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Towards a renewables-based future for West African States: A review of power systems planning approaches

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ABSTRACT

West African countries face a long-standing energy access issue stemming from historical low generation capacity, poor planning processes and financially-constrained power utilities. Within current frameworks, progress towards achieving universal access to electricity is slow. However, the region displays a huge endowment of renewables which clearly appear to be paramount to expanding electricity generation capacity and meeting an ever-rising demand. The clear evidence of the crescent role of utility-scale expansion of renewables-based generation has called for collective action in the region to improve electricity access and drive economic growth. Therefore, research on the design and implementation of a renewables-based future for West Africa is needed. However, the literature on electricity planning considering the use of renewables in West Africa is scarce and mostly limited to least-cost and/or low-resolution modeling. Through an exploratory approach, the present study contributes to enhancing current knowledge by capturing the essence of the existing literature on generation capacity expansion modeling approaches and critically analyzing their shortcomings to define potential improvement avenues for future research. Advancing academic knowledge in such direction would provide sound scientific evidence to key national and regional stakeholders in order to take a step closer towards building a resilient future for West African countries.

1. Introduction

In the words of Ban Ki-moon, Former United Nations Secretary-General, “Energy is the golden thread that connects economic growth, increased social equity, and an environment that allows the world to thrive" [1], thus describing the central role of access to energy services. Moreover, for any society, electricity is the main energy carrier, hence instrumental in sustaining people’s lives. Yet, as of 2016 over one billion people were lacking access to electricity services, *ca.* 55% of which were living in sub-Saharan Africa (SSA) [2]. The Economic Community of West African States (ECOWAS) displays some of the lowest electrification rates with high disparities among countries [2]. Most of the countries face long-standing generation capacity deficits with technical and financial constraints rendering grid expansion difficult and expensive [3,4]. It is expected that electricity demand in West Africa will significantly increase in the coming decades [5], however, total demand levels will remain too low to justify large investments in electricity infrastructure improvement and grid expansion [4]. Several studies report that regional grid expansion through interconnections could help reduce upfront capital and operating costs and improve system reliability [6,7].

The decision of establishing the West African Power Pool (WAPP) was formalized in 1999, and seven years later, WAPP was assigned the status of Specialized Institution of ECOWAS [17]. However, the ultimate goal of creating a fully-functioning regional electricity market in West Africa through WAPP is yet to be reached. Furthermore, countries are characterized by heavy reliance on imported fuels subject to global prices and supply fluctuations, despite a large endowment of renewable energy (RE) sources [10,11]. Nonetheless, the past few years have seen a rising drive for RE deployment at both country and regional levels, owing to concerns over security of supply and climate change effects.

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Nomenclature

AHP	Analytical Hierarchy Process
CAPP	Central African Power Pool
CGE	Computable General Equilibrium
DRC	Democratic Republic of Congo
DSS	Decision Support Systems
EAPP	Eastern African Power Pool
ECOWAS	Economic Community of West African States
ECREEE	ECOWAS Centre for Renewable Energy and Energy Efficiency
EFOM	Energy Flow Optimization Model
ELECTRE	Elimination and Choice Translating Reality
EREP	ECOWAS Renewable Energy Policy
FIT	Feed-in Tariff
GDP	Gross Domestic Product
GIS	Geographic Information System
GHG	Greenhouse Gas
HOMER	Hybrid Optimization Model for Electric Renewables
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IO	Input-Output
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Electricity
LEAP	Long-range Energy Alternatives Planning System
MARKAL	MARKet Allocation
MAUT	Multi-attribute Utility Theory
MCDM	Multi-criteria Decision-Making
MESSAGE	Model of Energy Supply Systems and their General Environmental Impacts
MILP	Mixed Integer Linear Program
MOO	Multi-objective optimization
MW	Megawatt
NGO	Non-Governmental Organization
NPV	Net Present Value
OECD	Organization for Economic Co-operation and Development
OSeMOSYS	Open Source Energy Modeling System
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PV	Photovoltaic
RE	Renewable energy
SAGE	South African General Equilibrium
SAPP	Southern African Power Pool
SHS	Solar Home System
SPLAT- W	System Planning Test model for Western Africa
SSA	Sub-Saharan Africa
T&D	Transmission and Distribution
TIMES	The Integrated MARKAL-EFOM System
WASP	Wien Automatic System Package
WAPP	West African Power Pool

This region-wide awareness has culminated into the ECOWAS Renewable Energy Policy (EREP). It is, therefore, expected that RE projects will be critical to bridging the region's capacity deficit [12]. This appears necessary and urgent as hydropower generation fluctuations will likely be compounded by increased seasonal variations in the coming decades due to climate change [13].

It has been highlighted that a major challenge to scaling up electrification in West Africa arises from poor planning processes due to lack of resources, and inadequate methodologies and objectives [3,14]. This is especially true with RE [15]. Compounding this issue is the scarcity of scholarly studies aimed at better recognizing the extent to which RE sources can be used to solve the issue of sustainable electricity access, particularly from a regional perspective. As reflected in Ref. [16] whereby a well-documented classification of energy planning techniques was proposed, there are several reviews on energy planning for SSA. Nonetheless, no review specific to generation capacity expansion modeling for West Africa seems to be available. Moreover, in the few instances where planning exercises were performed, they did not always translate into implementable steps. Therefore, the key contributions of this paper for West Africa are two-fold: (i) drawing attention to the status and shortfalls of the existing body of literature on capacity expansion modeling considering RE and; (ii) addressing critical gaps to the practical implementation of RE-based planning models.

The remainder of this paper is organized as follows. Section 2 presents the results of the literature review. Section 3 discusses the review outcomes. The conclusions are set out in Section 4, highlighting the contributions of this paper and suggesting avenues for future work.

2. Outcomes of the literature review

2.1. The electricity landscape of West Africa

ECOWAS consists of fifteen (15) independent states: Benin, Burkina Faso, Cape Verde, Cote d'Ivoire, the Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo (Fig. 1). All countries, except for the archipelago of Cape Verde, have their electric utilities members of the WAPP [17]. Only four countries hold electrification rates higher than 60%.

Table 1 provides an overview of the status of the electricity sector of the region. Sources of RE-based electricity include solar, wind, biofuels and waste. Electricity consumption figures cover domestic gross production and imports, and exclude exports and losses. The data was retrieved from Ref. [19] for Côte d'Ivoire and [20] for all other countries. The figures for national electrification rates should be carefully interpreted since even in countries with high rates, service reliability is an important issue with a significant number of power outages [21]. According to the latest surveys, the number of power outages in a typical month is on a rising trend with 3.5 in Côte d'Ivoire and 4.2 in Mali in 2016, 22 in Niger in 2017 and 32.8 in Nigeria in 2014 [22]. These power outages generated economic losses of 4.9% and 8.8% of firms' annual sales in Côte d'Ivoire and Mali and 5.5% in Niger [23].

Over the past few years, national economies have grown at high rates, reaching 6% in Burkina Faso, Senegal, Sierra Leone and 8% in Côte d'Ivoire [24]. This trend is set to continue and a similar or higher growth rate is expected for electricity demand [25]. Hence, determining the future mix of electricity generation is critical and should consider the adverse effects of climate change. Most countries are heavily dependent on costly fossil-fueled electricity generation, and the overwhelming majority import these fuels, thus are significantly exposed to global price fluctuations. Consequently, electricity prices are either excessively high or highly subsidized to allow for affordable access. The latter is the most common in West Africa where the electricity sectors are vertically integrated, therefore putting a strain on national budgets, limiting adequate investment in infrastructure maintenance and capacity expansion, and inhibiting RE deployment [15]. Currently, the electricity mix of the region is dominated by thermal generation from oil- and gas-fired power plants, and large-scale hydropower generation (Table 1). The contribution of renewable sources such as solar and wind energy remains marginal, and in most cases, limited to a few stand-alone systems and mini-grid installations in rural areas [26]. Paradoxically, these countries are endowed with some of the highest, yet untapped, RE potentials, particularly solar and wind (Table A-1, Appendix A). Yet,

Fig. 1. Political map of West Africa (Source: [18]).

Table 1
Summary of the status of ECOWAS electricity sectors.

Country	National electrification rate [2]	Electricity consumption (GWh) [19,20]	Net imports (GWh) [20]	Share of electricity production by fuel [20,21]		
				Thermal	Hydro	RE
Benin	32%	1149	1088	Diesel, gas: 98.2%	0%	1.8%
Burkina Faso	20%	1168	423	Diesel: 94.6%	5.4%	0%
Côte d'Ivoire	62%	5800	−1858	Gas: 82.5%	14.6%	2.9%
The Gambia	48%	149	0	Diesel: 98.1%	0%	1.9%
Ghana	84%	8416	−324	Gas: 57%	42.8%	0.2%
Guinea	20%	257	0	Diesel: 44.7%	55.7%	0.6%
Guinea-Bissau	13%	75	0	Diesel: 98.1%	0%	1.9%
Liberia	12%	73	0	Diesel: 100%	0%	0%
Mali	41%	3059	663	Diesel, gas: 64.4%	32.9%	2.7%
Niger	11%	975	779	Diesel, steam coal, gas: 99%	0%	1%
Nigeria	61%	25,308	0	Gas, steam gas: 81.7%	18%	0.3%
Senegal	64%	3734	297	Diesel, steam heavy fuel oil, gas: 90.5%	7.9%	1.6%
Sierra Leone	9%	133	0	Diesel: 43.4%	53.7%	2.9%
Togo	35%	1248	1140	Diesel, gas: 8.2%	83.2%	8.6%

countries display different levels of commitment to RE (Table 2) and their integration into the electricity mix lack from some policy documents.

The initial WAPP Master Plan envisaged natural gas and hydropower to be the core sources of the regional electricity mix [27]. However, its revision in 2011 coincided with the 2006–2008 energy crisis, unexpected lower rainfalls [28], and political and social instability in the Niger Delta [29]. Hence, the subsequently revised Master Plans promote a diversified portfolio of energy sources for electricity generation, including non-hydro renewables [27,30]. Following the 2006–2008 energy crisis, the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) was created in 2010. It is linked with a national focus entity in each member country and promotes the development of renewable energy, energy efficiency and national capacity-building [12]. With the swift decline in technology costs, RE generation is becoming competitive with conventional generation [31], adding to the

Table 2
Levels of integration of RE into national policy documents, and existence of RE agencies and targets.

	Benin	Burkina Faso	Côte d'Ivoire	The Gambia	Ghana	Guinea	Guinea-Bissau	Liberia	Mali	Niger	Nigeria	Senegal	Sierra Leone	Togo
Energy policy	Yes	Yes	To some degree	Yes	Yes	Yes	To some degree	Yes	Yes	Yes	Yes	Yes	Yes	Yes
RE law	Yes	Yes	No or not available	Yes	Yes	No or not available	No or not available	No or not available	Yes	No or not available	No or not available	Yes	To some degree	Yes
RE policy	Yes	Yes	To some degree	Yes	Yes	To some degree	To some degree	Yes	To some degree	To some degree	Yes	Yes	Yes	Yes
RE Agency	Yes	Yes	No or not available	Yes	Yes	No or not available	No or not available	Yes	Yes	Yes	Yes	Yes	To some degree	Yes
RE targets	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source: Own compilation from [15] *and a review of ministerial websites and national policy documents*

Legend: Yes; To some degree; In progress; No or not available

positive social and environmental impact yielded. Yet, there are potential issues from scaling up RE at national and regional levels due to their intermittent nature requiring flexibility of existing infrastructure and resource complementarity. This particularly holds a challenging truth for West Africa, being at a crossroads between their long-standing concerns about improving electricity access and the global drive for low-carbon economy. Balancing centralized and distributed generation is an added concern. Thus, fostering RE potential in these countries requires sound planning to spur the much-needed investments.

2.2. Centralized versus decentralized electrification

There is a low number of comparative studies on the roles of centralized and decentralized electrification, with most studies covering either one across technical, economic and environmental dimensions, and many studies discussing the success and failure stories of the actual implementation of both [32,33]. In West Africa, electrification processes are by default pursued via a centralized approach, i.e. the construction of large-scale power plants and the extension of transmission and distribution lines [4]. At the exceptions of Ghana, Senegal and Côte d'Ivoire, this approach has been slow and most of the population still lack access to electricity, either because they live far from the grid or because grid connection costs are unaffordable [14]. This segment mostly lives in rural areas, where the low population densities coupled with low levels of demand and high incidence of poverty render grid expansion technically unsound and financially unfeasible [12]. Furthermore, grid-connected areas experience unreliable services due to insufficient generation capacity and capacity reserves to meet a fast-growing demand [14].

State-owned utilities in most countries are financially-constrained [4] and grid expansion is capital-intensive, especially with the sparse population distribution. Due to the aging transmission infrastructure leading to huge losses, further generation capacity expansion requires transmission lines improvement/reinforcement [3,28]. Furthermore, grid expansion projects are supported by international donor organizations, led by the World Bank, as well as the American Government through the Power Africa initiative, the European Union, and the Organization for Economic Co-operation and Development (OECD) among others [34]. As for off-grid electrification, Non-Governmental Organizations (NGOs) and the private sector have emerged as the most important drivers [35]. Private-owned companies are becoming active players since off-grid electrification has gained increased commercial attractiveness with the development of new local business models. The successful off-grid electrification experiences of Kenya, for instance, are being adapted for replication in other SSA countries [14,36]. A key success factor in Kenya has been the introduction of innovative payment models combined with Information and Communication Technologies to reduce the relatively high initial investment cost for lower income/poor(er) households [36], as well as the deployment of community-based mini-grids [37]. Notwithstanding, in many instances, off-grid PV solutions remain costly due to excessively high tariffs, poor business models and low access to financing [36]. It is also worth mentioning the lack of mainstreaming of productive uses of electricity in off-grid electrification initiatives, without which the target of spurring local economic growth cannot be achieved [38,39]. Although there is evidence that access to electricity improves rural communities' lives, electricity on its own cannot create substantial local economic growth. It has been widely suggested that integrating productive uses of electricity into electrification programs may be the solution to achieving universal electricity access in SSA while driving socio-economic development [40]. Indeed, electricity use is two-fold: consumptive and productive. The ultimate goal of electricity for productive uses is economic growth by enhancing activities such as micro-irrigation, water pumping and agro-processing whereas promoting electricity for consumptive use is for human development by providing access to basic lighting services and mobile phone charging [40]. While a large proportion of rural communities in West Africa relies on crop farming or pastoralism, much of the attention has been on off-grid solar PV for lighting, entertainment and vaccine refrigeration purposes. An illustrative example is the donor-funded solar/wind/diesel micro-grid in Olosho Oibor, a Kenyan village which main economic activity is livestock farming. The micro-grid provides electricity to public facilities (school, church and clinic), small businesses and a few households [41]. In this case, off-grid electrification serves consumptive needs and other small activities. In pastoralist communities, enhancing local economies would require complementary inputs such as the availability of adequate facilities for dairy products processing, the capacity to compete in regional and international markets, and the ability to adapt to longer drought periods caused by climate change.

Even though off-grid solutions require lower initial cost investment and allow reaching non-electrified areas more quickly than the grid, their implementation costs remain prohibitive, particularly for local mini-grid companies [34,42]. With the rapidly falling costs of solar PV costs, these constraints are bound to significantly reduce [31]. Nonetheless, the need for energy storage in renewables-based mini-grids for optimized load management tends to increase electricity prices compared with existing grid tariffs [42], although battery costs are declining [43]. Another challenge of utility-scale renewables-based electricity generation is land availability which is subject to socio-cultural conditions [44], whereas political factors are applicable to both grid and off-grid electrification processes [35,45]. These factors include issues related to foreign direct investment, corruption and democracy [44–46]. In particular, cross-border interconnections and electricity trade are highly subject to the political environment of the countries involved. In the Central, Eastern, Southern, and West African Power Pools, political instability in some countries is one important issue accentuating national energy security concerns over regional electricity trade, hence the pursuit of electricity sovereignty [47].

On the whole, specific and common challenges exist at different levels for both grid and off-grid electrification approaches. Recent studies suggest that bridging the electricity gap in SSA necessitates a combination of grid expansion and off-grid solutions where extending the grid is not economically viable [3,14]. This is reflected in EREP, which makes provision for RE deployment through grid and off-grid applications to reach 100% access to electricity by 2030. Under financial constraints, countries have applied emergency investment decisions to meet unserved demand, resulting in investment in power plants with lower capital costs but higher operating costs [48]. This is furthermore demonstrated by Ref. [49] who found out that low-income SSA countries tend to resort to thermal generation from fossil-fuels rather than exploiting their untapped RE potential. Therefore, generation expansion planning in West Africa should most importantly address the questions of which power plants to invest in and the most efficient way to do it. This involves due consideration of the specific local conditions [44]. One requirement yet appears common, that is the need for transparency and coherence of electrification decisions on the level of complementarity between the grid and mini-grids [17,38].

2.3. A description of power systems planning models

Energy systems modeling encompasses different paradigms which can be classified into four groups: energy system optimization models, power systems and electricity market models, energy system simulation models, and qualitative and mixed-methods models [50].

Power systems planning has been described under narrow and broad perspectives [16]. Broadly defined, power systems planning aims at guaranteeing that investment plans and energy policy encompass technological, economic, environmental, social and political dimensions for power supply to sustainably satisfy existing and future demand [3,51]. Hence, planning approaches can either be supply- or demand-driven. Supply-driven approaches typically involve generation and T&D planning by electric utilities whereas demand-driven planning focuses on the provision of energy services and its socio-economic impacts. Power systems planning models and tools have extensively been used and reported [51–55]. In Ref. [51], power systems planning problems are classified into three broad categories differing by their timelines and types of decisions to be made: long-term, operational and short-term. While long-term planning spans across several years or decades and is useful for strategically deciding on the location of new capacity installations or generation expansion planning, short-term planning considers hourly, daily or weekly periods for decisions such as unit commitment, demand-side management (DSM) or power flows. In-between is operational planning in instances such as maintenance scheduling or reactive power planning. This is summarized in Fig. 2.

2.3.1. Optimization models

Multi-objective optimization (MOO) models have gained momentum as opposed to single-objective cost minimization models. Energy, and in particular electricity, requires different parameters to ensure its reliability and is intrinsically related to the environment, economy, social attributes, policies and technologies. It has thus become relevant to incorporate these concerns, goals and limitations into planning processes. MOO models translate given sets of objectives into mathematical programming aimed at finding the optimal solutions within a feasible region defined by constraints [51]. The objective functions may encompass the maximization of system reliability, the minimization of system expansion costs, the minimization of greenhouse gas (GHG) emissions, the minimization of external supply dependency of a country and the maximization of the share of renewables. The constraints generally denote technical requirements or limitations spanning from energy resource availability to generation capacity limits, as well as financial restrictions, political acceptance, energy security and competition for resource usage [51].

An extensive review of optimization modeling packages is presented in Ref. [53]. MESSAGE (Model of Energy Supply Systems and their General Environmental Impacts) is a widely employed package based on a linear optimization model and useful for medium-to long-term energy system planning with five-year timesteps. It allows building long-term scenarios – up to 50 years – to find the optimum energy supply path capable of meeting future demand considering a mix of technologies and informs energy policy direction. It was used in Ref. [56] to develop possible scenarios for the future electricity generation mix of Malaysia with a focus on expansion costs.

With a higher temporal resolution (hourly, daily or monthly timesteps), the MARket Allocation (MARKAL) tool minimizes the total cost of a national energy system based on technological and environmental considerations [53], and has been widely used with the Energy Flow Optimization Model (EFOM) as The Integrated MARKAL-EFOM System (TIMES). Authors in Ref. [57,58] applied TIMES to simulate future possible paths energy supply for South Africa and Canada, respectively, while [59] assessed scenarios towards decarbonization of the Portuguese energy system. MARKAL also served as a basis for the development of the Open Source Energy Modeling System (OSeMOSYS). OSeMOSYS uses linear optimization to compute the least-cost supply

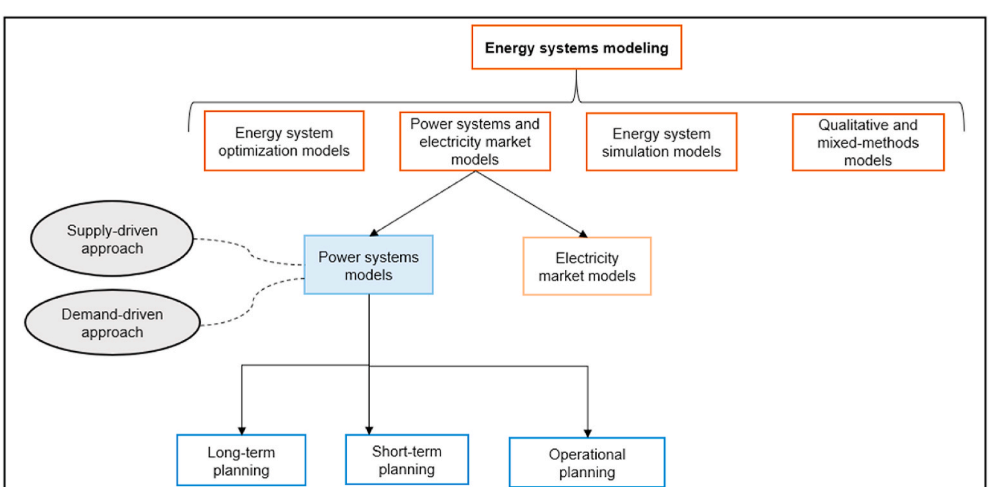

Fig. 2. An illustration of power systems planning models

scenario to meet pre-defined energy demand levels [54].

Another energy system analysis tool with an hourly temporal resolution is EnergyPLAN,. It models a set of future energy strategies encompassing an entire national or regional energy system, and accounts for electricity and heat supplies with a one-year timeframe [60]. Although the model includes some optimization, EnergyPLAN does not compute an 'optimum' solution defined by a set of constraints. It can rather be classified as a simulation tool providing various pathways for an energy system and focused on the future [61]. It has extensively been used to simulate the integration of renewables into different energy systems as well as 100% RE scenarios in case studies including Denmark, Ireland, Portugal, China, Finland and Mexico among others [61]. Authors in Ref. [62] simulated a 100% renewable energy system for Denmark for the years 2030 and 2050 using EnergyPLAN. The maximum feasible wind power integration into China's energy system, as well as the potential issues resulting from the use of intermittent renewable generation were investigated in Ref. [63].

It is worth mentioning the Hybrid Optimization Model for Electric Renewables (HOMER) which is generally used to optimize the integration of renewables in small-scale and off-grid power systems. HOMER has mostly been applied to carry out techno-economic design, sizing and environmental evaluation of RE technologies in distributed systems for rural areas of developing countries [16].

2.3.2. Multi-criteria decision-making models

Multi-criteria Decision-Making (MCDM) models consist of a set of a limited number of decision alternatives which are evaluated following multiple and often conflicting evaluation criteria. They are powerful in solving complex decision-making problems involving uncertainty, subjective views and preferences, and fall into four main categories, namely technical, economic, environmental and social [51]. Their application areas cover regional/national energy planning projects, RE planning, power systems planning and generation site selection. MCDM models involve a variety of methods which may be simultaneously used for results validation. They are the Analytical Hierarchy Process (AHP), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), Elimination and Choice Translating Reality (ELECTRE), Multi-Attribute Utility Theory (MAUT), fuzzy methods, and Decision Support Systems. The most commonly used are AHP, AUT, PROMETHEE and ELECTRE [64]. The latter two are classified as outranking methods whereas AHP and MAUT are referred to as value measurement methods [65].

AHP is the most used MCDM method. It consists in disaggregating a complex problem to organize its goal, criteria, sub-criteria, and alternatives, respectively from the top to the bottom of a hierarchy. A comparative evaluation of elements belonging to the same hierarchy level is performed according to a numerical scale to select the best alternative [64]. Relevant examples of studies featuring AHP include [66,67]. The former employed AHP to select suitable sites for concentrated solar power and PV installations to expand grid-connected solar-powered electricity in Tanzania. The decision-making tool augmented the use of a Geographical Information System (GIS) approach. In Ref. [67], different options of electricity generation plants in Jordan were evaluated according to costs and benefits. Similarly, MAUT uses cardinal ranking based on the elicitation of a utility theory [65]. In Ref. [68], MAUT was applied to assess energy policy options in the United Kingdom by measuring the viewpoints of individuals from several organizations. This is a complex process which might explain the low level of MAUT use.

Outranking methods involve pairwise comparisons of decision alternatives. According to Ref. [64], ELECTRE is the most used method in this category. With ELECTRE, the best alternatives are those which simultaneously satisfy most of the preference criteria and a tolerance threshold. The tolerance threshold ensures that undesirable levels of dissatisfaction are avoided for each of the criteria [64]. Specifically, ELECTRE III is mainly used for endorsing future energy sources and for ranking RE options [51]. An illustration is the study by Ref. [69] for which ELECTRE III was applied to support the deployment of RE technologies in the Sardinia island. PROMETHEE is another outranking method which allows ranking the alternatives following a given set of criteria using a preference index [65]. One instance is [52] with a combined application of PROMETHEE and a cost-benefit analysis to explore the extent to which higher RE penetration in Greece can balance economic, technical and environmental aspects. To account for uncertainty arising from RE-based generation, an extension of PROMETHEE was proposed in Ref. [70], applied to the case of geothermal field exploitation alternatives for rural Greece.

2.3.3. Economic models

Economic models used in energy systems problems typically follow a top-down approach. In Ref. [55], four types of models are distinguished: input-output (IO), econometric, system dynamics, and computable general equilibrium (CGE) models. In principle, these top-down models provide some insights into the impacts of simulated changes in a national/regional energy system on the economy as a whole, the potential effects of the introduction of an environmental scheme such as an energy tax, or the impact of different scenarios of economic changes on energy or the environment [55].

An IO model was used in Ref. [71] to perform an analysis of the economic and environmental impacts of the Japanese Government plans to develop energy technologies based on hydrogen produced from unutilized RE. Using a multi-region CGE model, the study by Ref. [72] evaluated the impacts of various carbon emission mitigation scenarios under the European Union climate and energy package on the Polish economy vis-à-vis the rest of the region. Effects such as changes in electricity prices, output and generation mix were quantified. Variations of wholesale electricity prices owing to higher penetration levels of wind power generation were assessed for the Australian national energy market in Ref. [73]. For this purpose, the authors used econometric techniques and found that the impact of wind generation on spot prices varies according to the existing generation mix by increasing with the inflexibility of the plant mix, for instance, coal and nuclear power plants. In Ref. [74], it was concluded, using a Vector Autoregressive model, that the lack of adequate capacity of the Spain-France interconnectors led to a low impact of wind power generation on the French electricity market. Energy-economy-environment (E3) models are also widely used to assess the sectoral interactions. Although studies specifically focusing on RE appear to be hardly found, there are some engaging pieces of work on sustainable development in emerging countries assessing the impacts of the implementation of a carbon trading mechanism for promoting renewables [75] and evaluating the socio-economic impacts of RE policies [76].

Because these top-down approaches involve macro-economic aggregation, they carry lower levels of detail than bottom-up approaches. The two can be combined to take advantage of both. Indeed, the key roles played by technologies, energy sources, energy services demand, market environment and socio-economic conditions often imply the need for a synergetic association of different types of energy planning models.

2.3.4. Hybrid models

As mixed-methods models, they involve processes referred to as soft-linking and hard-linking. Soft-linking allows maintaining the strengths of each model by running them independently and iteratively feeding the results from one model into the other until both models yield converging results. With hard-linking a trade-off has to be made as one model has to be simplified in order to be integrated into a single model with the other [77]. An example of hard-linking is the widely used simulation-based package LEAP (Long-range Energy Alternatives Planning System) which integrates bottom-up and top-down approaches into a single tool. It consists of a top-down macro-economic model with an optimization component based on OSeMOSYS. LEAP was employed in

Ref. [78] with a comparative analysis of the evolution of energy supply and demand and GHG emissions under different policy-based scenarios for Taiwan. In Ref. [79], LEAP served the development of different scenarios on the promotion of climate change mitigation, diversification of resources, and minimization of global warming potential. The aim was to highlight the resulting trade-offs. However, it seems that LEAP has not been used by scholars to simulate RE integration. In Ref. [80], a dynamic IO model was combined with a Mixed Integer Linear Program (MILP) to capture the interactions between energy supply and demand in China and determine the optimal options of generation technologies.

2.3.5. Spatial and temporal resolution in power systems modeling

Such planning exercises require key inputs such as demand forecasts [3] and system reliability factors. The latter is of specific importance for long-term planning studies on RE into the grid owing to their intermittency resulting in power output variability and additional system costs. This is more or less represented in planning models depending on the level of spatial and temporal resolution employed, and plays a crucial role in model output reliability [21,81,82]. Modeling high penetration of RE sources specifically, is highly impacted by the level of temporal detail [83]. Another influencing factor is the level of detail and accuracy in resource potential measures.

A study by Ref. [84] brought forth the limitations of considering average wind speeds for RE deployment. Hourly time steps analysis demonstrated that quality wind energy is not limited to the Northern part of West Africa as suggested by current wind suitability maps, but rather can potentially be harnessed across an extended geographical area, stretching continuously from Senegal to Nigeria. It was demonstrated that the differences in wind speeds between daytime and night time offer an exploitable potential for complementing solar power plants, particularly during the dry season. The literature displays manifold modeling approaches to generation capacity expansion planning, including or not low to high spatial and temporal resolution.

2.4. Planning approaches in West Africa

In [16], an extensive review of electricity planning research on SSA was carried out using a classification approach. The authors demonstrated that research is scarce and sparsely distributed, with nearly half of the articles addressing electricity planning focused only on six countries out of 49. These countries, at the exception of Ghana, are located in Eastern and Southern Africa. Moreover, although there has been an overall lack of scholarly attention on the four power pools – the Eastern African Power Pool (EAPP), SAPP, the Central African Power Pool (CAPP) and WAPP –, the latest two have received the least attention [16].

Research on electricity planning in SSA falls into three broad categories: quantitative, qualitative, and a combination of both. Quantitative analysis involves energy modeling simulation, single/multiple objective optimization, single/multiple criteria analysis, econometrics, and life-cycle assessment methods. The former two are the most commonly used, and cost minimization is usually the sole objective [16]. The use of MOO models has been rising since 2010 but is still marginal. Qualitative analysis covers policy and institutional assessments, as well as social and cultural roles in electricity planning. Several authors stressed that policy analysis is capable of providing instrumental insights for energy planning models in SSA, and should, therefore, be taken into consideration optimization models for electricity planning [46,85,86]. It was found in Ref. [16] that HOMER is the most prevalent tool employed in scholarly studies on electricity planning for SSA. The main shortfall of the studies based on this type of software is that they fail to provide practical steps for the implementation of their solutions. Additionally, HOMER does not allow for grid extension modeling and its use has, therefore, been restricted to community-level off-grid electrification [87]. Very few studies used LEAP, MESSAGE, MARKAL/TIMES and OSeMOSYS [16].

Modeling tools incorporating a GIS component with high spatial resolution to capture RE variability have also been applied. The Open-Source Spatial Electrification Tool (OnSSET) which allows for the integration of key socio-economic parameters alongside land and energy resources availability data beyond mere techno-economic considerations, is able to capture crucial, yet widely overlooked dimensions of generation capacity expansion planning [88–90] (seeFig. B-1, Appendix B [114]).

In West Africa, power systems planning has mainly been supply-driven for the expansion of conventional utility-scale power plants and carried out by state-owned electric utilities in the form of Master Plans translating the Government plans for electrification scale-up. After the 2002 Johannesburg Summit and the 2005 ECOWAS White Paper which called for a shift towards a more demand-driven approach in electricity planning for inclusive sustainable development, there has been a wave of liberalization of the electricity sector in some countries and the creation of government agencies or funds aimed at promoting decentralized rural electrification. As a result, more demand-driven planning studies have emerged to identify suitable solutions to provide access to basic energy services and spur economic growth. The most relevant instances of power systems planning featuring an ECOWAS Member State or the WAPP are described in Table 3.

3. Discussion

3.1. On power systems planning in West Africa

Considering the reviewed state-of-the art in power systems planning and the current drive for unlocking the potential of RE across West Africa, it is clear that scientific research in the field is yet to be fully explored. Moreover, it still lacks adequate consideration of the complexity of energy systems spanning across various socio-economic dimensions. The clear evidence of the crescent role of utility-scale RE, which has called for collective action to improve electricity access and drive economic growth, requires due scholarly consideration in carrying out related research to inform the design and implementation of a RE-based future for West Africa.

Furthermore, most studies do not account for the spatial variability of intermittent. In Ref. [103], the authors pointed to the need for higher resolution by modeling T&D lines in each country rather than the sole cross-border transmission network. This requires a huge amount of data which is often unavailable or difficult to obtain from local actors for 'confidentiality' reasons, depending on the country. Indeed, for most countries, specific information – if existing – can be more easily accessed via relevant field contacts. In addition, the scope of most studies remains limited to technical system operation and cost minimization without any further account for the key implications on socio-economic dimensions, climate action, and policy design and implementation.

From Table 3, it can be reasonably stated that no specific model may be presented as the golden approach but rather as potential avenues for future research. OnSSET encompasses several technologies including the centralized grid and off-grid RE technologies. Hence, it may be considered one important option since it fills the gap of the lack of country-wide electrification strategies. Provided that OnSSET is further enhanced to include other sectoral demands as well as hybrid mini-grids, it would better capture the ground reality and translate into clear, implementable steps for policy planning. OnSSET may also be soft-linked with other medium-to long-term modeling tools which have widely been used in the international arena to address the limitation of OnSSET in determining the optimal grid mix. This has been done for Kenya [89] but it is a blue ocean in the case of West African countries. In addition, the planning model described in Ref. [101] could provide key insights into both local and national planning for countries other than Senegal. Potential improvements of this model would put more focus on current challenges by accounting for wind technologies given that wind power – at large and small scales – is expected to play a role in the

Table 3
Literature review on scholarly applications of various power systems planning models and tools for West Africa.

Case study	Authors	Aim of the study	Model/Tool	Main results	Limitations of the study
Burkina Faso	[91]	*Demand-driven:* To comparatively analyze the suitability of off-grid hybrid (solar PV/diesel) and off-grid diesel systems to electrify a 65,000-people village, using the Levelized Cost of Electricity (LCOE) and Net Present Value (NPV) as criteria	HOMER	• The current pattern of using off-grid diesel technologies is inefficient and unsustainable as it yields the highest LCOE value and environmental impact; • A PV/diesel configuration has a much lower LCOE value than a PV system; • With the wide distribution of quality solar resource across the country, PV/diesel systems can sustainably meet unserved demand in rural areas.	• No sensitivity analysis on battery costs; • The potential contribution of other resources such as wind was overlooked, most probably owing to the initial consideration of low values of average wind speeds. Yet, in light of [84], a hybrid PV/wind system could reasonably be explored.
	[92]	*Demand-driven:* To produce a suitability map for different technologies to reach 100% electricity access in Burkina Faso by 2030	Geo-referenced LCOE model	Over half of the population is cost-optimally served by off-grid RE technologies even in simulations with lower grid extension costs and higher PV costs.	• The authors chose not to account for wind technologies (same observation as [91]); • The dynamics of electricity consumption were overlooked and the lack of sensitivity analysis on this variable does not allow assessing the robustness of the modelling results; • Non-cost related implications of the optimal technology mix could have involved quantifying GHG emissions in light of the country's climate obligations.
	[93]	*Supply-driven:* To forecast national electricity demand to 2025, to define scenario-based investment plans and evaluate investment costs for electricity production, T&D between 2017 and 2025 to meet demand and reach electrical coverage of 80% in 2020 and 90% in 2025 (corresponding to electrification rates of 45% and 55% in 2020 and 2025, respectively)	• Regression correlation for demand forecasting; • Techno-economic analysis based on existing and planned generation capacity and transmission lines.	• In a high demand scenario (electrification rates of 45% in 2020 and 55% in 2025), a capacity deficit occurs in 2018 and 2019; • In medium (electrification rate of 32.21% in 2020 and 45% in 2025) and low (business-as-usual) demand scenarios, there is an excess of production from the year 2022 therefore, the delay of some projects for generation capacity reinforcement projects was recommended; • The investment required for rural electrification by 2025 is around five times as much as the funds raised through technical and financial partners; • With the resulting high generation investment costs, a significant contribution from the private sector is expected through public-private partnerships.	• Electrification options with RE for both grid and off-grid are limited to solar PV and hybrid systems (diesel/PV); • To address the affordability issue raised by the authors, further analysis would be required to assess the evolution of electricity prices and connection costs for final end-users; • Potential trade-offs between increased energy supply and environmental protection considering the country's climate obligations were not evaluated.
Benin/ Togo[a]	[94]	*Supply-driven:* To produce scenarios for the electricity supply mix for two time periods: 2015–2018 and 2020–2035	2015–2018: Excel-based software specifically designed for the study 2020–2035: Wien Automatic System Package (WASP – a least-cost-optimization package)	• In the high demand scenario, solar PV represents 27% of the total installed capacity in 2035 (0% in 2016), i.e. 1120 MW of which 630 MW in Benin (26% of national capacity); • In the high scenario, if PV investment cost rises from $1000/kWp to $2000/kWp, the installed capacity drops to 640–680 MW in 2035 and their commissioning is delayed; • In the medium scenario, PV has an installed capacity of 740 MW (27.3% of the total) of which 440 MW in Benin (26.5% of the national capacity); • In the low scenario, 520 MW of solar PV are installed in 2035 (25.8% of the total capacity) of which 330 MW in Benin (27% of the total national capacity);	• Sensitivity analyses on PV investment costs were not performed for all scenarios. The pace at with PV costs are decreasing may lead to substantial differences from the baseline scenarios; • The study would have been more insightful by exploring the potential impact of subsidies such as feed-in tariffs (FITs) and investment tax credits on PV deployment.
	[95]	*Demand-driven:* To define the cost-optimal grid extension options for	GEOSIM	• Development Poles (i.e. areas with a strong potential for lifting people	Since no comparison with decentralized systems was performed, this approach

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Table 3 (*continued*)

Case study	Authors	Aim of the study	Model/Tool	Main results	Limitations of the study
		maximum socio-economic impact of rural electrification projects between 2016 and 2035		out of poverty were identified and ranked according to the existence of health facilities, education centers, economic activities and number of local people) were determined under three demand scenarios: high, medium and low; • The cost-optimal lengths of medium and low voltage transmission lines to be built to meet local demand were calculated.	does not guarantee that the extension lengths of transmission lines are indeed the cost-optimal electrification option for rural Benin.
Ghana	[96]	*Demand-driven*: To determine the cost-optimal electrification strategy for the whole country using a least-cost model based on GIS data	Network Planner	• Stand-alone and mini-grid systems provide the least cost option for most rural areas and can serve as an intermediate solution until the grid can be extended to more remote areas depending on Ghana's rural electrification plans.	Despite huge hydro resources endowment, mini-hydro was not included in the analysis thus potentially limiting the robustness of the results.
	[48]	*Supply-driven*: To determine the optimal electricity generation mix under several budget allocation scenarios and uncertainty of demand growth following a multi-period approach (2016–2035)	Stochastic MILP	• As budget allocations increase, decisions on the generation mix become less costly owing to an investment shift to power plants with higher capital and lower running costs; • 95% of Ghana's electricity demand can be met by financing investments in generation capacity with annual savings amounting to 0.75% of the Gross Domestic Product (GDP).	The contribution of non-hydro RE was not considered, despite substantial solar energy resources, even in scenarios with higher budget allocations.
	[97]	*Supply-driven*: The Integrated Power System Master Plan is a subset of Ghana's Strategic National Energy Plan. Its aim is to serve as a strategic planning document unraveling the development of the generation and transmission infrastructure to meet a growing demand and promote sustainable economic growth in a cost-effective manner.	Integrated Planning Model (a least-cost optimization tool)	• Additional generation capacity is not needed until the mid-2020s; • By 2027 and 2037, the shares of renewables (excluding large hydro) in the electricity generation mix increases and the increase rate depends on the scenario. In the Enhanced Nationally Determined Contribution scenario, the contribution of renewables is the highest with almost 20% of the generation mix in 2037. The Export-Oriented scenario shows a remarkable scale-up of PV (with and without storage) and wind generation by 2037.	• Although cross-cutting from generation to distribution and end-user consumption and holding significant cost-savings potential, energy efficiency was overlooked; • Energy efficiency and DSM promotion is a key function of the Energy Commission; as such including them in this integrated study would have perfectly fitted the scope of national energy priorities.
Mali, Niger	[98]	*Demand-driven:* To define the best electrification option (grid extension or off-grid diesel systems) for maximum socio-economic impact of rural electrification projects in two pilot regions (one in Mali and one in Niger)	IMPROVES-RE/GEOSIM	• For each pilot area, priority Development Poles, i.e. areas with a strong potential for lifting people out of poverty were identified and ranked according to the existence of health facilities, education centers, economic activities and number of local people; • The least-cost (NPV-based) electrification option was determined for each Pole; • The total investment costs to reach 100% electrical coverage in the pilot area were assessed.	• The potential contribution of local RE sources in stand-alone or hybrid systems was overlooked, which is not coherent with national priorities of tapping into endogenous resources.
Nigeria	[99]	*Demand-driven:* To investigate the potential role of off-grid hybrid (solar PV/wind/diesel) systems for 8 locations in Northern Nigeria using LCOE and NPV as criteria	HOMER	• The hybrid system (with or without battery) yields a lower LCOE value than a diesel-only system; • This LCOE value remains higher than the current grid electricity tariffs. Yet, such a hybrid system remains the most viable solution for serving remote areas where grid connection costs are too prohibitive.	• The typical electricity consumption of a single location was used in the techno-economic analysis of the other locations, thus neglecting consumption dynamics; • Sensitivity analysis on electricity consumption would have improved the results reliability.
	[100]	*Supply-driven*: To design a network of solar and hybrid (solar/wind) power plants based on energy resource availability and demographical conditions for South-Eastern Nigeria by 2020	Multi-step including integer linear programming	Making the region free of fossil-fueled generation by 2020 requires an annual increase by 41.5% of the 2013 capacity, met by 5 solar and 3 solar/wind power plants	• Sensitivity analysis on solar irradiation and wind speeds would have improved results reliability; • Practical recommendations on the implementation of the proposed RE network would have supported the theoretical results.

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Table 3 (*continued*)

Case study	Authors	Aim of the study	Model/Tool	Main results	Limitations of the study
Senegal	[101]	*Supply-driven*: To produce an electricity expansion planning model to be used at both local and national levels and analyze connection costs drivers in Senegal	Modified Kruskal's algorithm programmed in Java	• In the base scenario, unelectrified areas would be cost-effectively served by the grid rather than solar PV or diesel mini-grids; • When electricity demand doubles or grid-related costs reduce by half, grid connection is even more favorable for unelectrified communities; • Even when grid-related costs double or PV equipment costs decrease by half, almost 50% of the unelectrified populations is cost-effectively served by the grid.	No account for wind technologies (same observation as [91]).
Sierra Leone	[102]	*Supply-driven*: To develop power development planning scenarios to meet the electricity demand of the Western region of Sierra Leone for 2010–2025	WASP	• In the hydro-dominant scenario, the share of hydropower in the generated power in 2025 sharply increases after the construction of the Yiben-I hydropower plant - potential site with the lowest unit generating cost - in 2019 from less than 50% to over 90%; • Sensitivity analyses on fuel prices for the hydro-dominant scenario show that the year 2019 remains the desirable completion data of the Yiben-I hydropower plant. In a higher price scenario, the base hydro scenario is unchanged whereas in a lower price scenario (25% fuel price reduction), high-speed diesel becomes more cost-effective than mid-speed generators.	• Non-hydro RE sources were overlooked in the planning model (same observation as [48]); • No sensitivity analysis on hydropower availability.
WAPP	[21]	*Supply-driven*: To develop four scenarios of different electricity supply configurations by 2030, including a RE Promotion Scenario	SPLAT-W (System Planning Test model for Western Africa) (within MESSAGE framework)	• By 2030, the share of RE-based electricity generation in the WAPP rises by ten-fold to almost 60%. Hydropower (local and imports from Central Africa) makes up three-quarters of this share; • Even in the energy security scenario whereby imports between WAPP countries are restricted, RE-electricity still accounts for over 50% of the total added capacity; • Off-grid RE technologies will be key to meeting regional demand by 2030 with a contribution of 33%.	• Single-node modeling, hence not capturing RE spatial variability; • Load profiles in each sectoral demand category were defined according to 3 or 4 blocks in a 24-h time period across a three-season year but they were not considered as country-specific; • The potential shares of solar PV and wind power in the generation are limited by conservative assumptions rather than sound optimization results.
	[30]	*Supply-driven*: To develop a cost-optimal generation and transmission model for the WAPP with a focus on RE integration to meet electricity demand between 2017 and 2033	PRELE	• By 2022, gas turbines contribute to around two-thirds of the electricity generation mix whereas PV holds a share of 4% and wind, less than 0.1%. • By 2029, PV and wind respectively contribute to 13% and 1% of the generation mix whilst the contribution of gas turbines falls to 60%; • By 2033, the share of solar PV grows to 17% whereas it remains at 1% for wind and rises to 62% for gas turbines.	• The contribution of wind and solar PV to peak demand is limited to 10% using a conservative assumption rather than an optimization result; • The optimal power flows between countries, although essential for a well-functioning pool, were not assessed.
	[103]	*Supply-driven*: To develop a multi-node economic dispatch model with higher levels of solar PV power production in 2025	PLEXOS	• The high-level PV integration scenario shows a significant reduction by half of the supply-demand gap with decreasing generation costs compared to the business-as-usual scenario. • Increased import dependency occurs for several countries, hence potentially posing political challenges.	• No further implications of higher utilization of solar power at technical, social or policy levels were considered; • Although using an hourly temporal resolution suitable for such planning study, the spatial resolution of the transmission infrastructure remained at the level of interconnection nodes, and individual utility-scale power plants were not modeled.
SSA	[88]	*Demand-driven:* To find the cost-optimal technology split for 44 countries by 2030 following a costing algorithm based on LCOE	OnSSET	The shares of mini-grids vary according to electricity demand levels and diesel prices: with higher demand, RE-based mini-grids (PV and hydro) become cost-effective over diesel mini-	• Only residential demand was considered; • The study did not include further analysis of the optimal grid supply mix, thus disregarding the temporal

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Table 3 (*continued*)

Case study	Authors	Aim of the study	Model/Tool	Main results	Limitations of the study
				grids, especially in a high price scenario. The results for Burkina Faso are coherent with [92].	dynamics of grid supply which have an impact on LCOEs.
	[104]	*Supply-driven:* To determine a least-cost supply path hourly-resolved for 100%-renewables-based power system. The sub-Saharan African region.	Multi-node approach and a linear programming model	• SSA was sub-divided into multiple regions according to their areas, demography and grid connections. Electricity demands were aggregated into clusters in each sub-region, resulting into scattered consumption centers. For instance, five consumption centers were defined in West Africa: one in Senegal, one in Ghana, and three spreading from North to South Nigeria;	• Despite using a rather high temporal resolution, the spatial resolution was too high to truly reflect demand and supply levels across the region.
	[105]	*Supply-driven:* To propose a sub-continent-wide modelling of investment opportunities in electricity generation.	The Electricity Model Base for Africa (TEMBA) based upon OSeMOSYS.	The study substantiated TEMBA's ability to generate an optimal supply path matching exogenous demand in order to provide sound scientific evidence to foster investment and inform policy strategies in the power supply sector.	• No in-depth critical analysis of the scale-up of RE integration in the power system was carried out.

[a] The electrical networks of Benin and Togo form the Electrical Community of Benin (CEB). While some simulations were specific to the Beninese electrical grid, most of them considered Benin and Togo as a whole.

diversification of the generation mix. Given the location-specific and intermittency nature of RE, the use of high-resolution timesteps and geospatial data in long-term generation expansion planning would significantly improve the reliability of generation site locations, especially for region-wide applications, as generation variability can be smoothed out through resource complementarities and increased cooperation. Nonetheless, the study by Ref. [3] pointed out that RE alone in SSA is not capable of significantly reducing the supply-demand gap. It was found that energy efficiency is the most efficient way to narrow the gap and significantly reduce carbon emissions. Hence, it is paramount to include energy efficiency in planning models to ensure that any capacity available is used in the most efficient way at all levels.

Although a wide range of modeling packages have been developed, they still require a certain level of human expertise. It appears that the majority of existing studies on power systems planning for West Africa are performed by foreign scholars and entities and research agencies. The lack of human capital in developing countries has been identified as a crucial impediment to proper planning processes and served as the rationale behind the creation of OSeMOSYS. Although it is an open-source package with a reduced learning time curve in favor of energy planners and decision-makers in these countries [54], OSeMOSYS barely features in the literature for West Africa. Due to the low electrification rates and the vast RE potential, most of the research has focused on generation technology choice for rural settings. Yet, there has been very limited research on country-level grid-connected PV. It has been argued that achieving sustainable access to electricity in SSA requires complementary inputs of grid expansion, RE-based off-grid technologies, and strong and coherent policy measures to promote investments in supply- and demand-side energy efficiency solutions [3,15]. Hence, capacity-building of local actors (policy planners, the academic community, etc.) is crucial to deepen and hone sound scientific knowledge in the field.

The reviewed research papers show a common ground as to the latent potential of RE in scaling up electrification in West Africa. Business-as-usual paths will unlikely overcome the supply-demand gap, and stringent policy measures to disincentivize fossil-fueled generation over RE generation will be key to achieving sustainable development objectives. Besides, sound and transparent planning for the grid and off-grid options is required for each strategy to achieve its full potential.

3.2. On the practical implementation of planning models

In practice, there are critical gaps which need to be addressed for a successful RE scale-up. Some of these challenges are mentioned in Section 2.2 and include: infrastructure adequacy, regulatory framework, private sector involvement and resource mobilization capacity.

The large-scale deployment of RE sources, which are intermittent by nature, requires power plant short-term flexibility, as well as the ability of the transmission system to absorb fluctuating RE outputs. As for small-scale electrification, particularly with solar home systems (SHSs), past experiences have shown the need for community ownership, deep understanding of beneficiaries' financial capacity and their sustained commitment [106]. The areas where SHSs are cost-optimal are also the areas with the higher LCOEs [88–90]. These are typically rural areas which are home to the poorest strata of the population. Thus, reaching cost affordability both in "last-mile" and universal electrification efforts calls for appropriate tax levels, inducing retail market structures and adequate business models. However, some countries still lack tax exemption measures on RE products (Table 2).

In off-grid electrification, five delivery models exist through three main actors: rural electrification agencies which largely depend on donor funding and/or government support, NGOs and other international development institutions, and the private sector. Focusing on the private sector, it either delivers through a purely commercial model, a donor-led or finance institution-led credit approach, and fee-for-service models. Fee-for-service models are delivered by Energy Service Companies (ESCOs) which provide financing and responsible for installation, consumer education, maintenance and after-sales services, contrarily to other private-led models whereby these constitute shared responsibilities between the end-user, the vendor and the financial institution. The latest, therefore, highlight the need for capital and technical capacity from the consumer side, and has proven its limits in terms of project sustainability. For instance, the purely commercial model, necessitates local micro-finance institutions to provide schemes adapted to these specific technologies, which is usually not the case [107]. Besides making provision for productive uses of electricity, the 2005 ECOWAS White Paper draws attention to the need of providing energy services beyond technologies. The frameworks under which ESCOs operate, thus, make them fitted gamechangers. Given the relatively high capital costs incurred by the technologies which may hinder ESCOs development, various support funds are put in place. The Sustainable Energy Fund for

Africa (SEFA), a multi-donor trust fund administered by the African Development Bank, is one such example. Furthermore, de-risking RE investment and accelerating resource mobilization through private sector involvement in a context of financially constrained utilities, are two additional gaps to bridge. One solution includes clearing the regulatory environment to encourage private sector participation in RE production and service provision including DSM. Several countries such as Burkina Faso, Ghana, Mali and Senegal are honing their public-private partnerships frameworks. Incentives such as FITs and Renewable Energy Premium Tariffs (FIT-inspired for mini-grids in developing countries [108]) which can catalyze RE investment, are yet to be fully explored in planning models to inform policy and regulatory direction.

Regional integration can potential reduce large-scale storage needs and capital costs, thus facilitating RE deployment [109,110]. Three factors act towards the benefits of interconnected systems: different consumption profiles, different peak load times and duration, and different climatic conditions [110]. For West Africa, the diversity of RE sources spread across a large geographical area make it plausible to seriously explore increased RE integration from a regional perspective. Within the current context of regional integration in West Africa, the States are increasingly geared towards acting as a region, and the energy sector is no exception [111]. The WAPP was created to integrate national power systems with cross-border exchanges in view of culminating into a regional electricity market [17]. However, being that (i) cross-border interconnections and electricity trade are highly subject to political dynamics and national sovereignty issues over energy security concerns and (ii) utility-scale RE deployment is challenged by land availability due to socio-cultural dimensions, it is paramount to duly acknowledge and account for socio-cultural barriers and political risks and priorities to derive sound mitigation strategies in RE projects implementation.

4. Conclusions

Although hosting some of the world's fastest-growing economies, access to electricity services, an undeniable multiplier of development, remains a luxury for most of the West African population. This situation is an alarming paradox as the region enjoys the highest endowment of endogenous energy resources. The question of how best to close the gap between electricity supply and demand in SSA has stimulated much attention from governments, multilateral investment organizations, and international research agencies. Yet, despite recognizing West Africa's unique potential in RE sources, the sector still falls short of adequate investment. Scaling up access to electricity in the region requires a shared vision informed by substantial knowledge of their options. However, the literature on power systems planning with RE is scarce and confined within least-cost and/or low-resolution modeling. Specifically, regional power pooling with RE offers huge, yet untapped opportunities for taking advantage of resource diversity as well as reducing capital costs and storage needs for increased cost affordability for end-users.

This paper contributes to enhancing current knowledge by capturing the essence of the existing literature on capacity expansion modeling approaches and critically analyzing their shortcomings to define potential improvement avenues. As such, future work should focus on coupling high-resolution geospatial information with power systems planning models to ensure system reliability by better reflecting RE variability. Furthermore, the use of geospatial information merits better exploration to adequately characterize the complementary inputs of grid and off-grid systems rather than pursuing an unplanned and biased approach leading to costly investment decisions. Modeling tools such as OnSSET are well-suited for this. However, conclusions drawn from an OnSSET analysis requires further elaboration by determining the optimal electricity generation mix from the centralized grid. Such further modeling would have higher added value in policy recommendations. In Ref. [90], the same authors applied OnSSET to the cases of Burkina Faso and Côte d'Ivoire, and provided market assistance need insights. Additionally, novel resource assessment metrics should be considered in order to increase the accuracy of planning models. Most importantly, future research should aim to contribute to redesigning power systems planning by providing innovative solutions. Bearing in mind the end goal of spurring economic growth with accrued private sector involvement, it should capture multiple objectives involving engineering, economics, policy, regulatory and socio-technical design to culminate into actionable research. In particular, the inclusion of productive uses of electricity and environmental externalities could be useful to better assess costs and opportunities. Advancing research in such directions would provide sound scientific evidence to key national and regional stakeholders so as to take a step closer towards building a resilient future for West African countries.

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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Appendix A

Table A-1
Solar and wind energy potentials in WAPP member countries

Country	Global horizontal irradiance[a]		Wind energy potential[b]
	Daily solar radiation (kWh/m^2)	Annual radiation (kWh/year)	Mean wind speeds (m/s)
Benin	4.6–5.8	1680–2118	2–5
Burkina Faso	5.4–6.0	1972–2191	2–5
Côte d'Ivoire	4.4–5.6	1607–2045	2–5
The Gambia	5.6–5.8	2045–2118	2–6
Ghana	4.4–5.6	1607–2045	2–6
Guinea	5.0–6.0	1826–2191	2–6
Guinea-Bissau	5.4–5.6	1972–2045	2–6
Liberia	4.4–5.4	1607–1972	2–6

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Table A-1 (*continued*)

Country	Global horizontal irradiance[a]		Wind energy potential[b]
	Daily solar radiation (kWh/m^2)	Annual radiation (kWh/year)	Mean wind speeds (m/s)
Mali	5.8–6.4	2118–2337	2–8
Niger	5.8–6.6	2118–2410	5–8
Nigeria	4.2–6.2	1530–2264	2–7
Senegal	5.6–6.0	2045–2191	2–7
Sierra Leone	4.8–5.6	1753–2045	2–6
Togo	4.8–5.6	1753–2045	2–6

Source: Author's compilation, from Ref. [112,113].
[a] Daily and annual global horizontal irradiance values are 1994–2005 long-term averages, except for Benin (1999–2015) from Ref. [112].
[b] Measured at 50 m height with 1 km resolution in 2015, from Ref. [113].

Appendix B

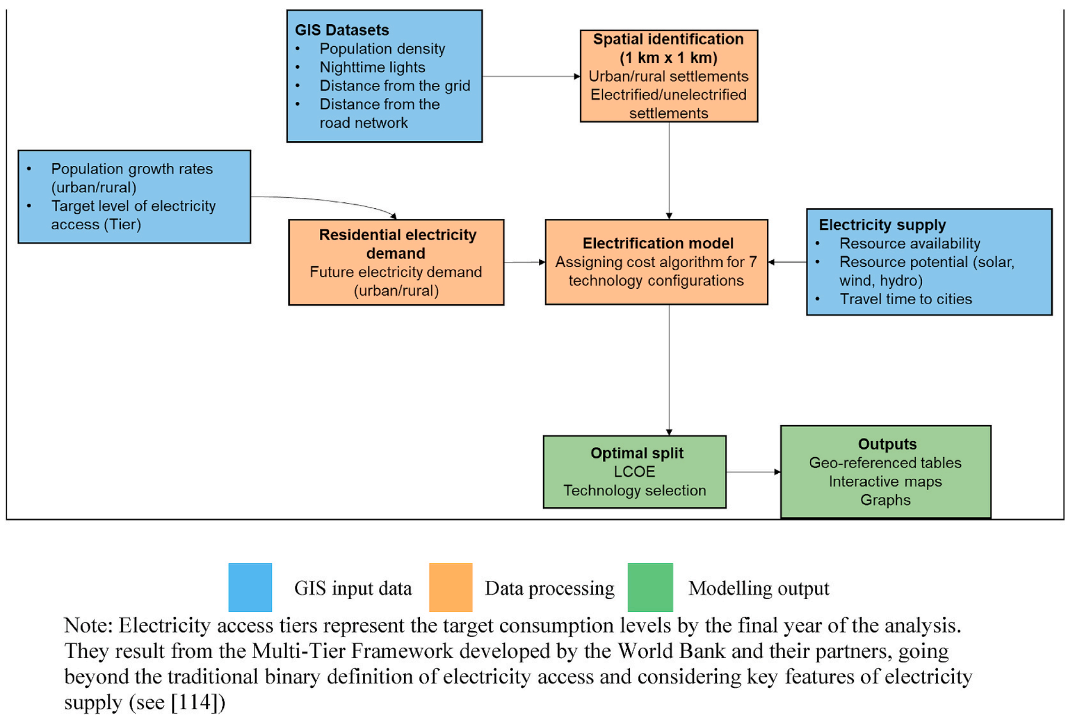

Fig. B-1. Flowchart of the OnSSET methodology GIS input data Data processing Modelling output.

References

[1] United Nations. Sustainable energy 'golden thread' connecting economic growth, increased social equity, secretary-general tells ministerial meeting. Meet Cover Press Releases; 2014.
[2] Daly H, Walton MA. Energy access outlook 2017: from poverty to prosperity. 2017. https://doi.org/10.1787/9789264285569-en.
[3] Ouedraogo NS. Modeling sustainable long-term electricity supply-demand in Africa. Appl Energy 2017;190:1047–67. https://doi.org/10.1016/j.apenergy.2016.12.162.
[4] Sebitosi AB, Okou R. Re-thinking the power transmission model for sub-Saharan Africa. Energy Pol 2010;38:1448–54. https://doi.org/10.1016/j.enpol.2009.11.025.
[5] International Energy Agency. Africa Energy Outlook: A focus on energy prospects in Sub-saharan Africa. Paris: OECD/IEA; 2014.
[6] Agbodo E, Maharaj A, Adeyemo B, Davidson IE. Transforming the West African regional electricity market — lessons and experiences. IEEE PES PowerAfrica 2017:198–201. https://doi.org/10.1109/PowerAfrica.2017.7991223. 2017.
[7] Pineau PO. Electricity sector integration in West Africa. Energy Pol 2008;36:210–23. https://doi.org/10.1016/j.enpol.2007.09.002.
[10] Ouedraogo NS. Africa energy future: alternative scenarios and their implications for sustainable development strategies. Energy Pol 2017;106:457–71. https://doi.org/10.1016/J.ENPOL.2017.03.021.
[11] Bazilian M, Nussbaumer P, Rogner H-H, Brew-Hammond A, Foster V, Pachauri S, et al. Energy access scenarios to 2030 for the power sector in sub-Saharan Africa. Util Pol 2012;20:1–16. https://doi.org/10.1016/J.JUP.2011.11.002.
[12] ECREEE. ECOWAS Renewable Energy Policy. Praia: ECREEE; 2013.
[13] Spalding-Fecher R, Joyce B, Winkler H. Climate change and hydropower in the southern african power pool and zambezi river basin: system-wide impacts and policy implications. Energy Pol 2017;103:84–97. https://doi.org/10.1016/j.enpol.2016.12.009.
[14] Avila N, Carvallo JP, Shaw B, Kammen DM. The energy challenge in sub-Saharan Africa : a guide for advocates and policy makers: Part 1 : generating energy for sustainable and equitable development. Oxfam Res Backgrounder Ser 2017. https://doi.org/10.13140/RG.2.2.25037.44001.
[15] Vilar (ed). In: Renewable Energy in Western Africa: Situation, Experiences and Tendencies. Praia: ECREEE, ITC Economy and Business Area, Casa África; 2012.
[16] Trotter PA, McManus MC, Maconachie R. Electricity planning and implementation in sub-Saharan Africa: a systematic review. Renew Sustain Energy Rev 2017;74:1189–209. https://doi.org/10.1016/J.RSER.2017.03.001.
[17] WAPP. Creation of WAPP. 2017. http://www.ecowapp.org/en/content/creation-wapp. [Accessed 23 May 2018].
[18] Nations Online Project. Political map of West Africa 2018. http://www.nationsonline.org/oneworld/map/west-africa-map.htm. [Accessed 7 May 2018].
[19] Mundi Index. Historical data graphs per year. 2018. https://www.indexmundi.com/g/g.aspx?c=xx&v=81. [Accessed 7 May 2018].
[20] AFREC. Africa Energy Database - Base de données énergétiques africaines Edition 2018. African Energy Commission; 2018.
[21] Miketa A, Merven B. West African Power Pool: Planning and Prospects for Renewable Energy. IRENA; 2013.

[22] World Bank. TCdata360 - infrastructure/Number of electrical outages in a typical month 2018. https://tcdata360.worldbank.org/indicators/h6ae7f138?country=BRA&indicator=244&viz=bar_chart&years=2009. [Accessed 1 December 2018].
[23] World Bank. Value lost due to electrical outages (% of sales for affected firms. https://data.worldbank.org/indicator/IC.FRM.OUTG.ZS?view=map&year=2017. [Accessed 1 December 2018].
[24] AfDB. West Africa Economic Outlook 2018: Macroeconomic developments and poverty, inequality, and employment - Labor markets and jobs. African Development Bank; 2018.
[25] Momodu AS. Energy use: electricity system in West Africa and climate change impact. Int J Sustain Energy Plan Manag 2017;14:21–38. https://doi.org/10.5278/ijsepm.2017.14.3.
[26] ECREEE. ECOWAS Renewable Energy and Energy Efficiency Status Report 2014. ECREEE; 2014.
[27] Tractebel Engineering. Update of the ECOWAS Revised Master Plan for the Generation and Transmission of Electrical Energy - Final Report Volume 1: Study Data. Tractebel Engineering - GDF Suez; 2011.
[28] Gnansounou E, Bayem H, Bednyagin D, Dong J. Strategies for regional integration of electricity supply in West Africa. Energy Pol 2007;35:4142–53. https://doi.org/10.1016/j.enpol.2007.02.023.
[29] Othieno H, Awange J. In: Energy resources in Africa: Distribution, opportunities and challenges. Switzerland: Springer International Publishing; 2016.
[30] Tractebel Engineering. Update of the ECOWAS Revised Master Plan for the Development of Power Generation and Transmission of Electrical Energy - Final Report - Volume 4: Generation and Transmission Master Plan. Brussels: Tractebel Engie; 2018.
[31] IRENA. Renewable Power: Sharply falling generation costs. IRENA; 2017.
[32] Kaundinya DP, Balachandra P, Ravindranath NH. Grid-connected versus stand-alone energy systems for decentralized power—a review of literature. Renew Sustain Energy Rev 2009;13:2041–50. https://doi.org/10.1016/J.RSER.2009.02.002.
[33] Ahlborg H, Hammar L. Drivers and barriers to rural electrification in Tanzania and Mozambique – grid-extension, off-grid, and renewable energy technologies. Renew Energy 2014;61:117–24. https://doi.org/10.1016/J.RENENE.2012.09.057.
[34] Quitzow R, Roehrkasten S, Jacobs D, Bayer B, Jamea EM, Waweru Y, et al. The future of Africa's energy supply: Potential and development options for renewable energy. Potsdam Institute for Advanced Sustainability Studies (IASS); 2016.
[35] MacLean LM, Brass JN, Carley S, El-Arini A, Breen S. Democracy and the distribution of NGOs promoting renewable energy in Africa. J Dev Stud 2015;51:725–42. https://doi.org/10.1080/00220388.2014.989994.
[36] Alstone P, Gershenson D, Turman-Bryant N, Kammen DM, Jacobson A. Off-grid power and connectivity: Pay-as-you-go financing and digital supply chains for pico-solar. Lighting Global/World Bank; 2015.
[37] Kirubi C, Jacobson A, Kammen DM, Mills A. Community-based electric micro-grids can contribute to rural development: evidence from Kenya. World Dev 2009;37:1208–21. https://doi.org/10.1016/j.worlddev.2008.11.005.
[38] Miller CA, Altamirano-Allende C, Johnson N, Agyemang M. The social value of mid-scale energy in Africa: redefining value and redesigning energy to reduce poverty. Energy Res Soc Sci 2015;5:67–9. https://doi.org/10.1016/J.ERSS.2014.12.013.
[39] Velumail T, Turton C, Beresnev N. The energy plus approach. In: Halff A, Sovacool BK, Rozhon J, editors. Energy poverty glob. Challenges local solut. New York: Oxford University Press; 2014. p. 391–410.
[40] Mahama A. International year for sustainable energy for all: African Frontrunnership in rural electrification. Energy Pol 2012;48:76–82. https://doi.org/10.1016/J.ENPOL.2012.04.046. 2012.
[41] Gollwitzer L, Ockwell D. Institutional innovation in the management of pro-poor energy access in East Africa. 2015. https://doi.org/10.2139/ssrn.2744604.
[42] Morrissey J. The energy challenge in sub-Saharan Africa: A guide for advocates and policy makers - Part 2: addressing energy poverty. Oxfam Research Backgrounder; 2017.
[43] IRENA. Electricity storage and renewables: Costs and markets to 2030. Abu Dhabi: International Renewable Energy Agency; 2017.
[44] Trotter PA, Abdullah S. Re-focusing foreign involvement in sub-Saharan Africa's power sector on sustainable development. Energy Sustain Dev 2018;44:139–46. https://doi.org/10.1016/j.esd.2018.03.003.
[45] Gossel SJ. FDI, democracy and corruption in Sub-Saharan Africa. J Pol Model 2018;1–16. https://doi.org/10.1016/j.jpolmod.2018.04.001.
[46] Trotter PA. Rural electrification, electrification inequality and democratic institutions in sub-Saharan Africa. Energy Sustain Dev 2016;34:111–29. https://doi.org/10.1016/j.esd.2016.07.008.
[47] Trotter PA, Maconachie R, McManus MC. The impact of political objectives on optimal electricity generation and transmission in the Southern African Power Pool. J Energy South Afr 2017;28:27–42. https://doi.org/10.17159/2413-3051/2017/v28i3a2451.
[48] Afful-Dadzie A, Afful-Dadzie E, Awudu I, Banuro JK. Power generation capacity planning under budget constraint in developing countries. Appl Energy 2017;188:71–82. https://doi.org/10.1016/j.apenergy.2016.11.090.
[49] Silva PP da, Cerqueira PA, Ogbe W. Determinants of renewable energy growth in Sub-Saharan Africa: evidence from panel ARDL. Energy 2018;156:45–54. https://doi.org/10.1016/J.ENERGY.2018.05.068.
[50] Pfenninger S, Hawkes A, Keirstead J. Energy systems modeling for twenty-first century energy challenges. Renew Sustain Energy Rev 2014;33:74–86. https://doi.org/10.1016/j.rser.2014.02.003.
[51] Antunes CH, Henriques CO. Multi-objective optimization and multi-criteria analysis models and methods for problems in the energy sector. In: Greco S, Ehrgott M, Figueira JR, editors. Mult. Criteria Decis. Anal. State Art Surv, vols. 1 & 2. International Series in Operations Research & Management Science; 2016. p. 1355. https://doi.org/10.1007/b100605.
[52] Diakoulaki D, Karangelis F. Multi-criteria decision analysis and cost–benefit analysis of alternative scenarios for the power generation sector in Greece. Renew Sustain Energy Rev 2007;11:716–27. https://doi.org/10.1016/J.RSER.2005.06.007.
[53] Bhattacharyya SC, Timilsina GR. A review of energy system models. Int J Energy Sect Manag 2010;4:494–518. https://doi.org/10.1108/17506221011092742.
[54] Howells M, Rogner H, Strachan N, Heaps C, Huntington H, Kypreos S, et al. OSeMOSYS: the open source energy modeling system: an introduction to its ethos, structure and development. Energy Pol 2011;39:5850–70. https://doi.org/10.1016/J.ENPOL.2011.06.033.
[55] Herbst A, Toro F, Reitze F, Jochem E. Introduction to energy systems modelling. Swiss J Econ Stat 2012;148:111–35.
[56] Fairuz SMC, Sulaiman MY, Lim CH, Mat S, Ali B, Saadatian O, et al. Long term strategy for electricity generation in Peninsular Malaysia – analysis of cost and carbon footprint using MESSAGE. Energy Pol 2013;62:493–502. https://doi.org/10.1016/J.ENPOL.2013.08.005.
[57] Arndt C, Davies R, Gabriel S, Makrelov K, Merven B, Hartley F, et al. A sequential approach to integrated energy modeling in South Africa. Appl Energy 2016;161:591–9. https://doi.org/10.1016/J.APENERGY.2015.06.053.
[58] Vaillancourt K, Alcocer Y, Bahn O, Fertel C, Frenette E, Garbouj H, et al. A Canadian 2050 energy outlook: analysis with the multi-regional model TIMES-Canada. Appl Energy 2014;132:56–65. https://doi.org/10.1016/J.APENERGY.2014.06.072.
[59] Amorim F, Pina A, Gerbelová H, Pereira da Silva P, Vasconcelos J, Martins V. Electricity decarbonisation pathways for 2050 in Portugal: a TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modelling. Energy 2014;69:104–12. https://doi.org/10.1016/j.energy.2014.01.052.
[60] Lund H, Duić N, Krajačić G, Graça Carvalho M da. Two energy system analysis models: a comparison of methodologies and results. Energy 2007;32:948–54. https://doi.org/10.1016/j.energy.2006.10.014.
[61] Østergaard PA. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Appl Energy 2015;154:921–33. https://doi.org/10.1016/J.APENERGY.2015.05.086.
[62] Lund H, Mathiesen BV. Energy system analysis of 100% renewable energy systems-The case of Denmark in years 2030 and 2050. Energy 2009;34:524–31. https://doi.org/10.1016/j.energy.2008.04.003.
[63] Liu W, Lund H, Mathiesen BV. Large-scale integration of wind power into the existing Chinese energy system. Energy 2011;36:4753–60. https://doi.org/10.1016/J.ENERGY.2011.05.007.
[64] Pohekar SD, Ramachandran M. Application of multi-criteria decision making to sustainable energy planning—a review. Renew Sustain Energy Rev 2004;8:365–81. https://doi.org/10.1016/J.RSER.2003.12.007.
[65] Løken E. Use of multicriteria decision analysis methods for energy planning problems. Renew Sustain Energy Rev 2007;11:1584–95. https://doi.org/10.1016/J.RSER.2005.11.005.
[66] Aly A, Jensen SS, Pedersen AB. Solar power potential of Tanzania: identifying CSP and PV hot spots through a GIS multicriteria decision making analysis. Renew Energy 2017;113:159–75. https://doi.org/10.1016/J.RENENE.2017.05.077.
[67] Akash BA, Mamlook R, Mohsen MS. Multi-criteria selection of electric power plants using analytical hierarchy process. Elec Power Syst Res 1999;52:29–35. https://doi.org/10.1016/S0378-7796(99)00004-8.
[68] Jones M, Hope C, Hughes R. A multi-attribute value model for the study of UK energy policy. J Oper Res Soc 1990;41:919–29. https://doi.org/10.2307/2583270.
[69] Beccali M, Cellura M, Mistretta M. Decision-making in energy planning. Application of the Electre method at regional level for the diffusion of renewable energy technology. Renew Energy 2003;28:2063–87. https://doi.org/10.1016/S0960-1481(03)00102-2.
[70] Goumas M, Lygerou V. An extension of the PROMETHEE method for decision making in fuzzy environment: ranking of alternative energy exploitation projects. Eur J Oper Res 2000;123:606–13. https://doi.org/10.1016/S0377-2217(99)00093-4.
[71] Nakano S, Washizu A. A panoramic analysis of hydrogen utilization systems: using an input-output table for next generation energy systems. Procedia CIRP 2017;61:779–84. https://doi.org/10.1016/J.PROCIR.2016.11.139.
[72] Böhringer C, Rutherford TF. Transition towards a low carbon economy: a computable general equilibrium analysis for Poland. Energy Pol 2013;55:16–26. https://doi.org/10.1016/J.ENPOL.2012.11.056.
[73] Forrest S, MacGill I. Assessing the impact of wind generation on wholesale prices and generator dispatch in the Australian National Electricity Market. Energy Pol 2013;59:120–32. https://doi.org/10.1016/J.ENPOL.2013.02.026.
[74] Figueiredo NC, Pereira da Silva P. Explanatory variables on South-West spot electricity markets integration. In: Godinho P, Dias J, editors. Assess. Methodol. Energy, mobil. Other real world appl. Imprensa da Universidade de Coimbra; 2015. p. 65–88.
[75] Zhao X, Zhang Y, Liang J, Li Y, Jia R, Wang L. The sustainable development of the economic-energy-environment (3E) system under the carbon trading (CT)

mechanism: a Chinese case. Sustainability 2018;10:98. https://doi.org/10.3390/su10010098.
[76] Kancs D, Wohlgemuth N. Evaluation of renewable energy policies in an integrated economic-energy-environment model. For Policy Econ 2008;10:128–39. https://doi.org/10.1016/J.FORPOL.2007.06.003.
[77] Meng S, Siriwardana M, McNeill J, Nelson T. The impact of an ETS on the Australian energy sector: an integrated CGE and electricity modelling approach. Energy Econ 2018;69:213–24. https://doi.org/10.1016/J.ENECO.2017.11.017.
[78] Yophy H, Jeffrey BY, Chieh-Yu P. The long-term forecast of Taiwan's energy supply and demand: LEAP model application. Energy Pol 2011;39:6790–803. https://doi.org/10.1016/j.enpol.2010.10.023.
[79] Mcpherson M, Karney B. Long-term scenario alternatives and their implications: LEAP model application of Panama's electricity sector. Energy Pol 2014;68:146–57. https://doi.org/10.1016/j.enpol.2014.01.028.
[80] Pan L, Li Z, Wang Y. A dynamic input–output method for energy system modeling and analysis. Chem Eng Res Des 2018;131:183–92. https://doi.org/10.1016/J.CHERD.2017.11.032.
[81] Blair N, Zhou E, Getman D, Arent DJ. Electricity capacity expansion modeling, analysis, and visualization: A summary of selected high-renewable modeling experiences. National Renewable Energy Laboratory (NREL); 2015.
[82] Cole W, Frew B, Mai T, Sun Y, Bistline J, Blanford G, et al. Variable renewable energy in long-term planning models: A multi-model perspective. National Renewable Energy Laboratory (NREL); 2017.
[83] Poncelet K, Delarue E, Six D, Duerinck J, D'haeseleer W. Impact of the level of temporal and operational detail in energy-system planning models. Appl Energy 2016;162:631–43. https://doi.org/10.1016/J.APENERGY.2015.10.100.
[84] Sterl S, Liersch S, Koch H, Van Lipzig NPM, Thiery W. A new approach for assessing synergies of solar and wind power: implications for West Africa. Environ Res Lett 2018;13. https://doi.org/10.1088/1748-9326/aad8f6.
[85] Bekker B, Eberhard A, Gaunt T, Marquard A. South Africa's rapid electrification programme: policy, institutional, planning, financing and technical innovations. Energy Pol 2008;36:3125–37. https://doi.org/10.1016/J.ENPOL.2008.04.014.
[86] Zvoleff A, Kocaman AS, Huh WT, Modi V. The impact of geography on energy infrastructure costs. Energy Pol 2009;37:4066–78. https://doi.org/10.1016/J.ENPOL.2009.05.006.
[87] Cader C, Blechinger P, Bertheau P. Electrification planning with focus on hybrid mini-grids – a comprehensive modelling approach for the global South. Energy Procedia 2016;99:269–76. https://doi.org/10.1016/J.EGYPRO.2016.10.116.
[88] Mentis D, Howells M, Rogner H, Korkovelos A, Arderne C, Zepeda E, et al. Lighting the World: the first application of an open source, spatial electrification tool (OnSSET) on Sub-Saharan Africa. Environ Res Lett 2017;12. https://doi.org/10.1088/1748-9326/aa7b29.
[89] Moksnes N, Korkovelos A, Mentis D, Howells M. Electrification pathways for Kenya–linking spatial electrification analysis and medium to long term energy planning. Environ Res Lett 2017;12. https://doi.org/10.1088/1748-9326/aa7e18.
[90] Bissiri M, Moura P, Figueiredo NC, Pereira da Silva P. A geospatial approach towards defining cost-optimal electrification pathways in West Africa. Energy 2020:117471. https://doi.org/10.1016/j.energy.2020.117471.
[91] Ouedraogo BI, Kouame S, Azoumah Y, Yamegueu D. Incentives for rural off grid electrification in Burkina Faso using LCOE. Renew Energy 2015;78:573–82. https://doi.org/10.1016/J.RENENE.2015.01.044.
[92] Moner-Girona M, Bódis K, Huld T, Kougias I, S S. Universal access to electricity in Burkina Faso: scaling-up renewable energy technologies. Environ Res Lett 2016;11. https://doi.org/10.1088/1748-9326/11/8/084010.
[93] Ministère de l'Energie du Burkina Faso. Plan Directeur National Production - transport - Distribution et d'Electrification Rurale. 2017.
[94] IED. Plan directeur de développement du sous-secteur de l'énergie électrique au Bénin - rapport Final - tome 2: plan d'expansion des moyens de production. IED Innovation Energie Développement; 2015.
[95] IED. Plan directeur de développement du sous-secteur de l'énergie électrique au Bénin - rapport final - tome 4: électrification rurale. IED Innovation Energie Développement; 2015.
[96] Kemausuor F, Adkins E, Adu-Poku I, Brew-Hammond A, Modi V. Electrification planning using Network Planner tool: the case of Ghana. Energy Sustain Dev 2014;19:92–101. https://doi.org/10.1016/J.ESD.2013.12.009.
[97] Energy Commission. Integrated power system master plan for Ghana - Volume#2 - Main report (2018 Draft). USAID/Ghana IRRP Project, Energy Commission; 2018.
[98] IED. Improving Economic and Social Impact of Rural Electrification (IMPROVES-RE): Amélioration de l'impact social et économique de l'électrification rurale - Burkina Faso, Cameroun, Mali et Niger - D5 - plans locaux d'électrification rurale: approche multisectorielle et impact sur la réduction de la pauvreté. IED Innovation Energie Développement; 2006.
[99] Adaramola MS, Paul SS, Oyewola OM. Assessment of decentralized hybrid PV solar-diesel power system for applications in Northern part of Nigeria. Energy Sustain Dev 2014;19:72–82. https://doi.org/10.1016/J.ESD.2013.12.007.
[100] Ikejemba ECX, Schuur P. Locating solar and wind parks in South-Eastern Nigeria for maximum population coverage: a multi-step approach. Renew Energy 2016;89:449–62. https://doi.org/10.1016/j.renene.2015.12.024.
[101] Sanoh A, Parshall L, Sarr OF, Kum S, Modi V. Local and national electricity planning in Senegal: scenarios and policies. Energy Sustain Dev 2012;16:13–25. https://doi.org/10.1016/J.ESD.2011.12.005.
[102] Japan International Cooperation Agency (JICA). Final report on the master plan study on power supply in western area in the Republic of Sierra Leone. JICA; 2009.
[103] Adeoye O, Spataru C. Sustainable development of the West African Power Pool: increasing solar energy integration and regional electricity trade. Energy Sustain Dev 2018;45:124–34. https://doi.org/10.1016/J.ESD.2018.05.007.
[104] Barasa M, Bogdanov D, Oyewo AS, Breyer C. A cost optimal resolution for Sub-Saharan Africa powered by 100% renewables in 2030. Renew Sustain Energy Rev 2018;92:440–57. https://doi.org/10.1016/j.rser.2018.04.110.
[105] Taliotis C, Shivakumar A, Ramos E, Howells M, Mentis D, Sridharan V, et al. An indicative analysis of investment opportunities in the African electricity supply sector — using TEMBA (The Electricity Model Base for Africa). Energy Sustain Dev 2016;31:50–66. https://doi.org/10.1016/J.ESD.2015.12.001.
[106] Mabuza LOK, Brent a C, Mapako M. The transfer of energy technologies in a developing country context-towards improved practice from past successes and failures. Proc World Acad Sci Eng Technol (PWASET), Prague 2007;22:237–41.
[107] Nygaard I. Compatibility of rural electrification and promotion of low-carbon technologies in development countries: the case of Solar PV for Sub-Saharan Africa. Eur Rev Energy Mark 2009;3:125–58.
[108] Moner-Girona M. A new tailored scheme for the support of renewable energies in developing countries. Energy Pol 2009;37:2037–41. https://doi.org/10.1016/j.enpol.2008.11.024.
[109] De Jonghe C, Delarue E, Belmans R, D'haeseleer W. Determining optimal electricity technology mix with high level of wind power penetration. 2011. https://doi.org/10.1016/j.apenergy.2010.12.046.
[110] Koltsaklis NE, Dagoumas AS. State-of-the-art generation expansion planning: a review. Appl Energy 2018;230:563–89. https://doi.org/10.1016/J.APENERGY.2018.08.087.
[111] Hancock KJ. Energy regionalism and diffusion in Africa: how political actors created the ECOWAS center for renewable energy and energy efficiency. Energy Res Soc Sci 2015;5:105–15. https://doi.org/10.1016/j.erss.2014.12.022.
[112] Solargis. Solar resource maps and GIS data for 200+ countries. 2018. https://solargis.com/maps-and-gis-data/overview/. [Accessed 12 May 2018].
[113] Global IRENA. Atlas for renewable energy. 2018. https://irena.masdar.ac.ae/GIS/?map=2742. [Accessed 7 May 2018].
[114] Bhatia M, Angelou N. Beyond connections: Energy access redefined. Washington DC: Energy Sector Management Assistance Program/World Bank; 2015.