Sustainability assessment for West Africa's interconnected electricity network.

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1. Introduction

In 2017, approximately 994 million people worldwide had no access to electricity, with 60% of this population living in sub-Sahara Africa [1]. Increasing electricity access is a necessity for the sustainable development of any country. Hence providing reliable and affordable electricity to people without access to electricity by 2030 is one of the targets of the Sustainable Development Goal (SDG) 7 and Sustainable Energy for All (SEforAll) initiative. In order to achieve this ambitious target for the 171 million people in West Africa without access to electricity, the ECOWAS (Economic Community of West African States) Renewable Energy Policy (EREP) was defined in 2015 with several targets for 2030 [2]. First, increase electricity access in all member states to 100%. Second, 75% of the ECOWAS population will be connected to the grid, with the remaining 25% connected to mini-grids and stand-alone systems. Third, increasing grid connected renewable energy installed capacity to 48%. Fourth, reduce greenhouse gas (GHG) emissions in the energy sector (no specific benchmark was set). Furthermore, a few of the member states of ECOWAS have set national RE policies to increase electricity generation from renewable energy sources (RES) with the targets varying between the countries [3]. In line with the EREP targets, the West African Power Pool in 2015 set additional targets for the region [4]. These targets include interconnecting the electricity grid of all fourteen member states, establishing a single regional electricity market and developing large regional RE power plants by 2025. Despite political cooperation between member states and increasing research on RE potentials in the region, lack of well-defined national RE policies and increasing oil and coal power plant developments to meet rapidly growing demand [5] continue to hinder the success of the aforementioned targets. These new fossil fuel power plants will consequently increase the GHG emissions from the electricity sector. Given the continuous conflicting implementation of national and regional projects, there is need for a consensus on an optimum electricity mix and interconnection expansion policy which will consider technical, economic and environmental aspects of each country. Therefore, the objective of this study is to answer the research question "What is the sustainability assessment of the proposed national and regional generation and interconnection plans for each West African country".

Numerous studies have modelled the optimization and operation of electricity networks with high integration of intermittent RES. These studies have used several methodologies which have been reviewed in literature [6–9]. These reviewed models deal with the economic dispatch of the examined electricity generation facilities in order to meet the system load requirements, while subject to a number of economic, technical and environmental criteria. Multi Criteria Decision Analysis (MCDA) methods are frequently used in assessing, ranking and selecting sustainable electricity technologies and policies. MCDM methods combine the various and sometimes conflicting sustainable objectives of stakeholders to produce potential collaborative solutions [10]. In-depth reviews of studies using MCDA methods in energy system planning are presented in several literatures [10–15], with the strengths and limitations of frequently used methods highlighted. Additionally, comprehensive lists of the sustainable assessment criteria/indicators that cut across technical economic, environmental and social aspects are presented in the aforementioned review papers. Majority of the academic studies on the use

MCDA in the electricity sector are focused on the selection/ranking of sustainable renewable energy technologies, with limited studies on future electricity policy assessments [13].

This study applies an optimization model and MCDA to identify, assess, and rank electricity generation and interconnection scenarios in West African countries. We first identify four scenarios for 2030 that differ in terms of potential RES integration and electricity interconnections. These scenarios incorporate national and regional policies/targets aimed at addressing the challenges facing the electricity sector in West African countries. We then optimize these scenarios and analyse the impact of increased cross-border electricity trade and high RES integration on each country. Finally, the four scenarios are compared using PROMETHEE II method and eight defined sustainable energy indicators. This comparison will help to inform energy policy makers on deciding sustainable strategies for the efficient integration of RES and interconnection capacities in ensuring a reliable electricity network, lower electricity prices and reduced GHG emissions.

2. Methods

2.1. Model

PLEXOS Integrated Energy Modelling tool is used in this study and is developed by Energy Exemplar for the planning, simulation and optimization of electricity systems. The model developed in PLEXOS for the West African region has a temporal resolution of 1 hour in 2025 and a spatial resolution of 33 sub-regions, with each sub-region's location equivalent to the interconnection point in each of the 14 countries under this study. By dividing the entire West African region into 33 sub-regions, we account for the hourly intermittent characteristics of the RES in various sites in each country, and also aggregate the power plants in each country based on their fuel type and sub-regions. The power plants in each country are aggregated based on their type of technology and their proximity to their closest region. We modelled the existing and planned 25 interconnection lines between the 14 countries by their maximum flow capacity. The optimization process used in this study is presented in Figure 1.

The thermal power plants (coal, gas, diesel, heavy fuel and biomass) are modelled by defining their heat rate, installed capacity, capacity factor, minimum stable levels and emission rates. To account for grid stability in the electricity network, the ramp rates of the hydro and conventional power plants have been modelled. In the event of sudden decrease in electricity production from solar and wind power plants due to the fluctuating nature of their resources, available power plants respond and increase their load levels according to their modelled ramp rates. Hydro power plants which include both dam and run-off-the river power plants, are modelled by defining their installed capacities and maximum annual energy production levels. Wind and solar power plants are modelled based on their installed capacity, capacity factor and hourly output profiles. The economic and operating assumptions for the generation technologies are presented in Table A.1 and A.2.

2.2.Scenarios

In order to quantify the technical and economic impact of increasing cross-border electricity trade and high RES integration, we examined four scenarios. In the *Business as Usual(BAU)* scenario, we assume all national and regional power plants currently in planning phase are fully operational. On the other hand, interconnection capacities remain the same as in 2019 with only 9 countries interconnected (2.5GW). The *Renewable* scenario has the same interconnection capacity as the *BAU* scenario and seeks to utilize the unexploited hydro resources in the West African region. We assume potential run-of-the-river hydro power plants (5GW) are in operation in addition to the *BAU* scenario installed capacities. Additionally, we identified pumped hydro energy storage (PHES) in the region (1GW). The technical potential of grid connected solar PV potential in West African region is estimated between 900 – 3200 TWh/year in suitable areas [16]. Based on these estimates, for the *Renewable* scenario we assume additional solar PV capacities (38 GW) in order to meet the EREP's objective of increasing grid connected renewable energy installed capacity to 48%. This additional solar PV capacities in the *Renewable* scenario, are then divided equally between the different regions in each country in order to represent the intermittent characteristics of solar resources in different locations. In the *BAU NewLines* and *Renewable NewLines* scenario we assume the plans for WAPP to interconnect all 14 west African countries is successful. Therefore, all the twenty-five existing and proposed interconnections fully operational. The installed capacities for the *BAU* and *Renewable* scenarios are presented in Table 1.

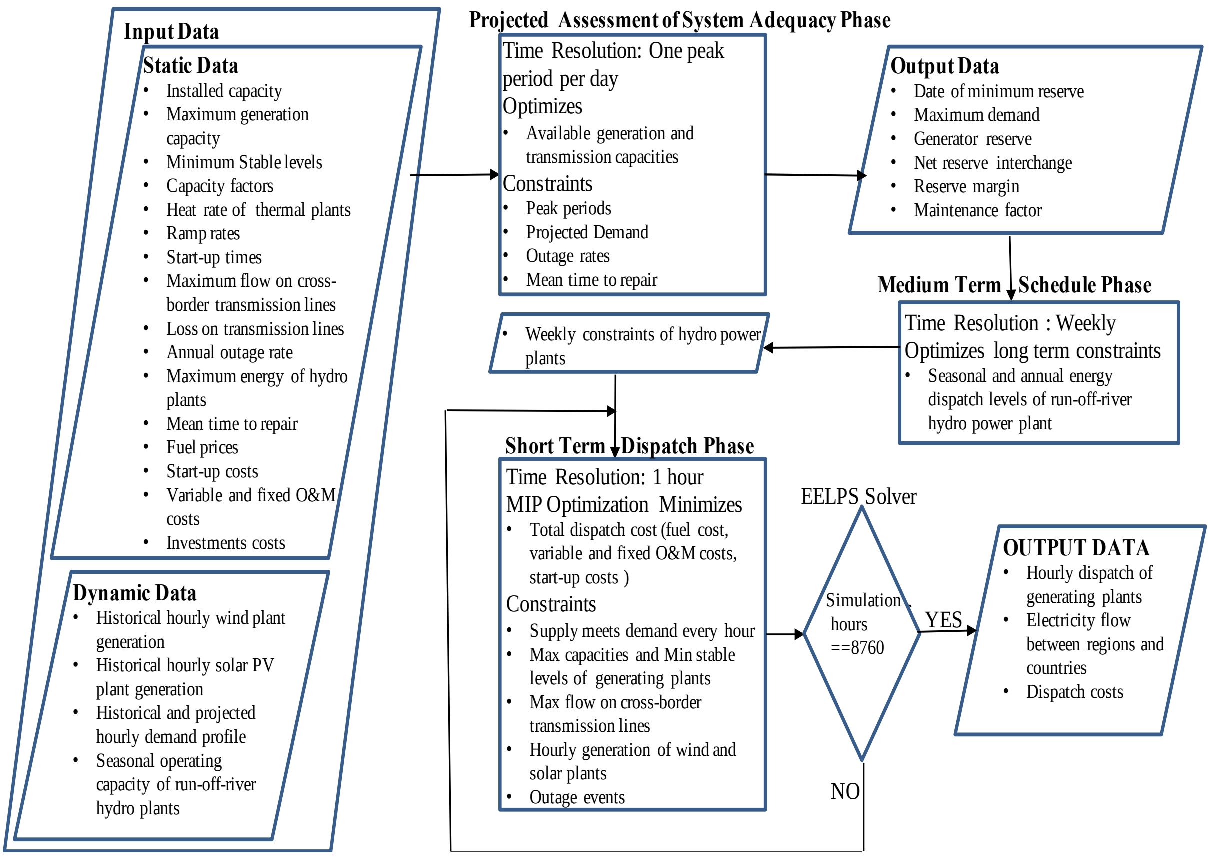

Figure 1. Flow Chart of West African PLEXOS model [17]

Country	*Business as Usual Scenario (MW)*									*Renewable Scenario (MW)*		
	Gas	Diesel	Heavy Fuel	Coal	Hydro	Solar PV	Solar CSP	Wind	Biomass	Hydro	Pumped Hydro	Solar PV
Benin	550	93	0	0	0	132	15	0	5	160	0	660
Burkina Faso	0	243	0	0	29	368	0	0	0	101	0	1840
Cote d Ivoire	1908	0	0	700	1257	438	0	0	71	1834	0	2190
Gambia	0	6	90	0	0	30	0	5	0	0	0	150
Ghana	1443	946	0	0	1580	678	0	225	0	1891	524	3390
Guinea	0	179	90	0	1802	0	0	0	0	3814	0	0
Guinea Bissau	0	21	0	0	20	0	0	0	0	20	0	0

Liberia	0	23	28	0	64	0	0	0	0	947	0	0
Mali	0	147	41	0	455	643	0	1	0	605	0	3215
Niger	0	144	0	636	130	152	0	0	0	279	0	760
Nigeria	12150	0	0	1200	6348	6491	600	10	0	6348	394	32456
Senegal	0	305	186	125	128	378	0	225	15	128	0	1890
Sierra Leone	0	64	0	0	238	5	0	0	15	827	128	25
Togo	0	31	100	0	214	137	15	25	0	264	0	685

Table 1: Installed capacities in the different scenarios.

2.3.Sustainability Criteria

In this study, we have identified 8 sustainability criteria which have been grouped into 3 categories: technical, economic and environmental. The technical criteria reflect the ability of the grid to continuously meet electricity demand at all times and they include: system reliability, electricity import independence and peak demand response. System reliability (%) is a measure of the total electricity demand met in the year, unmet demand is typically due to insufficient generating capacities which leads to unplanned outages and load shedding. Electricity import independence (%) estimates the security of supply of a national grid in terms of self-sufficiency, where countries with high dependence on electricity import are vulnerable to sudden disruptions in supply. Peak demand response is the ability of the installed capacity in a country to respond quickly to peak demand. A response factor is assigned to each of the power plants based on their ramp rates. PHES has the highest response factor (0.3) due to its electricity storage capability, while solar PV and wind have the lowest response factors (0) due to their intermittent nature. These 3 technical criteria are beneficial criteria which means that a higher value is better. The economic criteria are average marginal cost and annual electricity generation cost, which reflect the ability to provide affordable electricity to consumers and consequently encourage competition among suppliers in the electricity sector. Average marginal cost ($/MWh) is used to set the electricity price in each country, and takes into consideration the electricity supplied to the grid in addition to the fuel and variable O&M costs of the power plants. In addition to the fuel and variable O&M, the annual electricity generation cost includes the fixed cost of running and maintaining all the power plant over the year. It is important to note that investment cost for the additional power plants has not been included as a criteria because significant share of the proposed power plants are regional based and plan to be funded through WAPP and ECOWAS. Therefore, the impact of investment cost on individual countries will be a challenge to quantify. These 2 economic criteria are non-beneficial criteria which means that a lower value is better.

The environmental criteria include CO_2, NO_x, and SO_2 emissions and reflect the total amount of GHG emissions generated by each country in each scenario. Furthermore, they give an indication on the impact of RES in replacing electricity generated from fossil fuel plants. The emission from the different power plants used in this study are presented in Table A.1. Similar to the economic criteria, the 3 environmental criteria are non-beneficial. Each of the 8 aforementioned criteria are given a weight which signifies the relative importance of the criteria in achieving the sustainability targets. Consequently, the weight of a criteria plays a significant role in the resultant ranking of the different scenarios. Criteria weighing can be subjective, objective or a combination of both [6]. Subjective weighing is determined by the chosen preferences of stakeholders and decision makers. However, it was difficult to get technical, economic and environmental stakeholders in the electricity sector of the 14 West African countries to participate in weighing the 8 chosen criteria. Therefore, objective method was the selected method for weighing the criteria in this study. We assume 5 weighing outlooks to assess the sensitivity of the planning scenarios' ranking when the criteria categories are given equal importance, or when one or more of the categories is assigned a higher relative importance. In all the 5 weighing outlooks, the weight assigned to a criteria category is divided equally among its respective criteria. The first outlook is the *Equal Weight* where all the 3 categories are assumed to be equally important , and the second outlook is the *Technical Priority* which assumes the technical reliability of the grid is the most important criteria. The third outlook is the *Economic Priority* which has a business focus orientation and economic criteria are considered the most important. The *Techno-economic Priority* is a more realistic outlook where providing reliable and affordable electricity to consumers is considered the most important criteria. Finally, the *Environmental Priority* considers the GHG emission impact on the environment to be the most important criteria. A summary of each of the 5 weighing outlooks is presented in Table A.3.

2.4. Application of PROMETHEE II method

PROMETHEE methods for MCDA was developed by Brans et al [18] to rank alternatives using pair-wise comparison, while taking into account several criteria. PROMETHEE I and PROMETHEE II are used for partial and complete ranking of alternatives respectively. Therefore, PROMETHEE II method is applied to the above-mentioned scenarios and criteria. An evaluation matrix X is constructed as shown in Eq.(1). Where *m* is the number of scenarios (4), *n* is the number of criteria (8), and x_{ij} element in the matrix represent the i^{th} scenario of the j^{th} criteria.

$$X = \begin{bmatrix} x_{11} & \dots\dots\dots\dots & x_{1n} \\ x_{m1} & \dots\dots\dots\dots & x_{mn} \end{bmatrix} \quad (1)$$

The performance of the criteria of each scenario is measured in different units as shown in Table A.3. To carry out comparisons between the criteria, the evaluation matrix X is normalized using Eq.(2&3) to transform the elements into non-dimensional values.

$$R_{ij} = \frac{[x_{ij} - \min(x_{ij})]}{[\max(x_{ij}) - \min(x_{ij})]} \quad \text{, if criteria are beneficial} \quad (2)$$

$$R_{ij} = \frac{[\max(x_{ij}) - x_{ij}]}{[\max(x_{ij}) - \min(x_{ij})]} \quad \text{, if criteria are non-beneficial} \quad (3)$$

After normalization, Eq.(4) is used to calculate the performance difference of i^{th} scenario with respect to the other alternatives across all criteria. Where $R_j(a)$ and $R_j(b)$ are the performance of scenarios a and b with respect to criteria *j*.

$$D_j\,(a, b) = R_{aj} - R_{bj} \quad (4)$$

The preference function $P_j(a, b)$ is calculated using Eq.(5&6) and shows the preference between scenario *a* and *b* , with respect to criteria *j* as a function of the performance difference $D_j\,(a, b)$.

$$P_j\,(a, b) = 0, \qquad if\; D_j\,(a, b) \leq 0 \quad (5)$$

$$P_j\,(a, b) = \left(R_{aj} - R_{bj}\right), \qquad if\; D_j\,(a, b) > 0 \quad (6)$$

The next step is to calculate the aggregated preference function $\pi(a,b)$ using Eq.(7) while considering the criteria weight.

$$\pi(a,b) = \frac{\sum_{j=1}^{n} w_j P_j(a,b)}{\sum_{j=1}^{n} w_j} \tag{7}$$

The leaving and entering outranking flows for each i^{th} scenario in comparison to the other scenarios are calculated using Eq.(8&9). The leaving outranking flow φ^{+} for scenario a is the total degree to which scenario a outranks the other scenarios. On the other hand, the entering outranking flow φ^{-} for scenario a is the degree to which all the other scenarios outrank scenario a.

$$\varphi^{+}(a) = \frac{1}{m-1}\sum_{b=1}^{m} \pi(a,b), \qquad (a \neq b) \tag{8}$$

$$\varphi^{-}(a) = \frac{1}{m-1}\sum_{b=1}^{m} \pi(b,a), \qquad (a \neq b) \tag{9}$$

$$\varphi(a) = \varphi^{+}(a) - \varphi^{-}(a) \tag{10}$$

Finally, the net outranking flow for each scenario is calculated from Eq.(10), with the resultant values used to rank the scenarios. The "best" to "worst" scenario is ranked from the maximum to the minimum net outranking flow values.

3. Results

The performance of each country based on the 8 sustainability criteria, in the 4 planning scenarios are presented in Figures 1-7. The figure highlights the conflicting relationship between the technical, economic and environmental criteria for each country. For eleven countries (Benin, Burkina Faso, Gambia, Ghana, Guinea, Guinea Bissua, Liberia, Mali, Senegal, Sierra Leone and Togo) the results were stable across all the five weighing outlooks, with the same scenario (*Renewable NewLines*) having the top rank as the most sustainable scenario despite the varying importance of the different criteria categories. This is as a result of diversifying the electricity generation mix with the integration of RES (44GW), and the additional interconnection lines (7.1GW) in comparison to the *BAU* scenario. The *BAU* and *BAU NewLines* scenarios performed poorly in most of the criteria, and were ranked as the least sustainable scenarios for all the countries. This is due to these 2 scenarios characterized by insufficient generation capacities to meet demand, low share of RES in the electricity generation mix and relatively high utilization of expensive fossil fuel power plants to meet demand in neighbouring countries.

3.1. Benin

In 2018 Benin had an installed capacity of 193 MW, with gas and diesel having a share of 52% and 48% respectively. Benin is currently a net importer of electricity, with 61% (826GWh) of its electricity imported from Nigeria in 2018. The grid-connected electricity demand in Benin by 2030 is forecasted to have a peak demand of 865MW and a total consumption of 3510GWh, which is 3 times its 2018 level. The MCDA results show the most sustainable planning scenario for Benin in all the 5 weighing outlooks is the *Renewable NewLines* scenario, where there is a total installed capacity of 1.5GW. RES account for 57% of the installed capacity, however they have a share of 72% in the annual electricity mix. The interconnections from Niger and Nigeria in this scenario enables Benin to achieve 100% reliability, and lower its GHG emissions and electricity cost (Figure 1), as utilization of gas and diesel power plants are reduced . However, 39% of its annual load is expected to be met from electricity import, which leaves the security of electricity supply in Benin vulnerable to the capacity planning decisions in these 2 countries. Specifically, if an *Economic Priority* outlook is implemented in Nigeria, or if an *Economic or Environmental Priority* outlook is implemented in Niger.

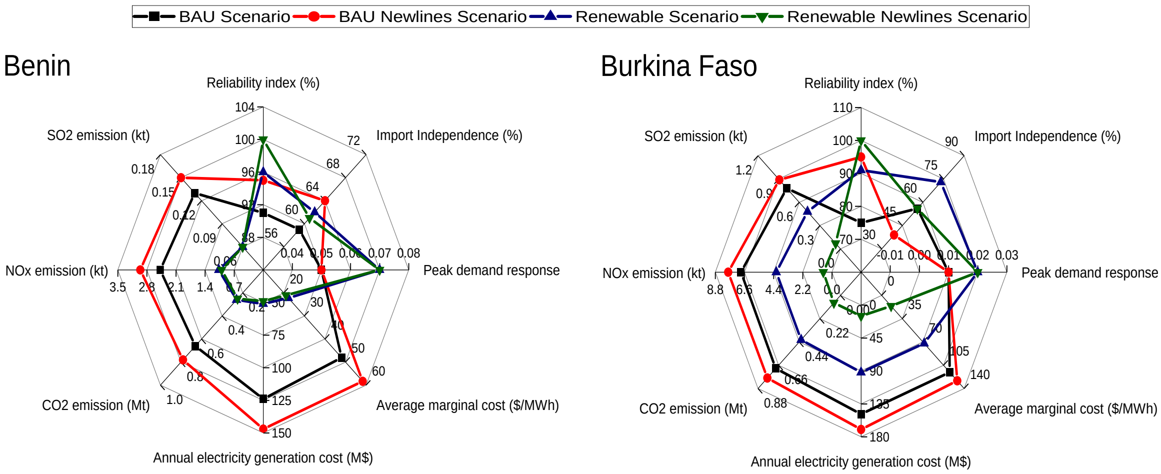

Figure 1. Performance of sustainability criteria in Benin and Burkina Faso's planning scenarios.

3.2 Burkina Faso

The electricity sector in Burkina Faso currently has an installed capacity of 305MW, with diesel power plants accounting for 80% and the remaining 20% are RES. Reliance on imported diesel for electricity generation makes it one of the countries with the highest electricity prices ($220/MWh) in the region. In 2018, 42% (573GWh) of the country's 2018 annual load was imported via the 225kV interconnector to Cote d Ivoire. The 2030 peak and annual demand forecast for Burkina Faso is 1.5GW and 5220GWh respectively. *Renewable NewLines* scenario ranks as the best sustainable scenario for Burkina Faso. With interconnections to 4 countries and 2.2GW installed capacity, RES in this scenario account for 97% of the total electricity generated. There is a significant improvement in performance of all the economic and environmental criteria when compared to the *BAU NewLines* scenario (Figure 1). For example, the average annual marginal cost decreases from $128/MWh to 16$/MWh. Despite the additional 1.5GW RES power plants, Burkina Faso is expected to import 2272 GWh to meet 44% of its grid connected electricity demand. Thereby leaving the security of supply susceptible to the capacity planning in interconnected countries. Niger is expected to be the largest electricity importer to Burkina Faso, however if an *Economic or Environmental Priority* outlook is implemented in Niger, the country's unmet demand and marginal cost will increase significantly.

3.3.Cote d Ivoire

Cote d Ivoire is currently the largest exporter of electricity in the West African region, with 15% (1630GWh) of its electricity supply exported to Burkina Faso, Ghana and Mali in 2018. Its electricity sector has a capacity of 2.9GW, with hydro and gas having 60% and 40% share respectively. Due to its electricity mix and gas reserves, Cote d Ivoire has the lowest electricity price in the region ($118/MWh). Its 2030 grid-connected demand is forecasted to be 14980GWh, with a peak demand of 2.9GW. *Renewable NewLines* scenario is ranked as the best sustainable scenario for Cote D Ivoire in the *Economic Priority* outlook, while *Renewable* scenario has the top position in the remaining four outlooks. In these 2 scenarios, the grid generation capacity of 6.7GW is characterized by 61% RES and they both have equal technical criteria performance (Figure 2). The integration of 2.3GW hydro and solar plants gives Cote d Ivoire the ability to supply 100% of its electricity demand without any reliance on electricity import. However, the interconnection to Liberia in the *Renewable NewLines* scenario provides an opportunity for the country to benefit from the hydro resources in Liberia, and reduce its gas power plant generation. Thus, making it the preferred scenario when economic cost is given more importance. On the other hand, the new interconnection to Ghana leads to the country increasing its coal generation to meet peak demand in Ghana. Consequently, increasing GHG emissions and making the *Renewable NewLines* scenario not the preferred scenario when the impact of electricity generation on the environment is given more importance.

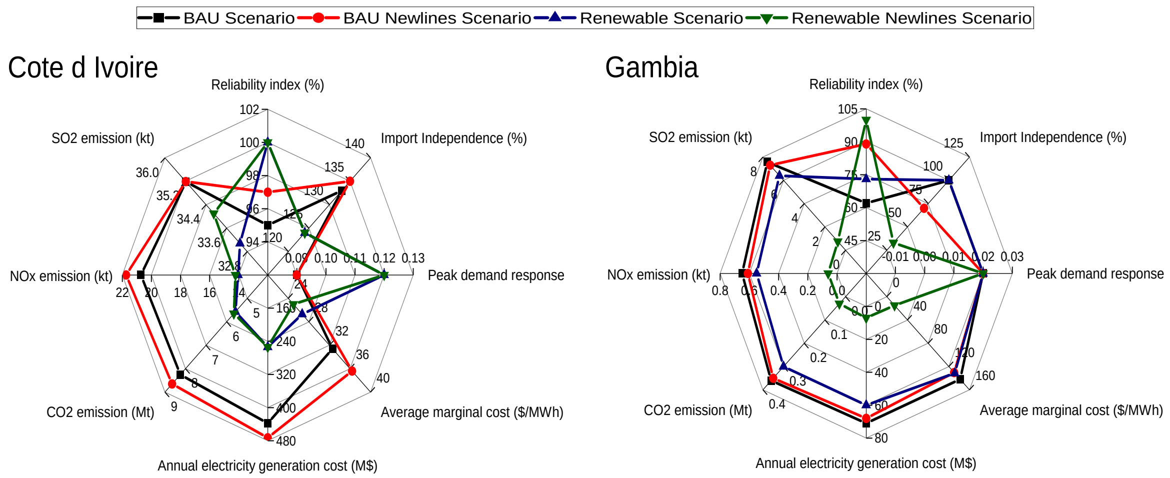

Figure 2. Performance of sustainability criteria in Cote d Ivoire and Gambia's planning scenarios.

3.4.Gambia

Gambia is one of the five countries currently not interconnected in the region, although the OMVG interconnection line which currently in its construction phase [4] will see the country interconnected to Guinea Bissua and Senegal. In 2018, Gambia had an installed capacity of 97MW, consisting of heavy fuel (93%), followed by diesel (6%) and wind (1%) power plants. Its 2030 electricity demand is forecasted to increase four times its 2018 level to 952GWh, with peak a demand of 268MW. The *Renewable NewLines* scenario is ranked the best sustainable scenario for Gambia in all the 5 sets of criteria weighing. This scenario integrates 120MW of solar PV into Gambia's grid and interconnects the country to Guinea Bissua and Senegal. However, Gambia retains its relatively low response to peak demand, as the heavy fuel plants are inadequate in meeting peak demands in the early morning and evening times. In addition to meeting 100% of its annual electricity demand, Gambia's electricity cost and GHG emissions are reduced significantly (Figure 2) in the *Renewable NewLines* scenario. However, these benefits are achieved at the expense of the county's import independence. The simulation results show that in this scenario Gambia relies on electricity import to meet 67% of its demand, which is the highest import dependency in the region. Guinea Bissua and Senegal have *Renewable NewLines* scenario ranked as their sustainable scenario across all criteria weighing outlook. Therefore, despite the risk of dependence on cross-border trading , the scenario is mutually beneficially for all 3 countries.

3.5.Ghana

In 2018, Ghana had the most diversified the installed capacity (3.8GW) which comprised of hydro (48%), gas (26%), diesel (25%), and solar PV (1%) . Ghana is currently a net exporter of electricity in the region, where it imports from Cote d Ivoire and exports to Togo. Ghana has the second highest demand in the region due having the highest electricity access rate in the region. This status is forecasted to continue in 2030, with a peak and annual grid connected demand of 5.8GW and 29.3GWh. The results from the MCDA analysis for Ghana shows that *Renewable NewLines* is the preferred scenario for Ghana in all weighing outlooks, the portion of RES in the electricity mix is 62%, thus aiding in reducing both the total generation cost and GHG emission by up to 15%. Additionally, the 0.5GW of PHES has improved the utilization of solar PV plants and the network's response to peak demand. In the *BAU* scenario, the interconnection to Cote d Ivoire was congested with a 100% capacity utilization. This situation is improved with an additional one to Cote d Ivoire and two interconnections to Burkina Faso. As mentioned earlier, *Renewable NewLines* is not a sustainable scenario for Cote d Ivoire when the impact of GHG emission is a main priority for the country. Therefore, a decrease in import from Cote d Ivoire will reduce the reliability index of Ghana up to 5% resulting in load shedding. The most impact will be the average marginal cost potentially increasing from \$38/MWh to 100\$/MWh.

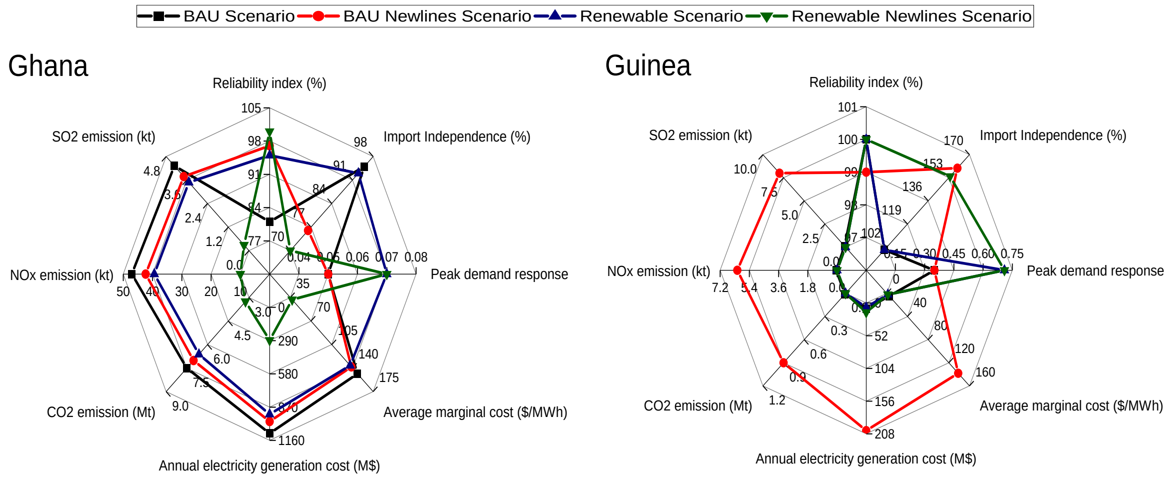

Figure 3. Performance of sustainability criteria in Ghana and Guinea's planning scenarios.

3.6.Guinea

Guinea has the largest hydropower potential in West Africa region, however in 2018 its hydro capacity was 477MW which accounted for 64% of its total installed capacity (746MW), while diesel and heavy fuel power plants accounted for 24% and 12% respectively. Guinea currently has no electricity interconnections, nevertheless given its unexplored hydro resources there are plans for interconnections to 5 neighbouring countries by 2030 [4]. Similar to most West African countries, its 2030 electricity demand is forecasted to increase considerably to 3424GWh and have a peak demand of 608MW. *Renewable NewLines* scenario is the preferred sustainable scenario for Guinea. The additional 2GW hydro power plants in this scenario makes Guinea the country with the highest response to peak load, and has one of lowest average marginal cost (\$2/MWh) (Figure 3). Furthermore, there is no GHG emission from Guinea as the fossil plants are categorized as reserves in case of emergency. With an import independence of 1.68, Guinea has autonomy over its security of supply regardless of the planning decisions in the 5 interconnected countries. It is important to emphasize that the additional hydro plants are planned as regional projects and Guinea is obligated to trade electricity from these plants in the regional market

3.7.Guinea Bissua

Guinea Bissua currently has the lowest demand in the region, a 21MW diesel power plant and no interconnection to any country. This reliance on expensive imported diesel has resulted in the country having the second highest electricity price in the region ($250/MWh). With plans to develop a 20MW hydro power plant and interconnect the country to Guinea and Gambia, 2030 grid connected demand is forecasted to be five times its 2018 level (165GWh with a peak demand of 37GW). The *BAU* and *Renewable* scenario for Guinea Bissua are identical because there is no unexplored hydro potential or proposed solar PV sites in the country . The MCDA results were constant across all five weighing outlooks with *Renewable NewLines* scenario ranked as Guinea Bissau's best sustainable scenario. In this scenario, Guinea Bissua electricity mix is 94% from its hydro plant, as the country imports 48% of its electricity supply from Guinea. The impact of this cross-border trade can be observed in Figure 4, where the average marginal cost is $6/MWh and reliability of supply is 100%. Without the interconnections, reliability was estimated at 96%, therefore any significant decrease in cross-border trading with Guinea will impact only electricity prices and GHG emissions.

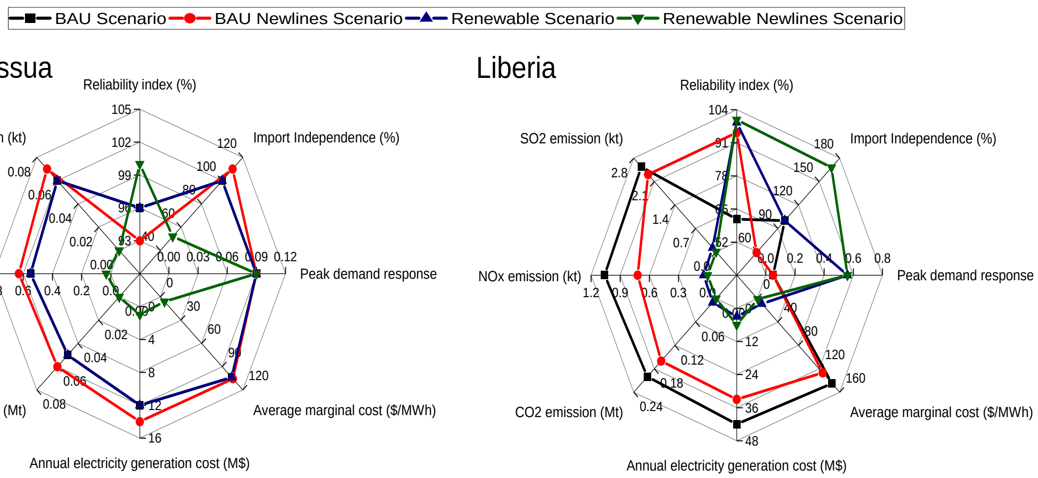

Figure 4. Performance of sustainability criteria in Guinea Bissua and Liberia's planning scenarios.

3.8.Liberia

In 2018, the electricity sector in Liberia had an installed capacity of 119MW, consisting of hydro (56%), heavy fuel (24%) and diesel (20%) power plants. Despite this high share of hydro, Liberia electricity price is $390/MWh, which is currently the highest in the region. This is due to the significant decrease in electricity generation from the hydro plant during dry seasons. Liberia is currently not interconnected, although there are projects in planning phase [4] that will interconnect the country to Cote d Ivoire, Guinea and Sierra Leone. With a 2030 peak and annual demand forecast of 190MW and 892GWh respectively, *Renewable NewLines* scenario is ranked as the best sustainable scenario for Liberia. In this scenario, the electricity generation mix is 100% hydro, thus no GHG emission from Liberia. This high integration of hydro plants gives the country the ability to meet 100% of its grid-connected demand, and a high response to peak demand (Figure 4). In the *Renewable NewLines* scenario, Liberia shifts from having the highest electricity price in the region to the lowest marginal cost ($1/MWh). Similar to

Guinea, the new hydro plants in Liberia are proposed to be financed regionally and are therefore required to trade electricity generated from them in the regional market.

3.9.Mali

The electricity sector in Mali currently has an installed capacity of 314MW, with hydro, diesel and heavy fuel having a share of 69%, 18% and 13% respectively. Mali currently imports an estimated 30% of its electricity supply from Cote d Ivoire, and concurrently exports 15% of its generation to Mauritania and Senegal. This is due to the inter-country hydro plant located on the Senegal river which was developed with the aim of supplying electricity generated to these three countries. The grid-connected electricity demand in Mali by 2030 is forecasted to have a peak demand of 1.2GW and a total consumption of 4830GWh. The MCDA results show that the most sustainable planning scenario for Mali in all the 5 weighing outlooks is the *Renewable NewLines* scenario, where there is an installed capacity of 4GW. RES have a share of 95% of the installed capacity, however they account for 100% of the annual electricity mix as the thermal plants are maintained as reserves. Mali is a net exporter in this scenario, however the interconnection from Guinea assists Mali to meet 100% of its demand and significantly lower its GHG emissions and marginal cost (Figure 5). 80% of the installed capacity in this scenario is from solar PV and due to its non-dispatchable attribute, frequent variation in demand will lead to deployment of the reserves, thus having a negative impact on the economic and environmental criteria.

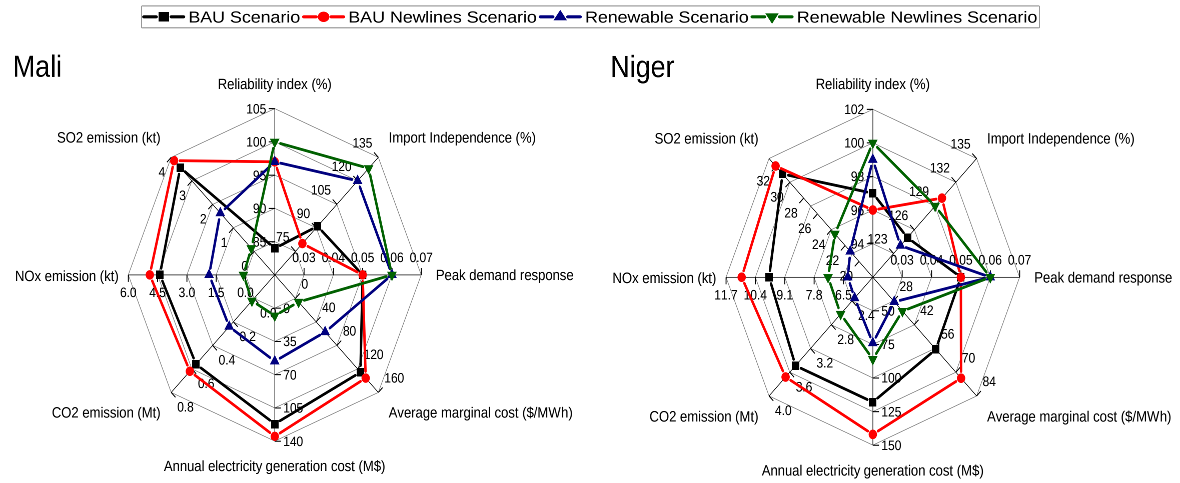

Figure 5. Performance of sustainability criteria in Mali and Niger's planning scenarios.

3.10. Niger

Niger is currently one of the largest importer of electricity in the region, with 58% (655GWh) of its electricity supply imported through the 2 interconnection lines to Nigeria. It has a capacity of 180MW, with diesel and coal accounting for 80% and 20% respectively. Its 2030 grid-connected demand is forecasted to be 3690GWh, with a peak demand of 1.1GW. *Renewable* scenario is ranked as the best sustainable scenario for Niger in the *Economic* and *Environmental Priority* outlooks, while *Renewable NewLines* scenario has the top position in the *Equal*, *Technical* and *Techno-economic Priority* outlooks. In these two scenarios, the grid capacity of 1.8GW is characterized by 57% RES, resulting in a relatively better economic and environmental performance than the *BAU NewLines* scenario (Figure 5). *Renewable NewLines* scenario not the preferred scenario when the impact of electricity generation on the environment and economic indicators are more importance. This is mainly because the new interconnection to Ghana leads to the country increasing its diesel and coal generation to meet peak demand in Burkina Faso. Consequently, increasing electricity generation cost and GHG emissions. Furthermore, in the *Renewable NewLines* scenario Niger has the highest GHG emission per capita.

3.11. Nigeria

Nigeria has the largest natural gas reserve in region and its installed capacity of 13.7GW consists of 85% gas plants and 15% hydro plants. Nigeria currently exports 4% of its generated electricity to Benin and Niger. The country's electricity demand is the highest in the region, and is forecasted to have an annual and peak demand of 115TWh and 25GW respectively by 2030.This will represent up to 60% of the grid connected demand in the region. In an effort to meet this rapidly growing demand, the independent power producers are focused on developing new gas, coal and hydro plants. *Renewable Newlines* scenario is the preferred sustainable scenario for Nigeria except when the economic criteria are given more importance, then the position goes to *Renewable* scenario due to the new interconnection to Niger. In these two scenarios the installed capacity is 53GW, with solar PV, gas and hydro having a share of 62%, 23%, 13% respectively. Despite the high integration of solar PV in the grid, there is no substantial impact on the average marginal cost, as electricity generation from gas still accounts for up to 40% of its annual mix. As expected, Nigeria is the largest contributor of GHG emission in the region, nevertheless the additional solar PV plants in the *Renewable Newlines* scenario reduces the country's emission up to 30% in comparison to the *BAU Newlines* scenario. The PHES is instrumental in reducing load shedding, however its relatively smaller size in comparison to the country's peak demand leads to no change in the country's peak demand response (Figure 6).

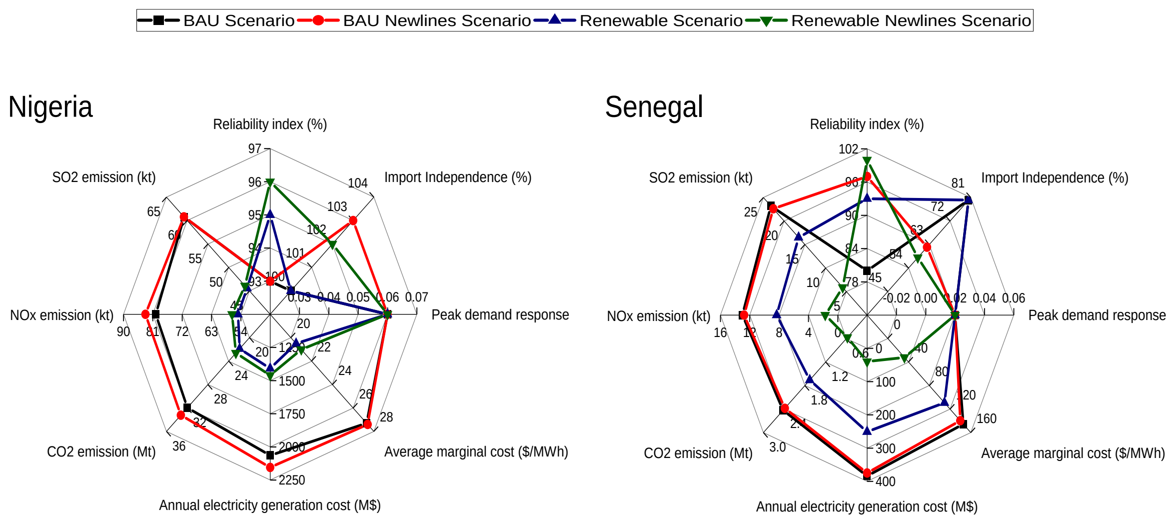

Figure 6. Performance of sustainability criteria in Nigeria and Senegal's planning scenarios.

3.12. Senegal

In 2018, Senegal was the only country in the region with a significant integration of solar PV in its centralized electricity grid. With an installed capacity of 595 MW, diesel, heavy fuel and solar PV had a share of 51%, 31% and 18% respectively. Senegal imported 15% (565GWh) of its electricity supply from Mali and through the OMVG interconnection project [4], Senegal will be connected to Gambia and Guinea by 2030. The grid-connected electricity demand in Senegal by 2030 is forecasted to have a peak demand of 2.2GW and a total consumption of 8615GWh. The most sustainable planning scenario for Senegal in all the 5 weighing outlooks is the *Renewable Newlines* scenario, where there is a total installed capacity of 2.9GW. RES account for 80% of the installed capacity and have a share of 86% in the annual electricity mix, thus highlighting the reduced operations of diesel and heavy fuel plants. The additional 1.5GW solar PV and the interconnections from Guinea and Mali in this scenario enables Senegal to achieve 100% reliability, and significantly lower its GHG emissions and electricity cost (Figure 6). However, 42% of its annual load is met from electricity import, which leaves the security of electricity supply in Senegal susceptible to the capacity planning decisions in Guinea and Mali. Specifically, if economic benefits are not given the most importance in Guinea.

3.13. Sierra Leone

The electricity sector in Sierra Leone currently has an installed capacity of 140MW, consisting of diesel (46%), hydro (43%) and biomass (11%) power plants. Sierra Leone has no electricity interconnections, however there are plans for interconnections to Guinea and Liberia by 2030 [4].Its 2030 electricity demand is forecasted to increase up to five times its 2018 level, to 862GWh and have a peak demand of 166MW. The *Renewable Newlines* scenario is ranked the best sustainable scenario for Sierra Leone in all the 5 sets of criteria weighing. The additional 590MW and 128MW hydro and PHES power plants respectively in this scenario has several benefits for Sierra Leone. First, the country is able to meet 100% of its centralized demand with one of the lowest average marginal cost ($2/MWh) in the region. Secondly it has the second highest response to peak load, and finally there is no GHG emission from the country as the diesel plants are designated as reserve plants. On the other hand, in this scenario there is insufficient low-cost capacity during off-peak periods for the pumping operation of the PHES plant and ends up mostly underutilized.

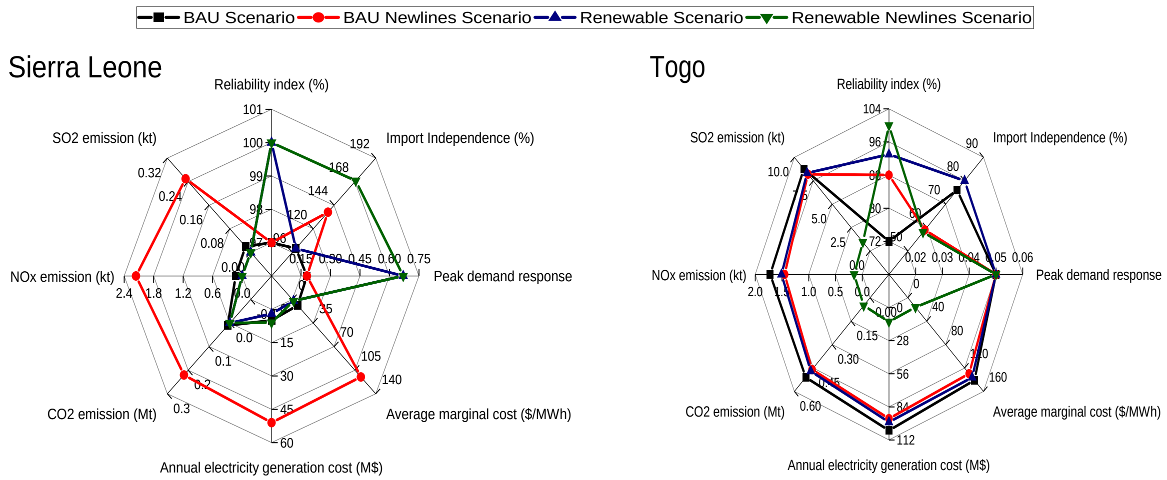

Figure 6.7. Performance of sustainability criteria in Sierra Leone and Togo's planning scenarios.

3.14. Togo

In 2018, Togo had an installed capacity of 167MW spilt between hydro (60%) and heavy fuel(40%) . Togo currently imports an estimated 60% (826GWh) of its electricity supply from Ghana, and there is a project in development to install an additional interconnector to Ghana by 2020 []. The grid-connected electricity demand in Togo by 2030 is forecasted to have a peak demand of 710MW and a total consumption of 3850GWh. The most sustainable planning scenario for Togo in all the 5 weighing outlooks is the *Renewable Newlines* scenario, where there is an installed capacity of 1.1GW. RES have a share of 88% in the installed capacity, and account for 97% of the annual electricity mix. The two interconnections from Ghana in this scenario enables Togo to meet 100% of its demand, significantly reduce its average marginal cost to $16/MWh, and lower its GHG emissions (Figure 7). It is important to note that of all the WAPP proposed interconnections in the region [4], Togo is the only country interconnected to just one country. This leaves the security of electricity supply in Togo vulnerable to capacity planning and cross-border trading policy in Ghana, as it is expected to import 42% of its annual load from Ghana in the *Renewable Newlines* scenario . Therefore, despite the scenario ranking as the preferred sustainable scenario for Togo, the country is at risk of not achieving its sustainability targets in the electricity sector by 2030.

4. Policy implications and recommendations

4.1.Reliability

WAPP and West African countries are making efforts to provide reliable electricity for the forecasted growth in electricity demand in the region. However, with the current generation and interconnection capacity plans (national and regional), only Guinea can meet 100% of its grid connected demand by 2030. Thus, leading to continued unexpected electricity outages and load shedding. On the other hand, by increasing interconnections between countries and the share of RES in the system through solar PV and hydro power plants, reliability in all the countries could potentially be increased to 100%. The presence of additional interconnections in the region provides the opportunity for some countries to import electricity generated from these RES in neighbouring countries. However, countries like Benin, Burkina Faso, Gambia, Guinea Bissua, Senegal and Togo could be dependent on other countries for up to 40% of their electricity supply. Therefore, future national and regional policies need to be orientated towards increasing integration of RES in the West African electricity system and ensuring implementation of cross-border electricity trading agreements.

Presently, all countries in the region have policies for the unbundling and liberalization of its electricity sector. The common motivation in all the countries for this reformation is to increase electricity access and supply, as a step towards economic growth and development. However, as of 2018 Burkina Faso, Guinea Bissua and Liberia were still vertically integrated, while Nigeria and Ghana were fully unbundled. The remaining nine countries are partially unbundled, with transmission and distribution mostly operated by a single government organization and generation opened to the private sector. Additional policies to accelerate the complete liberalization in these twelve countries is required. These policies will attract private investment in generation and distribution to meet and accommodate growing electricity demand respectively. Furthermore, renewable energy auctions should be introduced on a country by country basis to ensure a transparent and detailed commitment of RES electricity generation from independent power producers. As integration of intermittent RES increases, the need to increase the system’s flexibility to accommodate unexpected changes in supply is a priority for reliability of supply. Therefore, policies targeted towards improving system flexibility, such as the use of flexible power plants, energy storage and demand side response are recommended. On a regional level, the WAPP will need to implement policies to reduce import dependency risks, such as addressing the fulfilment of contract obligations and resolving disputes in situations of under-performance. Additional, energy security policies between interconnected countries need to be harmonized to ensure coordinated responses during emergency situations. For transparency, communication policies for frequency and dissemination of operational data are needed. Given the potential increase in cross-border electricity trading, policies to manage congestion and ensure reliable operation of the regional electricity market are needed.

4.2.Affordability

With the current generation and interconnection capacity expansion plans, generation costs in most West African countries are still relatively high, with average marginal cost ranging from an estimated $27/MWh to $140/MWh. This is due to the reliance of electricity generation on imported diesel and heavy fuel to meet national electricity demand and electricity export obligations. With the integration of high shares of RES and additional interconnections in the West African electricity system, average marginal cost could reduce significantly ranging from $1/MWh to $38/MWh. However, in this scenario diesel and heavy fuel are still maintained as reserves, which leaves them susceptible to global price fluctuations. Therefore, future polices need to focus on increasing investments in RES, ensuring affordable and stable electricity prices, and diversifying operating reserves in countries.

Some countries have opted to subsidize electricity tariffs for its citizens, however this financial burden has contributed in hindering several governments in adequately maintaining and expanding its generation capacity. Furthermore, non-payment of electricity bills by both residential and non-residential consumers (including government organizations) is another reason for the financial inadequacy of electricity utility companies in West African countries. On a national level, policies to aid the gradual removal of subsidies in urban cities and enforce the installation of pre-paid meters are encouraged. This strategy will provide revenue flow and enable governments to invest or cost-share with RES developments. Policies and financial support instruments that provide confidence and encourage private sector investments in RES are required. Cross-border electricity trading in WAPP is currently carried out through bilateral trading. This method of trading has the advantage of stable pricing for long periods of time. However, to increase competition and potentially reduce electricity prices by attracting RES generation companies to the regional market, policies for efficient trading in spot market operations are needed. These policies will cover the interconnection capacity allocation for congestion management and day-ahead/intra-day bidding process. In the event of electricity price volatility in the spot market due to the intermittent nature of RES, financial policy mechanisms that protect electricity prices of consumers are required. Bilateral trading and spot market operations can be implemented in parallel, although it will be prudent to revise existing agreements by considering the tariffs and marginal cost of electricity generation in the respective countries.

4.3.GHG emissions

Presently, developing countries do not contribute significantly to the global GHG emission, however this trend is expected to change with increasing economic and industrial changes. The total grid-connected electricity demand in 2030 is forecasted to be four times that of 2018. Given there are currently more plans for fossil fuel capacities in comparison to RES in the region, it is expected there will be an increase in GHG emissions from the electricity sector. The 2030 investment plans for generation and interconnection capacities will result in fossil fuel sources dominating the electricity generation mix with a share of 65%. On the other hand, by increasing RES and interconnection capacities, fossil fuel capacities could account for only 37% in the generation mix, resulting in GHG emissions decreasing by 44% in the region. The EREP's target is to reduce GHG emission by 2030, however there are no specific targets on a national or regional level. Environmental policies are therefore required to ensure that the EREP's other targets of providing reliable and affordable electricity does not result in increasing GHG emissions in the region.

There are no plans by any country for new diesel or heavy fuel generation capacities, however Cote d Ivoire , Niger, Nigeria and Senegal plan on installing new coal plants (2.5GW) before 2030 to meet its rapidly growing demand using a least-cost option. The Paris agreement signed by all the 14 countries in the region needs to be converted into GHG emission reduction polices to change the current investment direction of generation capacities. National policies with emission targets for the electricity sector will reduce the competition that coal capacities have with solar PV, thereby encouraging a switch in investment. Furthermore, policies with emission standards that support the installation of more efficient new power plants should be introduced. For example, the installation of ultra-super critical coal plants over sub-critical ones, or combined cycle gas plants over gas turbine plants. As RES capacities increase in the grid, policies that support the use of storage to balance the grid could reduce the use of stand-by dispatchable diesel and heavy fuel plants. In the absence of environmental policy targets, interconnections can lead to countries importing electricity from power plants with relatively higher GHG emission than the ones in their countries. A regional policy with emission prices will place power plants with higher GHG emissions lower in the electricity dispatch order, thus reducing GHG emissions in the region.

5. Conclusion

Selecting a long-term generation and interconnection capacity planning scenario can be a complicated task, as it requires simultaneously considering the impacts of sometimes conflicting technical, economic and environmental indicators. This study has applied optimization modelling and MCDA in evaluating future electricity planning pathways for West African countries. ECOWAS has set targets to provide affordable and reliable electricity in all 14 West African countries, thereby improving economic growth in the region. Results from this study show that cross-border electricity trading is a feasible option to achieve affordable electricity in the region, provided that there is an increase in grid connected hydro and solar power plants. The scenarios presented in our study show that investments in unexplored hydro and solar resources can achieve the aim of WAPP to reduce the supply-demand gap and GHG emissions in the region. The MCDA analysis of the generation and interconnection scenarios was useful in the sustainable assessment and ranking of future scenarios for West Africa's interconnected electricity network. This study has presented policy recommendations in achieving the multi-dimension objectives of ECOWAS in providing reliable and affordable electricity in a low-carbon system.

Appendix

Power Plant	Capacity factor (%)	Carbon emission ($kgCO_2/MWh$)	Heat Rate (GJ/MWh)	Ramp Rate (% full load/min)	Minimum Stable level (% full load)	Outage Rate (%)
Coal	85	870	9.5	4	20	15
Diesel	80	700	9	7	10	17

Heavy fuel	85	675	9	7	10	17
Gas	85	400	7.5	6	15	15
Biomass	60	-	9.6	6	25	15
Hydro	-	-	-	20	-	6
Pumped Hydro				25	-	6
Solar PV	-	-	-	-	-	5
Solar CSP				8		5
Wind	-	-	-	-	-	5

Table A.1: Operating parameter assumptions for the different generation technologies.

Power Plant	Domestic fuel price (\$/GJ)	Imported fuel price (\$/GJ)	Variable O&M cost (\$/MWh)	Capital cost (\$/kW)	Fixed O&M cost (\$/kW/year)
Coal	2.1	-	3.2	-	45
Diesel	-	15.7	10.1	-	75
Heavy Fuel	-	14	7.1		75
Gas	3.6	9.4	2	-	25
Biomass	3.6	-	4.2	-	75
Hydro	-	-	2	2100	55
Pumped Hydro	-	-	-	2000	200
Solar PV	-	-	-	1400	22
Solar CSP			-	-	150
Wind	-	-	-	-	44

Table A.2: Projected economic parameters for the different generation technologies.

		Weighing Outlooks				
Category	Criteria (Unit)	*Equal Weight*	*Technical Priority*	*Economic Priority*	*Techno-economic Priority*	*Environmental Priority*
Technical	System reliability (%)	0.111	0.233	0.050	0.150	0.050
	Electricity import independence (%)	0.111	0.233	0.050	0.150	0.050
	Peak demand response	0.111	0.233	0.050	0.150	0.050
	Σ	**0.333**	**0.700**	**0.150**	**0.450**	**0.150**
Economic	Average marginal cost (\$/MWh)	0.167	0.075	0.350	0.225	0.075
	Total cost of electricity generation (M\$)	0.167	0.075	0.350	0.225	0.075
	Σ	**0.333**	**0.150**	**0.700**	**0.450**	**0.150**
Environmental	CO_2 emission (Mt)	0.111	0.050	0.050	0.033	0.233
	NO_x emission (kt)	0.111	0.050	0.050	0.033	0.233
	SO_2 emission (kt)	0.111	0.050	0.050	0.033	0.233
	Σ	**0.333**	**0.150**	**0.150**	**0.100**	**0.700**

Table A.3. Weighing outlooks for criteria categories.

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