Understanding the State and Determinants of Water-Energy-Food Security in Africa: A Quantitative Study

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Abstract

To date, there are limited quantitative inter-comparisons and assessments of water-energy-food (WEF) resources availability in Africa, while existing studies do not reveal disparities in WEF security among different sub-regions thus failing to offer lessons for coordinated efforts. This study provides a quantitative evaluation of WEF resources across Africa. In so doing, it develops a composite indicator to assess the state of WEF security and explores the socioeconomic determinants of WEF security in Africa. Results show that, Africa is endowed with enormous resources, however, there are substantial disparities among countries and sub-regions. The water-energy-food security index (WEFSI) scores show that eight countries (15%) obtained high WEFSI scores (>0.61), 31 countries (57%) obtained moderate scores in the range 0.41 – 0.60 while the other countries (28%) obtained low scores (<0.40). Several countries are not on track to achieving water-energy-food security in the short to medium term. We also found that GDP per capita, government effectiveness, foreign direct investment and official development assistance correlate strongly with WEF security. Overall, our findings suggest that whilst WEF resources availability is essential, they do not guarantee WEF security; having the socioeconomic capacity to harness these resources is critical for achieving WEF security. Thus, prospects for achieving SDGs remain slender but centrally lie in national efforts at re-organising governance and economic efforts and how these relate to wider investments. We call for urgent steps to ensure targeted socioeconomic development within and across many countries, to enhance WEF security in Africa.

Keywords: WEF resources assessment; composite indicators; governance; GDP per capita; official development assistance; Sustainable Development Goals.

1. Introduction

The water-energy-food (WEF) security nexus has recently emerged as a new paradigm for understanding the interactions among the WEF systems and how to manage them in an integrated way to understand trade-offs, benefit from synergies and ensure sustainability (Li and Singh, 2020; Howells *et al.*, 2013). Adopting the WEF nexus approach has allowed scientists to raise awareness on the adverse socio-environmental and political outcomes that can result from unsustainable management of WEF resources (van Gevelt, 2020). The application of WEF frameworks are therefore crucial as they can help to inform strategies needed to tackle WEF insecurity, which in turn enhances the achievement of the Sustainable Development Goals (SDGs) given the synergies between SDG2 (no hunger), SDG6 (clean water and sanitation), SDG7 (renewable energy) and the other SDGs (Pham-Truffert *et al.*, 2020; Taka *et al.*, 2021).

Despite the promising contribution of WEF nexus research to the achievement of the SDGs, uptake of research findings appears to be limited. This has been attributed, in part, to the claim that much of the findings relating to WEF nexus-focused research have not yet been translated into implementable policies that can enhance the sustainable management of resources (Venghaus and Dieken, 2019). Stakeholders' inability to adopt WEF nexus research findings has also been linked to the plurality of scales including spatial (local, national, regional or global), temporal (present vs future), institutional and jurisdictional (transboundary river basin or sub-regional); making it difficult to assess interdependencies among the nexus components (McGrane *et al.*, 2019). There are also many different techniques for analysing the WEF security nexus including indicator-based methods, systems dynamic modelling and network analysis (Zhang *et al.*, 2018). Decisions on any specific method is influenced by a range of factors, including individual research priorities, expected WEF outcomes, scale of analysis and data availability (Liu *et al.*, 2017; McGrane *et al.*, 2019). While findings and policy recommendations using the different approaches and at different scales could be fit-for-purpose, their implementation may be hindered by a lack of technical, financial, and institutional capacity (Stein and Jaspersen, 2019). It could also be due to the absence of an integrated regional-scale strategy for monitoring WEF resources disparity and sustainability among countries especially where trade and resources links exist.

Apart from the limited uptake of current findings, there are also concerns regarding the dearth of studies that focus on regional level analysis especially in Africa. Previous published studies using indicator-based methods are limited to the global (Venghaus and Dieken, 2019; Kumar *et al.*, 2020; Yuan and Lo, 2020) and sub-regional scales e.g., southern Africa (Nhamo *et al.*, 2020). Global level assessments have the advantage of providing composite values to inform high level decision-making and international trade. However, such assessments can lead to gross over-simplification of WEF nexus, and the loss of valuable insights within different regions. One strategy to address this limitation is to introduce moderation analysis (through multi-group analytical techniques) where, for instance, regions and climatic areas are incorporated as potential moderators i.e., variables that could significantly influence the WEF nexus (Okumah *et al.*, 2019; Okumah, 2020). This kind of analysis helps to offer composite values for the global picture, while providing rich contextual evidence about different subgroups (in this case, regions). Previous studies have, however, failed to explore such moderators thus creating an important gap at the regional scale. For the existing sub-regional studies, while their findings provide rich insights for the sub-regions being studied, their fragmented nature implies that, they may not reveal the disparity in WEF security among different sub-regions because of their narrow focus. Given that different countries and sub-regions have some commonalities in terms of WEF challenges and opportunities, it is important to consolidate such evidence across the region, for coordinated efforts. This study adopts a quantitative indicator-based technique to understand the state and determinants of WEF security in Africa. Furthermore, only few studies (Yuan and Lo, 2020; Nepal *et al.*, 2021; Manero and Wheeler, 2022), have attempted to explore the socioeconomic determinants of WEF security at national and regional scales.

As countries continue to put in place strategies to achieve SDGs, an understanding of the socioeconomic determinants of WEF security in regions like Africa could provide important lessons that could be adapted to the needs and circumstances of different countries and sub-regions. This study focuses specifically on Africa for several reasons including (1) compared to the rest of the world, hundreds of millions of Africans lack access to electricity, reliable drinking water and sanitation services and one in four people in the continent are undernourished (Ouedraogo, 2017; Kanyerere *et al.*, 2018) and (2) there is a wide disparity in WEF insecurity in Africa (Nkiaka *et al.*, 2021b). Furthermore, an increasing number of studies have shown that knowledge of WEF interlinkages can be used to address a wide range of country-specific and regional WEF-related concerns in Africa including adapting to climate change (Nhamo *et al.*, 2018; Conway *et al.*, 2015). In addition, the population of Africa is expected to grow in the coming decades which will lead to an increase in water, energy, and food demand. Therefore, there is an urgent need for quantitative intercomparison and assessment of WEF security and to identify resource potential in each country and sub-region as this could further enhance sub-regional integration through sub-regional power pools and transboundary water management and attract more foreign direct investments in the WEF sectors.

Therefore, focusing on Africa, the objectives of this study were to: (1) carryout a regional-scale quantitative assessment of WEF resources, (2) develop a metric to assess the state of WEF security, and (3) determine key socioeconomic factors that influence WEF security and how these can shape prospects for achieving SDGs. This research follows recent urgent calls to measure the state of WEF security in different regions as a vital step towards achieving SDGs and climate adaptation (Venghaus and Dieken, 2019; Babel *et al.*, 2020). By addressing these issues, we hope to guide the development of targeted policies that can enhance WEF security in Africa and other developing regions.

2. Methodology

2.1. Study area

Figure 1 shows the different sub-regional economic blocks, following the approach used by the African Development Bank (AfDB). Grouping African countries into sub-regional economic blocks has helped to harmonize investment, standards, technical regulations, as well as policies relating to transportation, infrastructure and has enhanced intra-African trade (Kagochi and Durmaz, 2018). We note that grouping these countries into different economic blocks in no way violates or reintroduces any geopolitical boundaries or suggests countries should join any sub-regional block.

Table 1 provides information on the socioeconomic attributes of the different sub-regions (see Appendix A for a full list of the countries that make up each category). Information in Table 1 shows that although the Economic Community of West African States (ECOWAS) sub-region has the highest number of countries, is the most populated and recorded the highest average annual GDP growth, it has the smallest total surface area and a relatively low GDP per capita (when compared to North Africa). The mismatch between administrative, spatial, economic, and demographic variables could have implications on WEF security status thus reinforcing the need to explore socio-economic determinants and multi-group analysis across the continent.

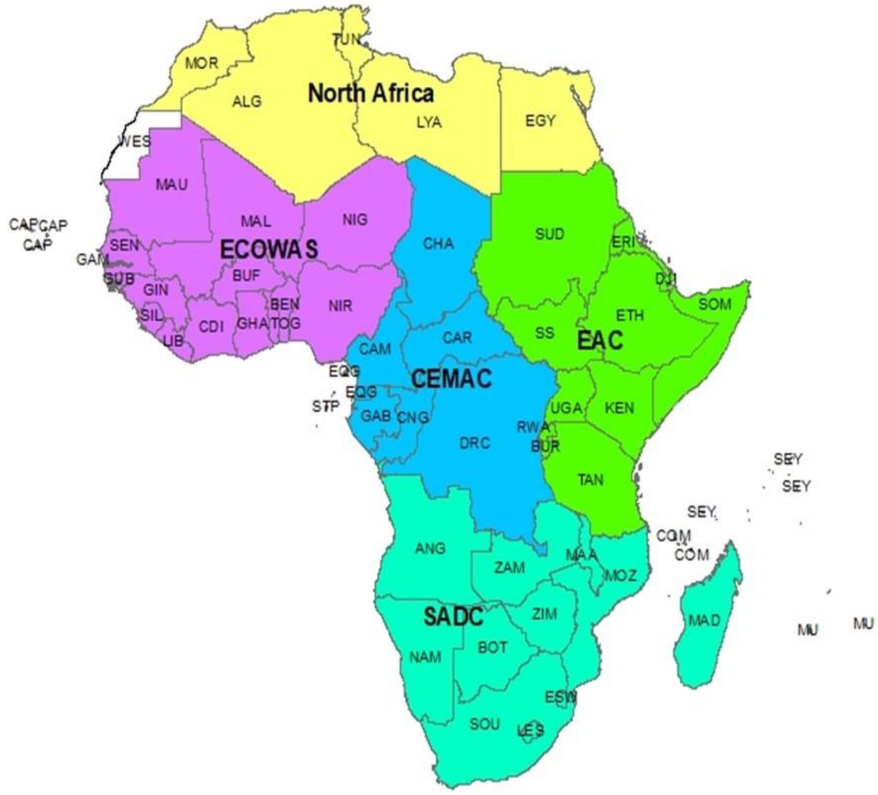

Figure 1: Study region depicting the different countries and sub-regional economic blocks: Central Africa Economic and Monetary Community (CEMAC), East African Community (EAC), Economic Community of West African States (ECOWAS), Southern African Development Community (SADC) and North Africa represents all the countries located in that economic block. Full country names are available in the Appendix.

Table 1: Socioeconomic characteristics of the different sub-regional economic blocks

Sub-region	Number of countries	Total surface area (km^2 thousand)	Population (thousand)	GDP per capita ($)	Ave. Annual GDP growth 2010-20 (%)
CEMAC	07	5,365	137,555	2,185	3.50
ECOWAS	15	5,115	377,437	4,483	4.00
EAC	13	6,214	362,265	2,603	3.50
North Africa	05	6,784	200,246	12,514	3.9
SADC	13	6,571	208,704	6,340	2.60

Note: Available from African Development Bank (AfDB, 2019). GDP per capital is based on purchasing power parity valuation.

2.2. Quantitative assessment of WEF resources availability

To assess WEF resources availability, we used country estimates of internal renewable water resources per capita, renewable energy (solar, wind and hydropower), land availability and irrigation potential. A focus on renewable energy sources enabled a consideration of the impact of climate change on WEF security and the mitigation of climate change. This is because efforts to limit global warming includes a radical increase in the supply of clean energy. Therefore, the supply of clean energy could simultaneously address energy insecurity as well as offer climate mitigation benefits.

We then used estimates of land availability for agriculture and irrigation to capture food security. Data on internal renewable water resources per capita, land availability and irrigation potential were obtained from FAO AQUASTAT[1]. According to the FAO, total internal renewable water resources represent the long-term average annual flow of rivers and aquifers recharge generated from precipitation within a country; land availability is the sum of arable land and area under permanent crops; irrigated area is the total area under irrigation; while irrigation potential is the total area of land which is potentially irrigable. Estimates for renewable energy (wind and solar) were taken from Hermann *et al.* (2014) while those for hydropower potential were obtained from UNEP (2017). Estimates for electricity generation were obtained from www.cia.gov/the-world-factbook.

2.3. Composite water-energy-food security index

Composite indicators are used in environmental research to measure and rank countries in terms of environmental performance, sustainability, and other complex concepts that are not directly measurable (Becker *et al.*, 2017). Recently, there have been numerous calls by scientists to develop indicators to measure progress towards the attainment of the SDGs (Bhaduri *et al.*, 2016; Becker *et al.*, 2017). Proponents of indicator-based techniques argue that the use of indicators in international development presents numerous advantages such as the possibility to benchmark, monitor and track progress made by countries towards achieving specific goals such as the SDGs (Bhaduri *et al.*, 2016). Others argue that using indicators to rank countries may force governments to question their standards and approaches, thereby, pushing them to adopt new strategies that may lead to better outcomes (Becker *et al.*, 2017). Furthermore, using indicators to monitor across countries can facilitate regional policy integration, promote evidence-based policy making, identify best practices, and align priorities between development partners (Jensen and Wu, 2018; Herrera, 2019). These benefits have triggered the wide use of composite indicators in research and practice.

Despite the widespread use of composite indicators in research and practice (Jemmali, 2017; Herrera, 2019; Yuan and Lo, 2020), there is no universally agreed upon number and scope of indicators (Greco *et al.*, 2019); different variables and scope of indicators are often aggregated

[1] http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en

depending on the focus and nature of assessment. In this study, just like many other studies using composite indicators, we combined different individual indicators into a single index. The different components include; water security (determined by the availability of, and access to sufficient and good quality water for human and ecosystem use (UN-Water, 2014)), energy security (determined by access to reliable and affordable energy for cooking, heating, lighting, communication, and productive uses (Willis *et al.*, 2016)) and food security (when all people have access to safe, nutritious and sufficient food all year round (FAO, 2021)).

2.3.1. Formulation of water-energy-food security index (WEFSI)

We developed a quantitative composite index to measure the status of water-energy-food security in all countries in Africa. Considering that data used for creating the composite index was obtained from different sources with different units of measurements, data were normalised into the same scale to allow direct comparison. As such, estimates for internal renewable water resources (provided in m^3/year/per capita) and land availability (in hectares) were converted into quantitative index scores and normalised into the range [0 1] using equation 1. A higher normalised index score indicates better performance while a lower score indicates poor performance.

$$N = \frac{X_i - X_{min}}{X_{max} - X_{min}} \qquad (1)$$

Where N is the normalized value, X_i is the observed variable, X_{min} is the minimum observed variable and X_{max} is the maximum observed variable. Prior to normalising the data, a scatter plot of total internal renewable water resources and land availability data revealed the presence of outliers in the data. The 5-95% method was used to eliminate the influence of outliers on the normalised scores. The 5-95% method is a technique where 5% of data from the maximum side and 5% data from the minimum side are systematically removed from the datasets prior to normalisation (Varis *et al.*, 2017). Post-normalisation, the outliers removed from the top and bottom of the ranges were then assigned values of 1 [top] and 0 [bottom]. Where outliers were not apparent, index scores provided in the range of 0 – 100 were simply converted to the standard range [0 – 1] via division by 100.

Prior to creating the composite water-energy-food security index (WEFSI), weights were assigned to each dimension of water, energy, and food sub-indicators (Table 2). We acknowledge that the weight attached to each dimension of the composite indicator can substantially affect the result and rankings. There are several methods for assigning weights during the development of composite indicators. However, each technique has its merits and demerits and there is no one-size-fits-all solution and the final decision depends on the index developer to choose a weighting scheme that best fits the purpose of construction (Greco *et al.*, 2019). As such, the weightings in

Table 2 were assigned based on their relevance and proven contribution towards achieving WEF security e.g., (Greco *et al.*, 2019; Yuan and Lo, 2020). Finally, the WEFSI was calculated as the arithmetic average of the water, energy, and food security sub-indicators obtained from a total of eleven variables grouped under each of the WEF components (Table 2). All other datasets were obtained from sdg-tracker.org except internal renewable water resources and land availability obtained from FAO.

As with other similar studies, approaches for developing composite indicators are mostly subjective because of the availability of a wide range of variables that can be used. This suggests that there is the potential to miss some important variables. To mitigate this potential limitation, our choice of variables was guided by the following context and data driven criteria:

1) Availability of data for each chosen variable and for the data to cover most if not all of the countries in our target region.
2) The chosen variable should be widely used or applied in the policy domain both by global and regional policy institutions as well as the wider scientific community,
3) The data should be representative of the biophysical and socioeconomic conditions prevailing in each country at the time of conducting this research.

This selection criteria enabled deployment of variables that have been applied in previous studies (Venghaus and Dieken, 2019; Yuan and Lo, 2020). Although integrated water resources management (IWRM) is a water centric paradigm and may not fit into WEF nexus planning, its inclusion here is intentional to capture institutional capacity, recognize horizontal or sectoral linkages in national and sub-regional planning (transboundary river basin initiatives, agriculture and irrigation policies, sub-regional power pools/energy connections), and other relevant factors that could influence WEF security at national and sub-regional scales.

After obtaining scores for the composite WEFSI and sub-indicators (water, energy, and food), geospatial mapping techniques in ESRI ArcGIS 10.7 were used to create thematic maps for each of the four indicators. To achieve this, the index scores were exported from a spreadsheet into an attribute table in ArcGIS 10.7 containing the shapefiles of all countries in Africa. The symbology tab under the layer properties was then used to create thematic maps for each indicator. We used thematic maps to present our indicator scores to facilitate comprehension of our findings. For example, readers can easily distinguish between countries that are performing well and those lagging behind in any of the WEF sectors based on the quantitative scores obtained by each country which have been transformed into a colour code using thematic maps.

Table 2: Data, description and weight attached to each dimension of WEFSI sub-indicators.

WEFSI component	Dimension (weight)	Description
Water security	Availability (40%)	Total internal renewable water resources in a country
	Access to drinking water (25%)	Percentage of total population with access to water supply. This indicator has significant impact on the health of a population due to consumption of untreated water.
	Access to sanitation (20%)	Percentage of total population with access to sanitation services. This indicator also has significant impact on the health of a population from contaminated water.
	IWRM (15%)	Measures the degree of implementation of IWRM in each country. It captures institutional capacity of governments towards achieving water security and horizontal linkages with other initiatives such as transboundary basin initiatives, sub-regional power pools and other factors that could influence WEF security.
Energy security	Access to electricity (20%)	This is the proportion of the population with access to electricity. Enhancing access to clean and affordable energy can increase economic growth.
	Access to clean fuel and technology (20%)	The total population with access to clean fuels and technologies for cooking. Access to clean fuel and technology are essential for ensuring energy sustainability
	Share of renewable energy (40%)	Proportion of renewable energy as a share of the total final energy consumption. Increase usage of renewable energy is key to mitigating the impact of climate change
	Energy Efficiency (20%)	This is measured as the quantity of kilowatt-hours produced per 2011 international-$ of gross domestic product.
Food security	Land availability (50%)	Sum of arable land and area under permanent crops. Land availability is a critical factors of production and has been identified as a limiting factor to food production and climate adaptation in some parts of Africa (Nkiaka and Lovett, 2018).
	Food sufficiency (25%)	Percentage of the population that is not under-nourished
	Cereal yield (25%)	Used to measure the kilograms per hectare of harvested land, including wheat, rice, maize, barley, oats, rye, millet, sorghum, buckwheat, and mixed grains. The efficiency of crop productivity is a critical indicator for monitoring improvements in food sustainability.

2.4. Exploring the determinants of WEFSI

To determine potential drivers of water-energy-food security, we selected seven independent socioeconomic variables that were not used in the development of WEFSI and its sub-components. The selection of variables for this purpose was guided by their successful use in previous studies to analyse country-level phenomena pertaining to developmental issues including WEF security (Yuan and Lo, 2020; Wang, 2021; Liu *et al.*, 2020). These independent variables include GDP per capita, government effectiveness index (GEI), human development index (HDI), percentage of urban population, infrastructural development, foreign direct investment (FDI), and Official Development Assistance (ODA) for water supply and sanitation (WSS), agriculture and energy. GDP per capita is a measure of a country's economic development and living standards and has been shown to significantly impact WEF security (Ding *et al.*, 2019). ODA is also important in boosting government investment in WEF sectors while human development (HDI) has the potential to enhance resource management practices though innovation in WEF sectors (Wang, 2021). FDI can also be used to supplement domestic capital and as such, countries with high FDI are likely to achieve WEF security (Munamati *et al.*, 2016). GEI represent the quality of public services, civil service, policy formulation, policy implementation and credibility of the government's commitment to raise these qualities or keep them high. Urbanization can influence WEF security because increasing population in densely settled areas can exacerbate resources scarcity (Jensen and Wu, 2018).

Data for the independent variables were obtained from the World Bank (www.data.worldbank.org). Infrastructural development data were obtained from the Africa infrastructure development index report (AIDI, 2020). We used the Government Effectiveness Index (GEI) from Worldwide Governance Indicators. Since the values of GEI are provided in the range -2.5 to 2.5, we normalised the data into the range [0 1] using equation 1.

Next, we conducted a collinearity test among the independent variables using the Pearson correlation test at 5% significance level to identify cases of overlap between variables as this may cause double-counting (Jemmali, 2017). Where two variables were found to show statistically strong correlations (>0.75), one of the variables was identified as a candidate for elimination or exclusion. Following the removal of overlap variables, we used linear regression to explore potential relationships between the independent variables and the WEFSI and sub-indicators to reveal how each independent variable was associated with each of the indicators.

3. Results

3.1. Quantitative estimates of water-energy-food resources.

Figure 2 shows the quantitative water-energy-food resources estimates for all economic sub-regions in Africa. Results in Figure 2 and show the total renewable water resources in Africa is estimated at about 5,000 km^3/per year, irrigation potential stands at about 56,000 hectares while renewable energy is estimated to be more than 1.5 million TWh/year (Table 3). However, there are substantial disparities in resources abundance among the sub-regions. For example, the CEMAC sub-region is the most endowed with water while EAC and North Africa sub-regions are the least endowed (Figure 2a). This result is consistent with findings from previous studies (Jemmali, 2017). Despite being the most endowed with water resources, our assessment revealed that water withdrawal for all purposes is lowest in the CEMAC region compared to other sub-regions while North Africa has the highest rate of water withdrawal with the agricultural sector being the highest consumer.

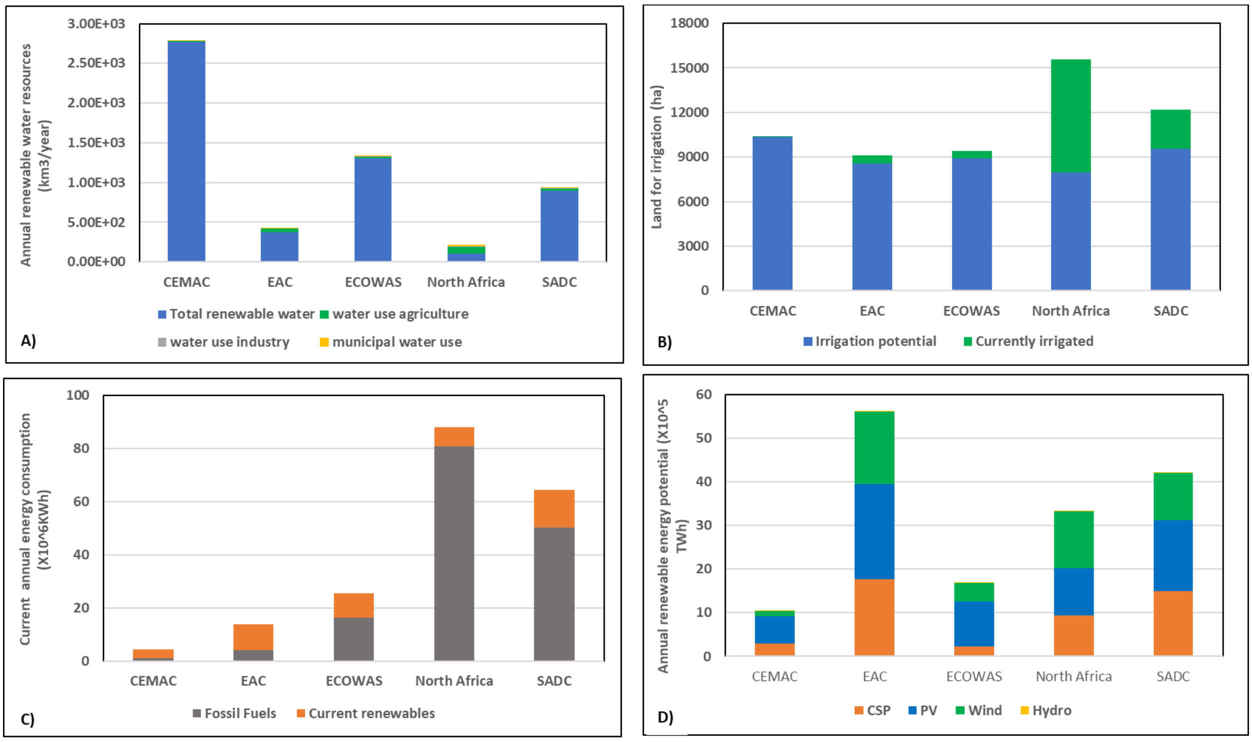

Figure 2: Sub-regional estimates of WEF resources in Africa. Current renewables include all the renewable energy sources. CSP: Concentrated Solar Power; PV: Photovoltaic.

Our assessment also shows that all sub-regions have similar irrigation potential (Figure 2b). However, irrigation agriculture is currently more developed in North Africa and the SADC sub-regions compared to other sub-regions (Figure 2b).

Whereas renewable energy estimates indicate that Africa has considerable renewable energy potential, substantial disparities also exist in renewable energy potential across the sub-regions. For example, the EAC and SADC sub-regions are the most endowed with wind and solar energy while the CEMAC sub-region is the least endowed (Figure 2d & Table 3). Conversely, CEMAC and SADC sub-regions are the most endowed with hydropower potential (Table 3). Our assessment also reveals that hydropower is the major source of electricity in many countries providing more than 50% of the total electricity supply in several countries (see Appendix A). Despite the strong dependence on hydropower and the huge potential in other renewables, electricity generation in Africa is still dominated by fossil fuels particularly in North Africa and the SADC sub-regions (Figure 2c). However, renewable energy mix appears to be more developed in the other four sub-regions compared to the CEMAC sub-region (Figure 2c). Our assessment also reveals that the potential for CSP, PV and wind energy is far superior to hydropower potential (Figure 2d).

Table 3: Estimated renewable energy potential in Africa.

Sub-region	CSP (taking into account all suitable areas) (TWh/year)	PV (taking into account all suitable areas) (TWh/year)	Wind using all available areas [capacity factor >20%] (TWh/year)	Hydropower (TWh/year)
CEMAC	29,909	61,643	12,395	570
EAC	175,777	219,481	165,873	335
ECOWAS	22,747	103,754	40,846	102
North Africa	93,544	109,033	130,316	60
SADC	149,610	162,817	108,235	416

CSP: Concentrated Solar Power; PV: Photovoltaic. Regional estimates were obtained by aggregating data for each country.

3.2. Water-energy-food nexus security index (WEFSI)

Eleven variables were employed to develop a composite indicator to assess the state of water-energy-food security in Africa. Results of our assessment are shown in Figure 3. The results indicate that more than 40 countries obtained water security index (WSI) scores >0.40 with all countries in the CEMAC sub-region obtaining high scores (>0.61) except Chad. Results further reveal that most countries in North Africa and the SADC sub-regions which are water-limited sub-regions obtained better WSI scores than countries endowed with abundant water resources. This can be attributed to the high percentage of the population in North Africa and the SADC sub-regions with access to water and sanitation services. In terms of country comparison, Gabon obtained the highest WSI score (WSI>0.81) while Eritrea obtained the lowest score (WSI<0.20) (Figure 3).

The energy security index (ESI) scores reveal that more than 40 countries also obtained ESI scores >0.40. This is surprising considering that access to electricity in most countries is low.

However, the moderate scores can be attributed to the fact that the share of renewable energy in most countries is relatively high since most countries depend on hydropower for electricity generation. There are also substantial disparities in ESI scores across Africa with Guinea-Bissau, Liberia, Niger, and Somalia obtaining the lowest ESI score (≤0.20) while Morocco obtained the highest score (≥0.70) (Figure 3).

Meanwhile, results of the food security index (FSI) indicate that more than half of the countries obtained FSI scores (>0.40). These results are also surprising because Africa has the highest number of under-nourished people compared to the rest of the world (FAO, 2021). However, the moderate FSI scores can be attributed to the higher weight (50%) attached to land availability in the calculation of the FSI. Our assessment also reveals that several countries have substantial portions of arable land that can be harnessed for agriculture. Equatorial Guinea and Seychelles obtained the lowest FSI (<0.10), followed by Burundi, Eritrea, Libya, and South Sudan (≤0.20) while South Africa obtained the highest FSI score (≥0.81) (Figure 3).

WEFSI scores indicate that Eritrea obtained the lowest WEFSI score (0.20). Seventeen countries (31%) obtained WEFSI scores in the range (0.20 – 0.40) which can be described as low suggesting that substantial effort is needed to enhance WEF security in these countries in the short to medium term. WEFSI and sub-indicators quantitative scores are also provided in Appendix A.

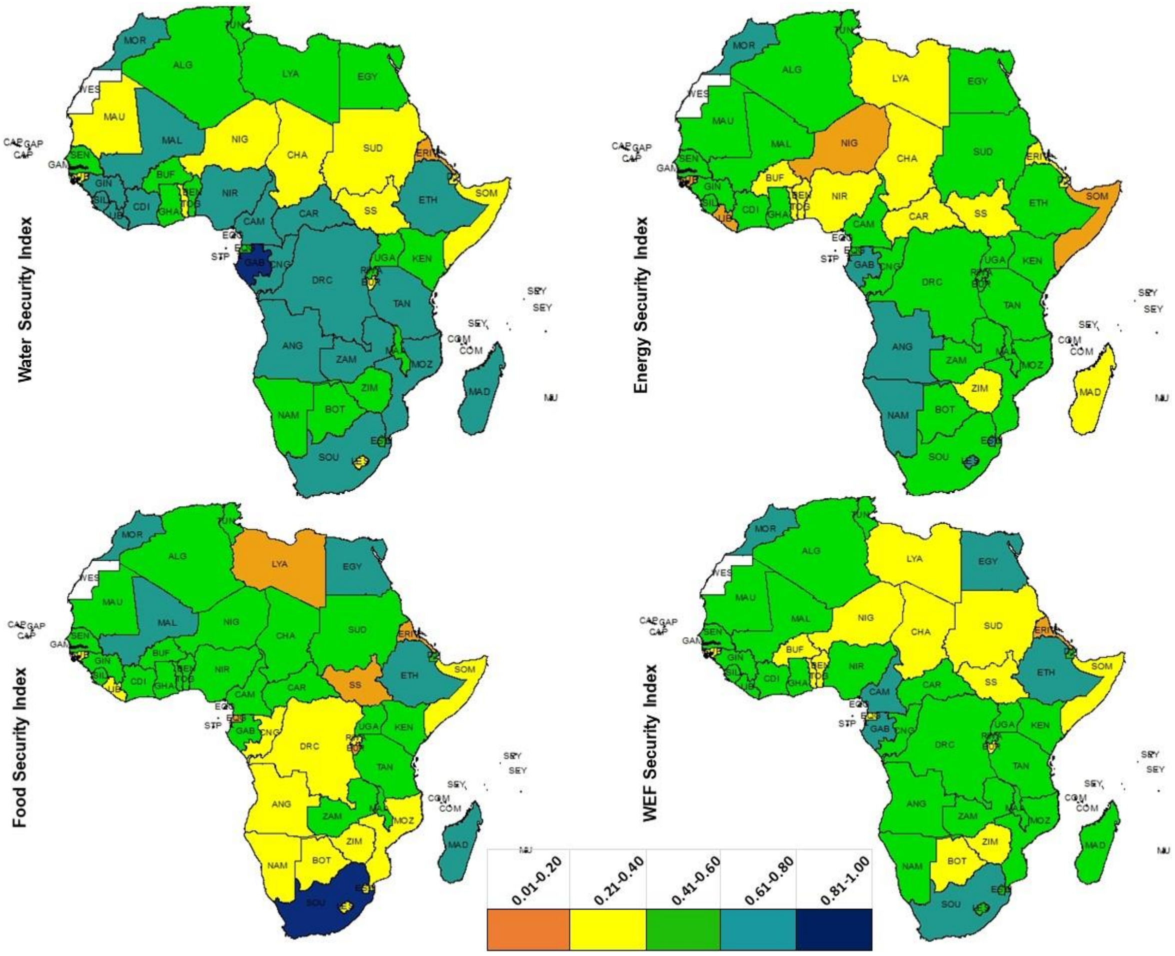

Figure 3: Spatial distribution of WEFSI and sub-indicators across countries in Africa

To track progress towards achieving WEF security in Africa, we used a radar diagram to identify sub-regions making advances and those lagging behind, revealing sectors where progress in any of the WEF sectors is being made. Data used to generate the radar diagram were obtained by averaging scores for WEFSI and sub-indicators for countries in each sub-region. The radar diagram reveals that North Africa, and the SADC sub-regions are making progress in all the WEF sectors, CEMAC and EAC sub-regions are stagnating in the food security sector while ECOWAS is stagnating in the energy security sector (Figure 4). The CEMAC sub-region appears to be doing better than all the other sub-regions in the water security sector (Figure 4). However, progress in the CEMAC sub-region could be attributed to the availability of water resources and does not reflect the level of water security due to limited access to water and sanitation services in the sub-region (Nkiaka *et al.*, 2021b).

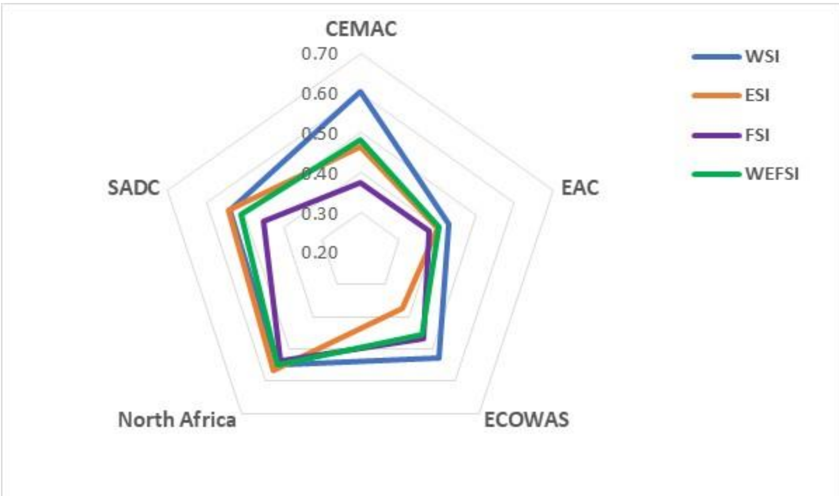

Figure 4: Radar diagram depicting progress in WEF security nexus across different sub-regional economic blocks in Africa

3.3. Socioeconomic determinants of water-energy-food security

Table 4 shows the results of the collinearity test among the different variables. Results show mostly positive albeit weak to moderate correlations among the independent variables with few negative but weak correlations in some cases (Table 4). Nevertheless, statistically strong correlations were obtained between HDI and GDP per capita, HDI and AIDI, AIDI and GDP per capita (Table 4). These strong correlations indicate that there may be overlap between these independent variables, therefore, HDI and AIDI were eliminated from the independent variables before further statistical analysis were performed.

Table 4: Correlation matrix of the independent variables

	ODA-WSS	ODA-Energy	ODA-Food	GDP per capita	GEI	HDI	Urban pop.	AIDI	FDI
ODA-WSS	1								
ODA-Energy	**0.560**	1							
ODA-Food	**0.668**	**0.521**	1						
GDP per capita	0.244	0.012	-0.205	1					
GEI	0.188	**0.327**	0.256	**0.446**	1				
HDI	-0.096	0.201	0.497	**0.843**	**0.523**	1			
Urban pop.	-0.205	0.003	**-0.289**	**0.517**	0.116	**0.590**	1		
AIDI	0.004	0.077	0.036	**0.784**	**0.462**	**0.858**	**0.441**	1	
FDI	**0.291**	**0.394**	**0.423**	0.132	0.195	0.243	0.055	**0.382**	1

Values in bold indicate statistically significant correlations at 5% significance level. ODA-WSS: official development assistance for water and sanitation; ODA-Energy: official development assistance for energy; ODA-Food: official development assistance for agriculture.

Table 5 shows the results of statistical analysis between the selected independent variables and WEFSI and sub-indicators. Results of the analysis show that all the independent variables produced positive correlations with the WEFSI and sub-indicators (Table 5). The results further reveal that the strongest relationships were found between GDP per capita and all the indicators while the weakest correlations were obtained between percentage of urban population and WEFSI and sub-indicators (Table 5). The low to moderate correlations values obtained suggests that beyond the determinants identified, there may be other factors influencing WEF security in Africa. Figure 5 also shows the relationship between GDP per capita and WEFSI and its sub-indicators.

Table 5: Relationship (R^2) between independent variables and WEFSI and sub-indicators

Indicator	ODA	GEI	GDP per Capita	Urban population	FDI
WSI	**0.467**[a]	0.179	**0.469**	0.101	**0.235**
ESI	0.113[b]	**0.276**	**0.574**	0.025	0.227
FSI	**0.260**[c]	0.150	**0.366**	0.009	**0.306**
WEFSI	0.209[d]	**0.261**	**0.493**	0.051	**0.268**

[a]ODA-WSS, [b]ODA-Energy, [c]ODA-Agriculture, [d]ODA-WSS+ ODA-Energy+ODA-Agriculture. Values in bold indicate statistically significant correlations at 5% significance level

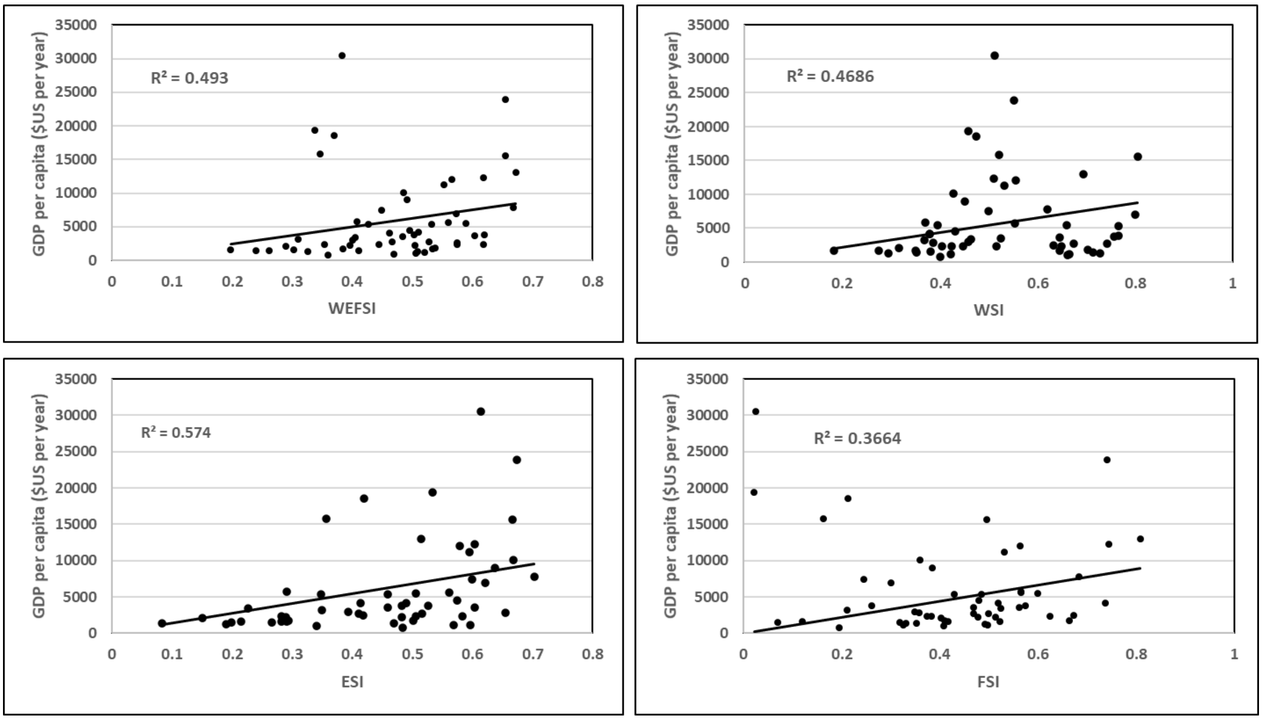

Figure 5: Relationship between WEFSI and sub-indicators and GDP per capita.

4. Discussion

This study conducted a quantitative assessment of WEF resources and used an indicator-based approach to assess the state of WEF security in the continent as well as identify the determinants of WEF security. In what follows, we provide a critical discussion of key findings in relation to the objectives of the study.

With respect to the first research objective, our quantitative assessment of WEF resources revealed that Africa is endowed with abundant WEF resources (water, land, and renewable energy) albeit, with varying potential across countries and sub-regions. There are reports that show Africa has considerable renewable energy potential, water and land resources that can be harnessed to meet the needs of the continent (Ouedraogo, 2017; Erdoğan *et al.*, 2021; MacDonald *et al.*, 2021). Whilst previous studies in the continent have focused on each WEF sector, this is one of the first study to provide a comprehensive assessment of all WEF resources. Our assessment also revealed substantial disparities in WEF resources within and across sub-regions. For example, water resources are unequally distributed among countries in the CEMAC sub-region. A recent study by Nkiaka *et al.* (2017) attributed this disparity to the spatiotemporal variability in rainfall which affects water availability. There are also substantial disparities in hydropower potential in the CEMAC sub-region because most of the hydropower potential is concentrated in the Democratic Republic of Congo (UNEP, 2017). Our assessment also revealed that Guinea, Mali, Niger, and Nigeria appear to be more endowed with arable land compared to the rest of the countries in the

ECOWAS sub-region. Taken together, our findings show that there is great potential for exploiting water, energy, and land resources to meet resources security in several countries and sub-regions.

The second objective was to measure the state of WEF security in Africa. As with most studies of this nature, the development of composite indicators is a subjective process due to the wide availability of datasets, weighting schemes and aggregation methods that may be employed (Jemmali, 2017). Despite the differences in methodology employed and data sources, WEFSI scores obtained in this study are comparable to results from other global assessments (Venghaus and Dieken, 2019). The WEFSI scores show strong disparities among countries and sub-regions which is consistent with results from related quantitative studies among African countries (Jemmali, 2017). This suggest that to achieve WEF security in Africa, there is a need to reduce socioeconomic disparity among countries and sub-regions so that no country or sub-region is left behind in the race to achieve SDGs by 2030.

The third objective was to explore the socioeconomic determinants of WEF security. This analysis enables a general focus on regional prospects for achieving development. Among the independent variables explored, GDP per capita had the strongest correlation with all the sub-indicators and WEFSI. This suggests that GDP per capita is closely linked to WEF security (Yuan and Lo, 2020). Indeed, there seems to be a two-way relationship between GDP and WEF security because services and investments in water, energy and food contribute to a country or sub-region's GDP while at the same time enhancing WEF security. Therefore, the higher the investments and services in these areas, the higher the country or sub-region's WEF security (all things being equal). Similarly, a higher GDP might suggest more services and investments in key sectors, and this is more likely to yield a positive influence on other aspects of WEF security such as infrastructural development, GEI, and human capacity[2]. For example, countries in North Africa and the SADC sub-regions are highly water-limited however, their investments in water-energy-irrigation infrastructure has increased access to water, energy, and food for their citizens while improving their GDP per capita (Jemmali, 2017; Weinthal and Sowers, 2020). This might explain why the two sub-regions performed relatively better than other sub-regions in all the WEF sectors (Figure 4). In contrast, several countries in SSA are endowed with huge water and land resources that can be harnessed but low GDP means these countries are unable to invest in critical infrastructure to increase access to WEF resources as revealed by this study. There are reports that cast doubt on regional progress towards achieving SDGs such as SDG 2, SDG 6, and SDG 7. It

[2] We note that while many services and investments such as mitigating the impact of accidents may not yield direct social progress but add to GDP growth. Therefore, we do not suggest a deterministic link between GDP and social progress.

can be argued that these prospects can greatly be improved by a focus on determining elements (Kedir *et al.*, 2017).

Our results also revealed that official development assistance (ODA) and foreign direct investment (FDI) correlate strongly with WEFSI and sub-indicators, reflective of studies that show FDI is an important factor influencing SDGs attainment in Africa (Lopes *et al.*, 2020). There is evidence that increasing per capita ODA for water and sanitation can enhance water security in Africa (Nkiaka *et al.*, 2021a). This is because ODA can be used to supplement domestic capital and increase the capacity of countries to invest in WEF infrastructure. For example, Seychelles has almost no arable land for agriculture, and depends mostly on imported food and fuel for electricity and desalinates most of its drinking water because of higher GDP per capita generated from FDI (Giampiccoli *et al.*, 2020).

GEI was also identified to be strongly associated with water, energy, and food security indicators. In fact, weak GEI which is strongly related to governance has been identified as a key factor that hinders the capacity of countries with abundant water, energy and land resources to implement policies that can enhance water-energy-food security (Rosa *et al.*, 2020; Cobbing, 2020; Nepal *et al.*, 2021). On the other hand, government effectiveness promotes citizen participation and support, facilitates resource generation, and ensures efficient use of state resources towards addressing critical challenges such as WEF security. Therefore, as this study has shown, whilst WEF resources availability is essential, having the socioeconomic capacity and a good governance status are critical to harness these resources to achieve WEF security. This study therefore adds to Liu et al.'s position, that, the availability of WEF resources is not enough in that more needs to be done to achieve resources security (Liu *et al.*, 2020). State and non-state actors require strengthened collaborations to build systems that work across governance, economic spheres, and investments.

5. Limitations of the method

Our results represent only the current situation and do not consider future scenarios. Nevertheless, these results may be used to understand the current situation thereby setting a benchmark to measure progress over a given time scale and for future planning. The aggregation of several variables into a single metric may also hide some important features like sectoral imbalances that exist within and across countries and sub-regions. The method used to calculate the WEFSI does not consider the dynamic interactions and feedbacks between the WEF resources systems. Furthermore, the number of socioeconomic determinants (independent variables) used in this study is not exhaustive as there could be other socioeconomic factors undermining WEF security in Africa. Future research could focus on other socioeconomic factors and also explore how these factors interact in different country contexts to influence WEF security.

6. Conclusions

The aim of this study was to assess water-energy-food nexus resources, develop a quantitative metric to measure the state of water-energy-food security and explore the socioeconomic determinants of the WEF security in Africa. Overall, results reveal the abundance of WEF resources in Africa, albeit with substantial disparities in WEF resources availability among countries and sub-regions. Resources assessment further indicates the potential to develop sub-regional renewable energy strategy to increase the share of renewable energy in existing sub-regional power pools.

Our assessment of water-energy-food security in Africa using a composite indicator revealed that several countries are not on track towards achieving WEF security. Statistical analyses show four key elements (GDP per capita, Foreign Direct Investment, Official Development Assistance, and governance) are strongly correlated with WEF security. Poor governance across most countries appears to be hindering their capacity to invest in WEF infrastructure, to enact policy reforms that can enhance WEF security in their respective countries and this seems to be partly responsible for the low GDP per capita recorded in many countries and sub-regions. We conclude that while WEF resources availability is essential, the capacity to harness these resources to meet local demand is critical for achieving WEF security, underscoring the need for national and international development efforts around capacity and infrastructure development. Thus, prospects for achieving SDGs are slender at the moment but can greatly be improved by efforts in governance, economic development, and investment spheres.

Our results highlight the urgent need for targeted socioeconomic reforms to enhance governance, infrastructural and socio-economic development. In fact, strong institutions, and effective application of the rule of law have been shown to attract FDI and ODA in Africa (Lopes *et al.*, 2020; Manero and Wheeler, 2022) and contribute to building human capacity. Moreover, capacity development and effective governance may contribute to the implementation of favourable economic policies that stimulate private sector investment in this area (Nkiaka and Lovett, 2018). This in turn, could facilitate uptake of renewable energy in Africa, with potential benefits in WEF security.

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.

Data Availability

Data will be made available on request.

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Appendix A: List of countries in each sub-region and WEFSI scores

Code	Country	WSI	ESI	FSI	WEFSI	% of electricity from Hydro
Economic Community of Central African States (CEMAC)						
CAM	Cameroon	0.76	0.53	0.57	0.62	47
CAR	Central Africa Republic	0.66	0.34	0.41	0.47	50
CHA	Chad	0.27	0.21	0.42	0.30	0

CNG	Congo-Brazzaville	0.77	0.48	0.26	0.50	36
DRC	Democratic Republic of Congo	0.67	0.57	0.33	0.52	98
EQG	Equatorial. Guinea	0.46	0.53	0.02	0.34	38
GAB	Gabon	0.81	0.67	0.50	0.66	49
Economic Community of East African States (EAC)						
BUR	Burundi	0.40	0.48	0.19	0.36	73
COM	Comoros	0.37	0.35	0.21	0.31	4
DJI	Djibouti	0.37	0.29	0.57	0.41	0
ERI	Eritrea	0.18	0.29	0.12	0.20	0
ETH	Ethiopia	0.65	0.58	0.62	0.62	86
KEN	Kenya	0.43	0.57	0.48	0.50	34
RWA	Rwanda	0.45	0.51	0.38	0.45	51
SEY	Seychelles	0.51	0.61	0.03	0.38	0
SOM	Somalia	0.35	0.08	0.35	0.26	0
SUD	Sudan	0.38	0.27	0.07	0.24	50
SS	South Sudan	0.38	0.49	0.52	0.46	0
TAN	Tanzania	0.67	0.41	0.50	0.53	40
UGA	Uganda	0.52	0.48	0.51	0.50	68
Economic Community of West African States (ECOWAS)						
BEN	Benin	0.46	0.23	0.52	0.40	9
BUR	Burkina Faso	0.42	0.29	0.48	0.40	9
CAP	Cabo Verde	0.50	0.60	0.25	0.45	0
CDI	Cote d'Ivoire	0.66	0.51	0.60	0.59	40
GAM	Gambia	0.40	0.28	0.38	0.35	0
GHA	Ghana	0.55	0.56	0.57	0.56	42
GIN	Guinea	0.74	0.52	0.47	0.58	67
GIB	Guinea Bissau	0.32	0.15	0.40	0.29	0
LIB	Liberia	0.71	0.20	0.32	0.41	43
MAL	Mali	0.63	0.42	0.67	0.57	31
MAU	Mauritania	0.39	0.46	0.43	0.43	16
NIG	Niger	0.29	0.19	0.49	0.33	0
NIR	Nigeria	0.77	0.35	0.48	0.53	20
SEN	Senegal	0.52	0.46	0.47	0.48	7

SIL	Sierra Leon	0.70	0.50	0.41	0.54	51
TOG	Togo	0.35	0.28	0.52	0.39	29
North Africa						
ALG	Algeria	0.56	0.58	0.56	0.57	1
EGY	Egypt	0.51	0.60	0.74	0.62	6
LYA	Libya	0.52	0.36	0.16	0.35	0
MOR	Morocco	0.62	0.70	0.68	0.67	16
TUN	Tunisia	0.53	0.60	0.53	0.55	1
South African Development Community (SADC)						
ANG	Angola	0.80	0.62	0.30	0.57	64
BOT	Botswana	0.47	0.42	0.21	0.37	0
LES	Lesotho	0.39	0.65	0.36	0.47	99
MAD	Madagascar	0.64	0.29	0.66	0.53	24
MAA	Malawi	0.42	0.60	0.50	0.51	93
MU	Mauritius	0.55	0.67	0.74	0.66	7
MOZ	Mozambique	0.73	0.47	0.33	0.51	83
NAM	Namibia	0.43	0.67	0.36	0.49	64
STP	Sao Tome & Principe	0.38	0.41	0.74	0.51	11
SOU	South Africa	0.69	0.51	0.81	0.67	1
SWA	Eswatini	0.45	0.64	0.38	0.49	20
ZAM	Zambia	0.64	0.60	0.56	0.60	93
ZIM	Zimbabwe	0.46	0.39	0.35	0.40	37