as the highest-ranked political challenge that hinder RE growth in Ghana. Lack of coordination among the various state agencies can be linked to why policies enacted are not enforced. Government agencies such as the tax department, port authorities, regulatory agencies, and utilities are involved in planning, implementing and monitoring RE OGPS projects. There are delays in project

Table 2
Literature on policy/political studies of RE-based OGPS in WA

Ref	Aim	Methods	Findings
Akom et al. [59]	Develop an integrated energy planning (IEP) framework for Ghana to promote renewable energy integration and energy efficiency. Analyse the various barriers to renewable energy development in Ghana.	Content analysis of issues, challenges of renewable energy integration. Use of LEAP for a case study: energy projection modelling from 2017 to 2050	Many of the barriers are manifested at the implementation phase. The overall results of this study propose 40% of non-conventional renewable energy resources into the country's energy mix, energy efficiency promotion in both demand and transmission, and the utilization of RES integration to save the nation up to about 40% CO_2 emissions reduction.
Atubuga & Tuokuu [60]	Critical appraisal of the renewable energy law in Ghana	Desktop review approach complemented with analysis of government policy documents	Institutional weakness, ambiguous regulatory frameworks, implementation challenges, lack of proper planning and coordination, and dependencies on donor support are responsible for the poor development of renewable energy in Ghana.
Agyekum et al. [55]	Examine opportunities and challenges to Ghana's renewable energy environment using PESTLE analysis	AHP used to rank the various indicators from 20 experts	Geographical location and availability of RE resources were ranked as the highest opportunity. High cost of capital and volatile foreign currency exchange rate contributed to 53% of challenges to RE development.
Akinyele et al. [62]	Comprehensively review microgrid technologies and their applications	Used the social, technical, economic and policy (STEEP) model to critically examine the failure factors with Nigeria as a case study.	Lack of adequate considerations for the enabling factors is the main reason microgrids fail in several off-grid communities.
Liu et al. [29]	Review of challenges, opportunities and applicability of microgrid technology for rural electrification with emphasis on Sub-Saharan Africa	Exploratory approach to find relevant literature on microgrids in SSA	SSA has made progress towards implementing RE-based microgrids but adequate support via policy and proper planning of project implementation is seen as the two major challenges.

execution due to inadequate coordination among these government agencies.

Meanwhile, Liu et al. maintain that politics contribute to the lack of enforcement of policies and the eventual failure of OGPS projects in the region [29]. According to them, progress for such projects is impacted when there is a change in government. There is a lack of political will to continue policies and projects started by the previous government [62]. New governments usually prioritize their policy agenda, which is often divergent from the previous government.

Political instability is another challenge that erodes the confidence in foreign companies investing in OGPS in WA. Between 2020 and 2021, three WA countries (Mali, Guinea and Burkina Faso) had their democratically elected leaders ousted through military takeovers [63]. Moreover, the president of Guinea-Bissau, in 2021, survived an attempted coup after armed assailants attempted to seize control of the country. These military actions can potentially destabilize the entire ECOWAS region and relegate long-term investments such as RE-based rural electrification to the background. Further, a SWOT analysis of Ghana's renewable energy developed by Agyekum (2020) showed that political stability is a major strength in boosting investors' confidence in the RE industry [64]. A summary of policy/political studies on implementing OGPS in WA is shown in Table 2.

Economic

Until recently, most rural communities in WA used diesel-based generators to meet power demands. However, due to global fossil fuel price fluctuations, the economic uncertainty has given investors a golden opportunity to turn to RE mini-grids for rural electrification. Moreover, since international donor agencies focus on providing funds for sustainable solutions, RE-based mini-grids have an advantage over fossil-based systems for rural electrification.

The availability of RE sources is another economic factor that can drive the successful implementation of OGPS in WA. Oyewo et al. (2019) investigated pathways toward a decarbonized WA from 2015 to 2050 using linear optimization modelling [65]. The results showed that a 100% solar PV-battery power system was the least-cost solution for the region and advocated for WA governments to prioritize solar PV in policy development. Adefarati et al. (2017), conducted an economic analysis of a PV-wind-battery standalone power system in a remote area and found that the scenario with the highest RE fraction had the least cost of electricity (COE) and net present cost [66]. Similarly [67], showed that RE fraction and COE are inversely proportional. Similar studies that support the conclusion that it makes economic sense to use RE for rural electrification in WA are in Refs. [10,66,68–72].

Despite these drivers, many economic challenges impact the successful implementation of OGPS projects. High capital expenditure (Capex) incurred in installing OGPS is one significant challenge to its promotion. The cost of the storage system is one main component that increases Capex. According to Ref. [73], energy storage can contribute up to 15% of Capex. Ochiegbu et al. [74] compared the life cycle cost and COE of a PV/Hydro/Battery to a PV/Hydro system. The results showed that the PV/Hydro/Battery system had a higher life cycle cost of USD 380,075 and COE (USD 0.13/kWh) than the PV/Hydro system.

High interest rate is another crucial economic challenge that influences the financial viability of OGPS projects in WA. Using Levelized Cost of Energy (LCOE) and Net Present Cost (NPC) metrics in HOMER, Agyekum and Nutakor (2020) conducted a techno-economic feasibility of PV/Wind/DG/Battery and Wind/DG/Battery hybrid power plants in Mankwadze, southern Ghana [75]. The modelling resulted in an LCOE of 0.382 $/kWh and NPC of US $8,649,054 for the PV/Wind/DG/Battery system, while the Wind/DG/Battery system showed a LCOE of 0.396 $/kWh and an NPC of $8,966,700. In both scenarios, the LCOE was higher than the current cost of electricity generation from the grid. Further analysis showed that high interest rates in Ghana contributed significantly to the high values recorded.

However, a study by Ref. [76] in Gambia showed that generating electricity from RE hybrid systems at a cost below the national grid tariff is feasible. Again, Odou et al. used HOMER to model a PV/DG/Battery hybrid system for a rural community in Benin. The results showed a more cost-effective LCOE (USD 0.207/kWh) than the national grid tariff (USD 0.22/kWh) [77]. Table 3 compares LCOE from various studies among selective WA countries.

A common feature among these studies is that access to an efficient financial mechanism remains crucial in reducing the LCOE. Most mini-grid developers implement OGPS using debt financing but need help to secure equity or concession. Foreign companies and existing small-scale local companies can be supported with financial mechanisms such as capital subsidies, investment tax credits and rebates to leverage against high investment costs. Fig. 9 shows existing fiscal incentives and public financing policies for RE development in WA countries. It shows that apart from reductions in energy taxes, several countries lack the necessary financial incentives that create an enabling environment for investors.

Table 3
Summary on energy resources and their LCOE of different projects in WA countries

Project location	System configuration	LCOE ($/kWh)	Reference
Ekwe, Nigeria	PV/wind/diesel/battery	0.11	Oladigbolu et al. [78]
Upper West Region, Ghana	PV/Biodiesel	0.76	Adaramola et al. [79]
Pissila, Burkina Faso	Hybrid PV/Diesel	0.5	Ouedraogo et al. [80]
Mankwadze, Ghana	PV/Wind/Diesel/battery	0.39	Agyekum & Nutakor [75]
Ondo state, Nigeria	Wind/PV/Diesel	0.58–0.68	Adaramola, M [81].
Fouay, Benin	PV/Diesel/Battery	0.21	Odou et al. [77]
Ala-Ajagbusi, Nigeria	Wind/diesel/battery	0.37	Ayodele, T [82].
Kaduna state, Nigeria	PV/Diesel/battery	0.49	Sofimieari et al. [83]
Coastline communities, Nigeria	PV/Wind/Diesel	0.79	Diemuodeke et al. [84]

Country	Reductions in sales, energy, CO2, VAT or other taxes	Investment or production tax credits	Energy production payment	Public investment, loans, grants, capital subsidie or rebates
Benin	✗	✗	✗	✗
Burkina Faso	✓	✓	✓	✗
Cape Verde	✗	✓	✓	✗
Cote d'Ivoire	✓	✗	✗	✗
Gambia	✓	✗	✗	✗
Ghana	✓	✗	✗	✓
Guinea	✓	✗	✗	✗
Guinea-Bissau	✗	✗	✗	✗
Liberia	✓	✗	✗	✗
Mali	✗	✗	✗	✓
Niger	✓	✗	✗	✗
Nigeria	✓	✗	✗	✓
Senegal	✓	✗	✗	✗
Sierra Leone	✗	✗	✗	✗
Togo	✓	✗	✗	✗

Fig. 9. Authors' own illustration of RE fiscal incentives and public financing policies for WA countries, 2020. Source of data [58]:

Pahwa (2016) claimed that most developing countries use the top-down approach to implement OGPS projects [85]. Whilst there are merits to this approach, the private sector is needed to build on the momentum gathered by OGPS development in WA. However, pricing directly hinders the sustainability of such projects significantly. At the second International Off-grid Renewable Energy Conference held in 2014 in Accra, developing a commercially viable business model in situations where grid electrification is significantly subsidized was identified as a key condition [86].

Using Ghana as a typical example, consumers connected to the national grid in urban cities enjoy the uniform national tariff (UNT), which is heavily subsidized [87]. With no subsidies, rural communities served with mini-grids operated by private investors would have to pay a higher tariff than the UNT to make it profitable, which is a social injustice. The results of a feasibility study by Arranz-Piera et al. (2018) to generate electricity using local agricultural residues in rural Ghana supports the earlier assertion [88]. The study showed that it is not profitable for an entrepreneur to self-fund such a project.

The success of OGPS in rural WA is impacted by low electricity demand and consumers' inability to pay. Residents in rural communities usually engage in subsistence farming to sustain their family. A small portion of the community receives income by cultivating cash crops. However, the proceeds are seasonal and it is difficult to acquire money during off seasons to pay for electricity [89]. A workable ownership model is pivotal in ensuring profitability in this uncertain revenue generation scenario. The choice

Table 4
Ownership models for OGPS development. Source: [18,53,87,90–92].

Ownership Model	Description	Major advantage	Major disadvantage	Country dominant in
Utility-based	Design, procurement and construction by a state-owned agency and handed over to a state utility	Customers have low tariffs	Highly reliant on cross-subsidies	Ghana, Senegal, Niger
Private Sector	All aspects of establishing a mini-grid system are overseen by a private sector operator	Less reliant on subsidies	Require higher, cost-reflective tariffs	Niger, Nigeria, Sierra Leone, Mali, Senegal, Cape Verde
Community-based	The mini-grid is owned, operated and managed by local cooperative groups.	Community buy-in	Technical and managerial barriers	Cote D'Ivoire Liberia, Sierra Leone, Cape Verde
Hybrid	Integrates the first three models. Ownership, generation and distribution is normally shared among government companies and private firms whiles the community organizations remain in charge of daily operations	Financial security due to shared responsibilities	Conflicts over long-term responsibility	Sierra Leone, Senegal, Cape Verde

depends on local socio-economic settings and the availability of a regulatory framework in the country. Several literature classify the ownership models into four main categories, as shown in Table 4 [18,53,87,90–92].

The utility-based model is the most prevalent in WA because state-owned utilities can provide quality services at lower tariffs [87]. However, lower tariffs can only be achieved with some form of subsidy. For instance Ref. [89], found that supplying electricity to consumers at the UNT requires a 60% subsidy from the government to enable a 15% profitability for the supplier. In the private sector model, a private operator oversees the system's design, procurement, installation and operation. This approach is gaining prominence in the region but charging cost-reflective tariffs is a hindrance.

The hybrid model uses the Public-Private-Partnership (PPP) approach based on short- and long-term concessions and leases. This model requires roles and responsibilities to be clearly defined from the onset to avoid disputes in the future. The community-based ownership model is applied where public and private sector participation is unavailable. This model has a high acceptance rate since the community members are the system's owners. Capacity building is required to improve the technical and managerial skills needed to operate and maintain the systems.

Socio-cultural

The willingness of residents in rural WA to participate in the implementation of OGPS projects is a crucial driver. The ambition to improve their living standards by having access to quality education, healthcare, and communication is an unflinching driver. Apart from using it for domestic purposes, the possibility of productive use of electricity to make some income arouses residents' interest. Babalola et al. (2022) attempted to find evidence of how electricity from mini-grids influenced productive activities. They used descriptive statistics to assess the impact of an 85 kW solar hybrid mini-grid on the socio-economic growth of a remote village in Nigeria [93]. The results showed that the mini-grid brought innovative businesses such as commercial electric motorcycles for transportation to the village.

T. van Gevelt et al. reported that Smart Villages Initiative organized consultation workshops in over 70 countries to identify the conditions necessary to provide electricity to rural communities [19]. The lack of end user participation in the planning of energy services was identified as a constraint by most participants. A comprehensive review of community participation in mini-grid projects worldwide by Ref. [94] supported the claim that community participation is vital to social sustainability. The review also showed that inclusion was dominant in the operations and maintenance phase but was least involved in the design phase. A study by Liu and Bah provided evidence from rural Sierra Leone to support the claim that community engagement is a catalyst for renewable energy based mini grids acceptance [95].

When the locals are not involved from the onset, it creates mistrust that may result in irreversible consequences. Firstly, the residents may reject the system with the notion that mini-grids will impede their connection to the central grid in the future, which they perceive to be a better option [96]. Secondly, ignoring the views of the community members often lead to costly mistakes in determining the load profile, resulting in issues with sizing. However, depending solely on the community's judgment of their needs may lead to future challenges. Lessons learned from a study in Senegal by Ref. [97] showed that estimating the electricity needs of the

Table 5
Literature on socio-cultural studies of RE-based OGPS in WA

Ref	Aim	Methods	Findings
Babalola et al. [93]	Investigates the impact of a solar hybrid mini-grid on the socio-economic growth of local entrepreneurs in Gbamu village in Nigeria.	83 micro and small-scale enterprises were surveyed and paired sample *t*-test and chi-squared test were used to assess the performance.	1. Higher number of female entrepreneurs than males 2. The presence of the mini-grid has led to innovative businesses. 3. Vast majority of businesses has swapped fossil-fuelled generators for the mini-grid system.
Van Gevelt et al. [19]	Identify and analyse the challenges to energy access for rural development.	Organized consultation workshops to gather the views of frontline workers, entrepreneurs, NGOs, policy makers, finance community and international experts in science, engineering and social science.	1. Lack of end user participation in energy services planning a major huddle. 2. Achieving energy access for rural development requires smart villages to be a norm not an exception.
Liu & Bah [95]	Investigate the mediating role of the community during mini-grid projects implementation in Sierra Leone	Through a survey, beneficiaries were asked to assess the impact mini-grid services have on their daily life against their expectations. A simple mediation model was used with renewable energy potential and poverty reduction as independent and dependent variables respectively.	1. Community engagement in mini-grid projects partially mediates the impact of RE on poverty reduction. 2. Lack of commercial loads poses a major challenged to rural electrification
Almeshqab & Ustun [97]	Review rural electrification initiatives in eight developing countries including Senegal	Case study review of rural electrification initiatives in Kaolack, Fatick and Thies regions in Senegal	1. Government reforms of the energy sector are desirable. 2. Instead of basing on the community judgments, better ways are needed to estimate their demand

community by solely basing on the customers judgment of their needs can lead to demand challenges in future. Most consumers tend to purchase more appliances in the future.

The misconception can be tackled by disseminating information; however, the educational gap threatens effective communication. In addition, the lack of education makes it difficult to train these residents to acquire the needed skills to operate and manage the systems [55]. Ayodele et al. [98] studied the factors that affected the willingness of rural Nigerians to pay for electricity produced from RE. Analysis of responses from 400 participants showed that their level of education had a positive correlation with their willingness to pay.

IRENA (2017) developed a mini-grid project guide for small islands to address project uncertainties and challenges [99]. It identified developing a comprehensive financial model as a crucial stage during project planning. However, for this model to succeed, the society setting must be considered. Regional level solutions are needed to ensure sustainable OGPS growth in WA.

Nuru et al. attempted to identify the socio-technical barriers to solar mini-grid deployment in rural Ghana by conducting semi-structured interviews, focus group discussions and direct observation of key community members in three island communities [100]. The study showed the following as critical social barriers:

i. Land disputes
ii. Non-involvement of indigenes
iii. Poor knowledge of solar mini-grid systems
iv. Dishonesty with estimates during load assessment
v. Illegal connections
vi. Dispersed rural settlements.

Table 5 summarises relevant socio-cultural studies carried out on RE-based OGPS in WA.

Technical

The emergence of advanced techniques for designing and producing of RE components have made the development of RE-based OGPS projects cost-competitive. IRENA reported in 2018 that since 2009, there had been an 80% fall in solar PV prices while solar PV costs have declined by 73% [47]. Through research and development, mini-grid technologies ranging from component efficiency, storage capabilities, monitoring and metering have improved drastically. Pay-*as*-you-go metering using cell phones and smart grids for remote, real-time monitoring are some of the advances in the field. Emerging batteries store more electricity and discharge at a lower rate than prevalent lead acid batteries [101]. It offers an adequate solution for sparsely populated, low demand areas, which are characteristics of rural WA.

However, technical challenges to implementing OGPS in WA need attention. Abdullahi et al., investigated the barriers to solar energy initiatives in Nigeria by seeking the views of 25 key stakeholders [102]. All the interviewees asserted that inadequate technology and infrastructure is a major barrier hindering the sector. Furthermore, another technical challenge is a lack of technical know-how of local content to install and maintain solar PV in the country. Akinyele et al. [62] used the social, technical, economic, environmental and political (STEEP) model to discuss the challenges to microgrids in remote communities in Nigeria in a case study. Their findings were consistent with Mahama et al.'s study [103] in Ghana. They identified that substandard materials and scarcity of local skilled practitioners are major challenges affecting the industry.

In addition, the need for monitoring systems and poor project supervision was identified as technical challenges. Williams et al. [89] noted that the remoteness of certain villages creates a logistic hurdle in transporting spare parts on time to perform regular maintenance. Ikejemba et al. investigated why RE projects failed in SSA with Ghana and Nigeria part of the six countries studied [104]. Maintenance of the projects after their implementation was identified as one critical challenge. The researchers observed that all the projects inspected neither had a maintenance plan nor monitoring systems installed to check the system performance. One participating project developer opined that the challenge of proper maintenance was due to the selection of incompetent organizations to implement, manage and maintain the RE projects.

Legal

Well-laid regulatory guidelines act as a catalyst in propelling the growth of OGPS in developing countries. Asante et al. used the Multi-Objective Optimization based on Ratio Analysis (MULTIMOORA) integrated with the Evaluation based on Distance from Average Solution (EDAS) method to rank barriers to RE development in Ghana [105]. Among the six categories adopted, regulatory barriers ranked the highest. The study also found that RE standards and simplification of certification procedures are required to promote the growth of RE development in Ghana. The work by Ref. [102] revealed that the lack of standard and quality control is a major constraint to developing solar energy projects in Nigeria. They claimed the Nigeria solar market is flooded with substandard components eroding the trust in promoters.

The absence of a coherent regulatory framework, particularly for off-grid mini-grids, that spells out technical design specifications, tariff settings and standards hampers private sector participation. As mentioned earlier, several WA countries have RE policies and targets. However, there are no specific regulations for mini-grid development in their electrification plans [106]. Tariff schemes ranging from flat-rate pricing, load-based to electricity services-based [1] are adopted, but invariably, private operators are not allowed to charge more than the UNT. This rigid, politically motivated policy directly impacts private developers' revenue margins making it challenging to recover operational cost, let alone capital costs [96]. Williams et al. also support the claim that lack of regulatory independence is sometimes due to political pressure to maintain affordability [89].

In addition, when complex and bureaucratic hurdles undermine license and permit applications, investors lose interest in investing in the region. Apart from delays in obtaining licenses and permits, the cost implication deters investors. A report by IRENA in 2016 indicated that licenses and permit costs alone sometimes exceed 10% of a project's capital cost. However, as a general guideline, it should not exceed 1–2% of the total cost of a project [107]. A report by Ref. [108] indicates that, as of 2019, though private companies in Senegal could finance, own and operate mini-grids, they have yet to successfully negotiate through the licensing process.

Obeng-Darko, in dissecting why Ghana will not achieve its renewable energy target for electricity, reasoned that though there is a Renewable Energy Act (Act 832), the non-existent of a renewable energy authority with the requisite independent legal power to implement RE policies and projects is a major impediment [109]. The lack of an explicit regulation or policy on the arrival of the central grid at OGPS sites is another pressing challenge in some parts of WA that make investors contemplate investing in the sector [110].

Environmental

The call for action by world bodies such as the Intergovernmental Panel on Climate Change (IPCC) to mitigate the threat of climate change is well documented. However, considering the Covid-19 pandemic and its associated economic impact, WA countries must adopt economically feasible practices to combat climate change. If a country's electricity production continues to be from fossil-fuelled energy sources, that country is choosing to emit GHGs [111] and ignore climate change science. To continue the path of environmental sustainability and create a resilient power system while progressing with rural electrification requires the use of RE-based mini-grids.

OGPS is suitable for high population density areas where households in a cluster are connected to the system in a ring layout. However, rural areas in WA are characterized by sparsely populated settlements and sometimes treacherous terrain. The financial implication is evident since the overall cost of installing such projects is impacted by transportation costs [112]. Moreover, land use change is another challenge that affects the smooth implementation of RE microgrids in WA. As mentioned earlier, most residents are peasant farmers who cultivate farm produce and fish. It is problematic when arable land suitable for agriculture is used to grow jatropha for biodiesel or PV panel installations.

Stinder et al. assessed the environmental performance of a mini-grid in Tema, Ghana using the Life Cycle Assessment method. The results indicated that the mini-grid system had a lower emissions factor, 0.055 $kgCO_2eq/kWh$ than emission factors of the central grid (0.46 $kgCO_2eq/kWh$) and a diesel generator (1.65 $kgCO_2eq/kWh$) [113]. However, they did not consider emissions due to the transmission and distribution of electricity to the users in their calculations. Geographically and demographically, rural settlements in

Table 6
Summary of drivers and challenges impacting the successful implementation of RE-based OGPS in WA

Category	Drivers	Challenges/Barriers
Political	Poverty mitigation ambitions	Inadequate long-term electrification strategy
	Universal electricity access ambitions	Corruption and nepotism
	Election campaign promises	Lack of coordination among government agencies
		Project abandonment due to change of government
Economic	Cost-competitiveness	High upfront capital cost
	Skills development	Low return on investment/Unsteady revenue generation
	Donor support	Lack of long-term subsidies/funds
	Fluctuations in oil prices	Currency stability risk/currency fluctuations
		Inadequate incentives
		Small market size
Social	Community empowerment	Poor community involvement at the planning stage/Neglect of user's inputs during planning
	Local job creation	Deficiencies in human resource to operate and manage the systems
	Increase in local demand	Social acceptance
	Public awareness	Ethnic or language barrier
		Education gap
Technological	High cost of grid extension	No monitoring and advanced communication infrastructures
	Increased performance of mini grid technologies	Fluctuating resource supply
	Proven Technology solutions	Components incompatible with location conditions
		Operation & Maintenance issues
Legal	Existence of policies and targets for RE development	Absence of coherent regulations
	Existence of regulatory bodies	Complex and bureaucratic licensing procedures
	No human right violations	Inadequate institutional capacity
		Unworkable tariff
		Lack of technical standards
		Lack of grid creep protection policy
Environmental	Environmental sustainability target	Geographical constraints/Rough terrain
	Climate resilience	Lack of energy resource map
	Concern for GHG emissions	Scattered population
		Land use change issues

WA are scattered and located in terrains (islands, hilly areas) that are difficult to navigate and far from the central grid. For instance, 40% of households in Niger are located greater than 20 km from the grid [114].

Summary of drivers and challenges

Table 6 shows the summary of drivers and challenges that impact the successful implementation of RE-based OGPS in WA after the review.

4.2. Findings of a short survey in Ghana

Out of the 50 expert stakeholders targeted, 41 (82%) returned the filled questionnaire. However, one questionnaire was incorrectly filled and therefore rejected. The AHP analysis resulted in weights assigned by the expert stakeholders, as shown in Fig. 10.

The results indicate that economic and political challenges are by far the most impactful, whiles environmental challenges have the most negligible impact on OGPS implementation in Ghana. Interestingly, government agencies (policy makers) think the legal challenges have the least impediment to the development of OGPS. Another interesting observation is the views of academia on economic challenges. The graph shows that nearly 38% of the respondents think economic challenges have the worst impact on OGPS development in Ghana, with political challenges coming at a distant second. A further analysis shown in Fig. 11 indicates that apart from RE company stakeholders (private sector), the remaining stakeholders agreed on economic challenges being the worst impediment to implementing sustainable OGPS in Ghana.

5. Discussion on increasing energy access through renewable energy-based off-grid projects in WA

In using PESTLE to dissect the drivers and challenges in implementing RE-based OGPS for rural electrification in WA, the study found that access to input RE sources is not an issue since the region has adequate RE potential to meet demand.

However, confronting the complex synergies in achieving 100% rural electrification in WA by 2030 requires total commitment from central governments. Two of the primary measures that need to be in place are national targets backed with short-term and long-term policies. Targeted policies are a merely documented piece of paper if strategies are not formulated alongside to ensure proper implementation, coordination, and monitoring. Furthermore, relevant technical stakeholders must be consulted when the strategies are developed to ensure they are effective and practicable.

The review showed that economic/financial challenges pose the greatest threat to the successful implementation of OGPS. This finding is supported by the findings from the case study where the stakeholders rated economic challenges as the worst hindrance to OGPS development. The results, however, contradicts the findings of a similar case study by Ref. [6] where political barrier came ahead of economic barriers. The disparity may be linked to two world events, namely, the COVID-19 pandemic and the Russian-Ukraine war. Although the effects are felt worldwide, it is most profound in Africa and has made it difficult to assess the international market to finance energy projects. When analysing the results, it was apparent that high interest and CAPEX contributed the most to the cost of installing RE-based OGPS.

To counter the effects, prudent strategies must be implemented to cushion the burden on future energy projects. The study showed that the storage system makes up about 15% of the CAPEX; therefore, more import duty subsidies will lessen the burden. Capital subsidy is another strategy that can be adopted to alleviate the plights of the private sector during these uncertain times. Evidence from the study (see Fig. 8) shows that only Nigeria, Mali and Ghana have public investment, capital subsidy, loans and grants policies in place. The other countries can use these similar strategies or rebates to augment expenditure.

The empirical findings from the study verified that the involvement of the community in project ownership has a positive impact on the success of projects and are in fact cheaper than utility owned systems. However, due to inadequate technical know-how of the community-based cooperatives to efficiently maintain and manage the system, the government must invest in them by organizing training workshops designed to improve the technical skills of members of the cooperative groups. Skills acquired will propagate their employability especially among the youth and women.

The technical analysis revealed that improved technological advancement in storage devices has driven down the cost of RE-based OGPS. However, the technical know-how of residents needs to improve. Tackling this challenge should be holistic by updating the curricula for technical education in these countries to be research-based and include more practical lessons on current technologies. To remain current, academics should be continuously exposed to new trends and innovations to be at pace with the industry.

The study revealed that incoherent regulations and licensing regimes are stumbling blocks to OGPS development in WA. One way to facilitate this is establishing a clearance facility hosted at a government agency. As indicated by Ref. [107], the existence of a one-stop agency that coordinates stakeholders, manages the approval process, facilitates capacity building and administers financial incentive schemes for rural off-grid electrifications can streamline the process and lower transaction costs considerably. Our analysis also identified the lack of local standards as a factor in using incompatible components in OGPS projects in the region. With similar climatic conditions, WA countries can collaborate to formulate and adopt a single standard. This standard should include codes for installation, operation, maintenance and monitoring.

The lack of reliable data such as documented lessons, resource mapping and open source quality data on OGPS in WA impacts on energy planning [115]. Our analysis showed that environmental constraints such as rough terrain and scattered settlements in rural WA are detrimental to the successful implementation of OGPS.

In summary, the PESTLE analysis revealed patterns and linkages among the challenges, making it detrimental to focus solely on the

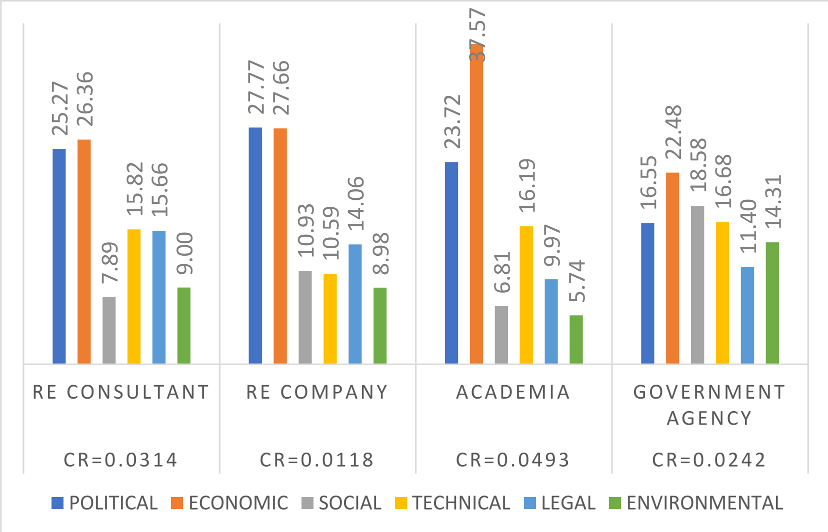

Fig. 10. Percentage distribution of weights of challenges by expert stakeholders

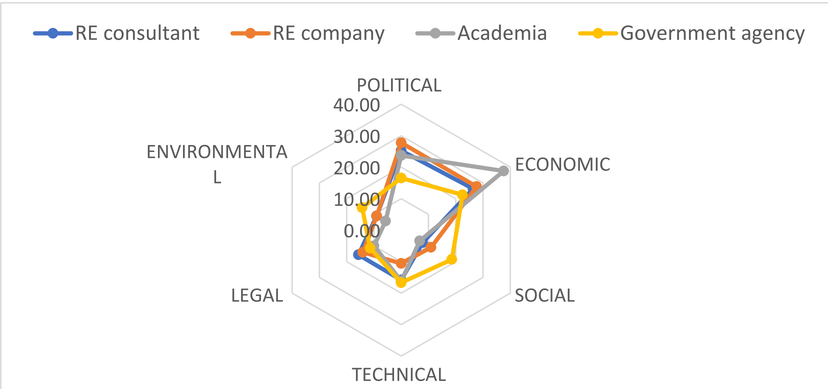

Fig. 11. Radar view of weights of indicators by expert stakeholders

most pressing challenges. For instance, solving the social acceptance challenge has a knock-on effect of increasing the demand size and boosting revenue collection. In another example, a legal issue of unworkable tariffs can be linked to an economic issue of low return on investment. The examples demonstrate that harnessing RE sources for off-grid applications needs all conditions under PESTLE (shown in Fig. 12) to be in place to overcome the challenges and build a robust OGPS.

6. Conclusion and recommendations

Using the PESTLE approach, this study attempted to identify the drivers and challenges of off-grid RE project implementation in WA. The PESTLE approach was used to tackle the macro-environment conditions holistically. The review showed that the status of RE-based OGPS projects and resource potential in WA provides a unique opportunity to expand the sector since access to electricity in the rural areas is low but has a high resource potential. In the sphere of PESTLE, there are driving forces under each category to propel the agenda to meet intended targets.

The literature review and case study analysis revealed that overcoming economic challenges contributed the most to unsustainable OGPS projects and needs the most attention in WA. But an in-depth analysis of the articles reviewed shows that overcoming these challenges largely depends on implementing internal mechanisms to solve all the other challenges under PESTLE. The study was limited because only documents written in English were included in the review; hence most of the results were research from Anglophone countries in WA.

Overall, the outcome from the review demonstrates that sustainable implementation of RE-based OGPS for rural electrification in WA will be successful if:

1) policies that stimulate OGPS development are not generic but targeted.

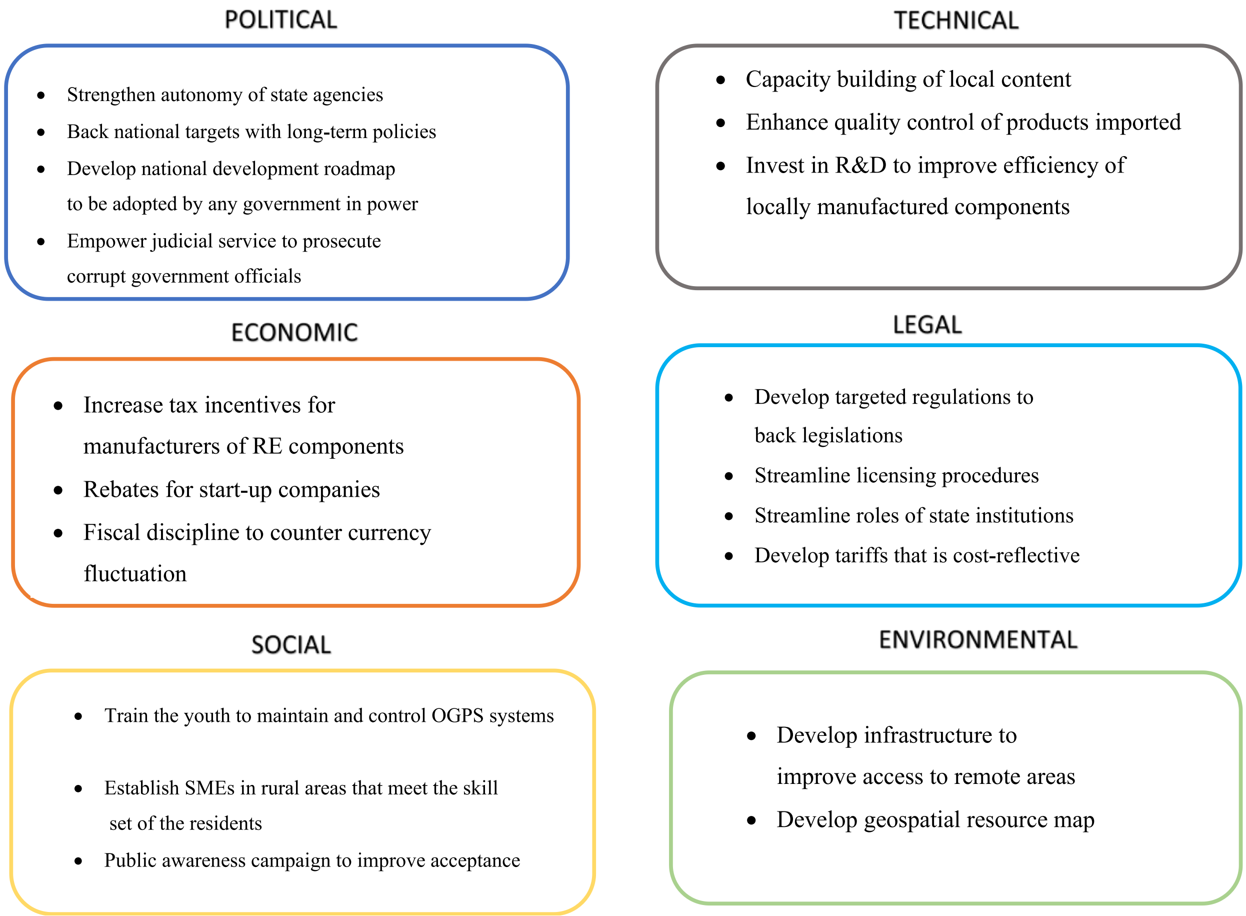

Fig. 12. Summary of factors needed for the successful implementation of OGPS in WA

2) policies are backed with specific regulations to create a strong foundation for market development.
3) prudent steps are taken to wean away from relying solely on external funding.
4) the consumers should be involved in the overall planning of the project.
5) the technology selections dwells on the local socio-cultural, economic and environmental settings.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

Data will be made available on request.

Declaration of competing interest

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

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References

[1] S.C. Bhattacharyya, D. Palit, A critical review of literature on the nexus between central grid and off-grid solutions for expanding access to electricity in Sub-Saharan Africa and South Asia, Renew. Sustain. Energy Rev. (2021) 141.
[2] L. Al-Ghussain, et al., 100% Renewable energy grid for rural electrification of remote areas: A case study in Jordan, Energies (18) (2020) 13.
[3] IEA, Defining energy access: 2020 methodology, Available from: https://www.iea.org/articles/defining-energy-access-2020-methodology, 2022. (Accessed 10 March 2022).
[4] UN, Sustainable development goals, Available from: https://sdgs.un.org/goals/goal7, 2022. (Accessed 10 March 2022).
[5] J.F. Alfaro, S.A. Miller, Analysis of electrification strategies for rural renewable electrification in developing countries using agent-based models, Energy Sustain. Dev. 61 (2021) 89–103.
[6] D. Bukari, et al., Towards accelerating the deployment of decentralised renewable energy mini-grids in Ghana: review and analysis of barriers, Renew. Sustain. Energy Rev. (2021) 135.
[7] C. Mazur, et al., A holistic resilience framework development for rural power systems in emerging economies, Appl. Energy 235 (2019) 219–232.
[8] D.G. Fullerton, N. Bruce, S.B. Gordon, Indoor air pollution from biomass fuel smoke is a major health concern in the developing world, Trans. R. Soc. Trop. Med. Hyg. 102 (9) (2008) 843–851.
[9] M. Kanagawa, T. Nakata, Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries, Energy Pol. 36 (6) (2008) 2016–2029.
[10] O.M. Babatunde, et al., Hybrid power system for off-grid communities: techno-economic and energy mix analysis, in: 2017 IEEE 3rd International Conference on Electro-Technology for National Development (NIGERCON), 2017.
[11] S. Chakravarty, M. Tavoni, Energy poverty alleviation and climate change mitigation: is there a trade off? Energy Econ. 40 (2013) 567–573.
[12] A.I.M. Iskanderani, et al., Analyzing the off-grid Performance of the hybrid photovoltaic/diesel energy System for a Peripheral village, Int. J. Photoenergy (2020) 2020.
[13] D. Palit, A. Chaurey, Off-grid rural electrification experiences from South Asia: Status and best practices, Energy Sustain. Dev. 15 (3) (2011) 266–276.
[14] International Energy Agency, SDG7: data and projections, Available from: https://www.iea.org/reports/sdg7-data-and-projections, 2021. (Accessed 29 April 2021).
[15] The World Bank, Tracking SDG 7: the energy progress report, Available from: https://trackingsdg7.esmap.org/, 2021. (Accessed 20 March 2022).
[16] The World Bank, Access to Electricity (% of population), Available from: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?end=2019&locations=ZG&name_desc=false&start=1960, 2022. (Accessed 3 April 2022).
[17] The World Bank, Access to electricity, rural (Sub-Saharan Africa), Available from: https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS?end=2018&locations=ZG&start=2018&type=shaded&view=map&year=2018, 2022. (Accessed 3 April 2022).
[18] E.L. Hobson, Mapping and assessment of existing clean energy mini-grid experiences in West Africa, ECOWAS Centre for Renewable Energy and Energy Efficiency (2016).
[19] T. van Gevelt, et al., Achieving universal energy access and rural development through smart villages, Energy Sustain. Dev. 43 (2018) 139–142.
[20] X.S. Musonye, et al., Integrated energy systems' modeling studies for sub-Saharan Africa: A scoping review, Renewable Sustain. Energy Rev. 128 (2020) 109915.
[21] B. Mainali, S. Silveira, Alternative pathways for providing access to electricity in developing countries, Renew. Energy 57 (2013) 299–310.
[22] N.U. Blum, R. Sryantoro Wakeling, T.S. Schmidt, Rural electrification through village grids—assessing the cost competitiveness of isolated renewable energy technologies in Indonesia, Renew. Sustain. Energy Rev. 22 (2013) 482–496.
[23] O.M. Longe, F.I. Oluwajobi, F. Omowole, Electricity access in Sub-Saharan Africa — case for renewable energy sources microgrid, in: 2013 IEEE International Conference on Emerging & Sustainable Technologies for Power & ICT in a Developing Society (NIGERCON), 2013.
[24] B. Ugwoke, et al., Demonstration of the integrated rural energy planning framework for sustainable energy development in low-income countries: Case studies of rural communities in Nigeria, Renew. Sustain. Energy Rev. (2021) 144.
[25] T. Prabatha, et al., Analyzing energy options for small-scale off-grid communities: a Canadian case study, J. Clean. Prod. (2020) 249.
[26] IRENA, Quality infrastructure for smart mini-grids, International renewable energy agency, Abu Dhabi (2020).
[27] Y. Mekonnen, A.I. Sarwat, Renewable energy supported microgrid in rural electrification of Sub-Saharan Africa, 2017 IEEE PES PowerAfrica (2017).
[28] R. Kempener, et al., Off-grid Renewable Systems: Status and Mehtodological Issues, Available from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_Off-grid_Renewable_Systems_WP_2015.pdf, 2015. (Accessed 15 March 2022).
[29] Q. Liu, K.M. Kamoto, X. Liu, Microgrids-as-a-service for rural electrification in sub-Saharan Africa, Comput. Mater. Continua 63 (3) (2020) 1249–1261.
[30] R. Ghotge, et al., A Global Analysis on Microgrids Through the PESTEL Framework, Institute of Electrical and Electronics Engineers Inc, 2020.
[31] C. Zalengera, et al., Overview of the Malawi energy situation and A PESTLE analysis for sustainable development of renewable energy, Renew. Sustain. Energy Rev. 38 (2014) 335–347.
[32] P.J.M. Thomas, et al., A PESTLE analysis of solar home systems in refugee camps in Rwanda, Renew. Sustain. Energy Rev. 143 (2021) 110872.
[33] R. Puliti, Putting Africa on the path to universal electriicty access (2022).
[34] The World Bank, cited 2022, Rural population (% of total population) (2022). Available from: https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?end=2019&locations=ZG&name_desc=false&start=1960. (Accessed 4 April 2022).
[35] Africa Energy Portal, Regional profile-West Africa, Available from: https://africa-energy-portal.org/region/west-africa, 2022. (Accessed 19 August 2022).
[36] Y. Zhou, et al., A comprehensive view of global potential for hydro-generated electricity, Energy Environ. Sci. 8 (9) (2015) 2622–2633.
[37] The World Bank, Access to electricity, urban (Sub Saharan Africa), Available from: https://data.worldbank.org/indicator/EG.ELC.ACCS.UR.ZS?end=2018&locations=ZG&start=2018&type=shaded&view=map&year=2018, 2022. (Accessed 4 April 2022).
[38] J.M. Aberilla, et al., Design and environmental sustainability assessment of small-scale off-grid energy systems for remote rural communities, Appl. Energy (2020) 258.
[39] P.K. Ainah, K.A. Folly, Development of micro-grid in sub-Saharan Africa: An overview, Int. Rev. Electr. Eng. 10 (5) (2015) 633–645.
[40] J. Morrissey, Achieving universal electricity access at the lowest cost: A comparison of published model results, Energy Sustain. Dev. 53 (2019) 81–96.
[41] A. Aliyu, N. Tekbiyik-Ersoy, A novel framework for cost optimization of renewable energy installations: A case study of Nigeria, Energies (22) (2019) 12.
[42] R. Baños, et al., Optimization methods applied to renewable and sustainable energy: A review, Renew. Sustain. Energy Rev. 15 (4) (2011) 1753–1766.
[43] O. Hafez, K. Bhattacharya, U.N.Y. Brookhaven National Lab, Optimal planning and design of a renewable energy based supply system for microgrids, Renew. Energy 45 (2012) 7–15.
[44] IRENA, Planning and prospects for renewable power: West Africa, Int. Renew. Energy Agency Abu Dhabi (2018).
[45] The World Bank, Solar resource maps of SSA, 2020.
[46] S.J.D. Schillebeeckx, et al., An integrated framework for rural electrification: adopting a user-centric approach to business model development, Energy Pol. 48 (2012) 687–697.
[47] International Renewable Energy Agency, Off-grid renewable energy solutions to expand electricity access: an opportunity not be missed, Abu Dhabi (2019).
[48] University of Strathclyde and Community Energy Malawi, Renewable Energy Mini-Grids in Malawi - Status, Barriers and Opportunities, 2018.
[49] ESMAP, Mini grids for half a billion people market outlook and handbook for decision makers executive summary, Washington DC (2019).
[50] F. Antonanzas-Torres, J. Antonanzas, J. Blanco-Fernandez, State-of-the-Art of mini Grids for rural Electrification in West Africa, Energies 14 (4) (2021) 990.
[51] E.I. Come Zebra, et al., A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries, Renew. Sustain. Energy Rev. (2021) 144.
[52] USAID, Off-grid solar market assessment-Ghana (power Africa off-grid project), Available from: https://www.usaid.gov/sites/default/files/documents/1860/PAOP-Ghana-MarketAssessment-Final_508.pdf, 2019. (Accessed 15 June 2021).

[53] Trama TecnoAmbiental, Design, Supply, Installation, Operation and Management of Mini-Grid Electrification for Selected Island Communities in Ghana, 2018.
[54] M. Tsangas, et al., The application of analytical hierarchy process in combination with Pestel-SWOT analysis to assess the hydrocarbons sector in Cyprus, Energies (5) (2019) 12.
[55] E.B. Agyekum, et al., A bird's eye view of Ghana's renewable energy sector environment: a Multi-Criteria Decision-Making approach, Util. Pol. (2021) 70.
[56] USAID, Off-grid solar market assessment (Washington), Liberia (Power Africa Off-grid Project) (2020).
[57] A. Mostafaeipour, et al., Wind energy feasibility study for city of Shahrbabak in Iran, Renew. Sustain. Energy Rev. 15 (6) (2011) 2545–2556.
[58] REN21, Renewables, Global Status Report. 2021 (2021).
[59] K. Akom, et al., Energy framework and policy direction guidelines, Ghana 2017–2050 Perspectives. IEEE Access 8 (2020) 152851–152869.
[60] R.A. Atuguba, F.X.D. Tuokuu, Ghana's renewable energy agenda, Legislative Drafting in Search of Policy Paralysis. Energy Research and Social Science (2020) 64.
[61] O.M. Babatunde, et al., Off-grid hybrid renewable energy system for rural healthcare centers: a case study in Nigeria, Energy Sci. Eng. 7 (3) (2019) 676–693.
[62] D. Akinyele, J. Belikov, Y. Levron, Challenges of microgrids in remote communities: a STEEP model application, Energies (2) (2018) 11.
[63] Aljazeera, ECOWAS holds emergency summit after coups in West Africa, Available from: https://www.aljazeera.com/news/2022/2/3/ecowas-emergency-summit-coups-west-africa, 2021. (Accessed 11 April 2022).
[64] E.B. Agyekum, Energy poverty in energy rich Ghana: a SWOT analytical approach for the development of Ghana's renewable energy, Sustain. Energy Technol. Assessments (2020) 40.
[65] A.S. Oyewo, et al., Transition towards decarbonised power systems and its socio-economic impacts in West Africa, Renew. Energy 154 (2020) 1092–1112.
[66] T. Adefarati, R.C. Bansal, J.J. Justo, Techno-economic analysis of a PV–wind–battery–diesel standalone power system in a remote area, J. Eng. 2017 (13) (2017) 740–744.
[67] S.O. Oyedepo, et al., Assessment of decentralized electricity production from hybrid renewable energy sources for sustainable energy development in Nigeria, Open Eng. 9 (1) (2019) 72–89.
[68] S.O. Babalola, M.O. Daramola, S.A. Iwarere, Socio-economic impacts of energy access through off-grid systems in rural communities: a case study of southwest Nigeria. Philosophical Transactions of the Royal Society A, Math. Phys. Eng. Sci. (2221) (2022) 380.
[69] U. Deichmann, et al., The economics of renewable energy expansion in rural Sub-Saharan Africa, Energy Pol. 39 (1) (2011) 215–227.
[70] W. Arowolo, et al., Seeking workable solutions to the electrification challenge in Nigeria: minigrid, reverse auctions and institutional adaptation, Energy Strategy Rev. 23 (2019) 114–141.
[71] A.A. Masud, The application of homer optimization software to investigate the prospects of hybrid renewable energy system in rural communities of sokoto in Nigeria, Int. J. Electr. Comput. Eng. 7 (2) (2017) 596.
[72] H. Abid, et al., Energy storage integration with solar PV for increased electricity access: a case study of Burkina Faso, Energy (2021) 230.
[73] F. Antonanzas-Torres, J. Antonanzas, J. Blanco-Fernandez, State-of-the-Art of mini Grids for rural Electrification in West Africa, Energies (4) (2021) 14.
[74] C.V. Ochiegbu, S. Gyamfi, E. Ofosu, Modeling, Simulation and Design of Hydro-Solar Isolated Micro-grid without a Battery Storage System: A Case Study for Aba Business Cluster, Nigeria. (2022).
[75] E.B. Agyekum, C. Nutakor, Feasibility study and economic analysis of stand-alone hybrid energy system for southern Ghana, Sustain. Energy Technol. Assessments 39 (2020) 100695.
[76] Frankfurt School and UNEP, Renewable Energy in hybrid mini-grids and isolated grids (FS-UNEP: Frankfurt), Economic benefits and business cases (2015).
[77] O.D.T. Odou, R. Bhandari, R. Adamou, Hybrid off-grid renewable power system for sustainable rural electrification in Benin, Renew. Energy 145 (2020) 1266–1279.
[78] J.O. Oladigbolu, M.A.M. Ramli, Y.A. Al-Turki, Feasibility study and comparative analysis of hybrid renewable power system for off-grid rural electrification in a typical remote village located in Nigeria, IEEE Access 8 (2020) 171643–171663.
[79] M.S. Adaramola, et al., Multipurpose renewable energy resources based hybrid energy system for remote community in northern Ghana, Sustain. Energy Technol. Assessments 22 (2017) 161–170.
[80] B.I. Ouedraogo, et al., Incentives for rural off grid electrification in Burkina Faso using LCOE, Renew. Energy 78 (2015) 573–582.
[81] M.S. Adaramola, Feasibility study of off-grid hybrid energy systems for applications in Ondo state Nigeria. Journal of Engineering and Applied Sciences 7 (1) (2012) 72–78.
[82] T.R. Ayodele, Feasibility study of stand-alone hybrid energy system for rural electrification in Nigeria: the case study of Ala-Ajagbusi community, Int. J. Renew. Energy Resour. 4 (1) (2014) 1–12.
[83] I. Sofimieari, M.W.B. Mustafa, F. Obite, Modelling and analysis of a PV/wind/diesel hybrid standalone Microgrid for rural electrification in Nigeria, Bulletin of Electrical Engineering and Informatics 8 (4) (2019) 1468–1477.
[84] E.O. Diemuodeke, S. Hamilton, A. Addo, Multi-criteria assessment of hybrid renewable energy systems for Nigeria's coastline communities, Energy, Sustainability and Society (1) (2016) 6.
[85] A. Pahwa, Partnerships to facilitate electricity access for the remote rural communities of sub-Sahara Africa, 2016 IEEE PES PowerAfrica (2016).
[86] IRENA, Accelerating off-grid renewable energy: key findings and recommendations, in: 2nd International Off-Grid Renewable Energy Conference, IOREC, Accra, 2014.
[87] ESMAP, Ghana, Mini-grids for Last Mile Electrification- Exploring Regulatory and Business Models (2016).
[88] P. Arranz-Piera, et al., Mini-grid electricity service based on local agricultural residues: feasibility study in rural Ghana, Energy 153 (2018) 443–454.
[89] N.J. Williams, et al., Enabling private sector investment in microgrid-based rural electrification in developing countries: a review, Renew. Sustain. Energy Rev. 52 (2015) 1268–1281.
[90] L. Odarno, et al., Accelerating mini-grid deployment in Sub-Saharan Africa-Lessons from Tanzania (2014). Available from: https://documents1.worldbank.org/curated/en/532751512396163620/pdf/WP-acceleratingminigriddeploymentsubsaharanafrica-PUBLIC.pdf. (Accessed 27 July 2021).
[91] A. Pedersen, Deconstructing the concept of renewable enegy-based mini-grids for rural electrification in East Africa, WIREs Energy Environ 5 (2016) 570–587.
[92] R. Berahab, Thinking outside the Grid: the role of decentralized power systems in electrifying Sub Saharan Africa, Policy brief (2019).
[93] S.O. Babalola, M.O. Daramola, S.A. Iwarere, Socio-economic impacts of energy access through off-grid systems in rural communities: a case study of southwest Nigeria. Philosophical transactions. Series A, Math. Phys. Eng. Sci. 380 (2221) (2022) 20210140.
[94] A. Gill-Wiehl, et al., Beyond customer acquisition: a comprehensive review of community participation in mini grid projects, Renewable and Sustainable Energy Reviews (2022) 153.
[95] Y. Liu, Z. Bah, Enabling development impact of solar mini-grids through the community engagement: evidence from rural Sierra Leone, Energy Pol. (2021) 154.
[96] J. Peters, M. Sievert, M.A. Toman, Rural electrification through mini-grids: challenges ahead, Energy Pol. 132 (2019) 27–31.
[97] F. Almeshqab, T.S. Ustun, Lessons learned from rural electrification initiatives in developing countries: insights for technical, social, financial and public policy aspects, Renew. Sustain. Energy Rev. 102 (2019) 35–53.
[98] T.R. Ayodele, et al., Willingness to pay for green electricity derived from renewable energy sources in Nigeria, Renew. Sustain. Energy Rev. (2021) 148.
[99] IRENA, Mini-Grid Project Guide Developed for Small Islands, Available from: https://irena.org/newsroom/articles/2017/Sep/Mini-grid-project-guide-developed-for-small-islands, 2017. (Accessed 21 April 2022).
[100] J.T. Nuru, J.L. Rhoades, J.S. Gruber, The socio-technical barriers and strategies for overcoming the barriers to deploying solar mini-grids in rural islands: evidence from Ghana, Technol. Soc. (2021) 65.
[101] USAID, Mini-grids emerging technologies, Available from: https://www.usaid.gov/energy/mini-grids/emerging-tech, 2021. (Accessed 23 September 2021).
[102] D. Abdullahi, et al., Barriers for implementing solar energy initiatives in Nigeria: an empirical study, Smart and Sustainable Built Environment (2021).
[103] M. Mahama, N.S.A. Derkyi, C.M. Nwabue, Challenges of renewable energy development and deployment in Ghana: perspectives from developers, Geojournal 86 (3) (2020) 1425–1439.

[104] E.C.X. Ikejemba, et al., Failures & generic recommendations towards the sustainable management of renewable energy projects in Sub-Saharan Africa (Part 2 of 2), Renew. Energy 113 (2017) 639–647.
[105] D. Asante, et al., Exploring the barriers to renewable energy adoption utilising MULTIMOORA- EDAS method, Energy Pol. 142 (2020) 1.
[106] EEP Africa, Opportunities and Challenges in the Mini-Grid Sector in Africa, 2018.
[107] IRENA, Policies and regulations for private sector renewable energy mini-grids, International Renewable Energy Agency, Abu Dhabi, 2016.
[108] USAID, Off-grid solar market assessment-Senegal (Power Africa Off-grid Project), 2019.
[109] N.A. Obeng-Darko, Why Ghana will not achieve its renewable energy target for electricity. Policy, legal and regulatory implications, Energy Policy 128 (2019) 75.
[110] J. Alfaro, S. Miller, Satisfying the rural residential demand in Liberia with decentralized renewable energy schemes, Renew. Sustain. Energy Rev. 30 (2014) 903–911.
[111] Y.S. Mohammed, M.W. Mustafa, N. Bashir, Hybrid renewable energy systems for off-grid electric power: review of substantial issues, Renew. Sustain. Energy Rev. 35 (2014) 527–539.
[112] A.S. Duran, F.G. Sahinyazan, An analysis of renewable mini-grid projects for rural electrification, Soc. Econ. Plann. Sci. (2021) 77.
[113] A.K. Stinder, et al., A generic GHG-LCA model of a smart mini grid for decision making using the example of the Don Bosco mini grid in Tema, Ghana. Procedia CIRP 105 (2022) 776–781.
[114] USAID, Off-grid solar market assessment- Niger (Power Africa Off-grid Project), 2019.
[115] M. Moner-Girona, et al., Electrification of Sub-Saharan Africa through PV/hybrid mini-grids: Reducing the gap between current business models and on-site experience, Renew. Sustain. Energy Rev. 91 (2018) 1148–1161.