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Examining the water–energy–food (WEF) nexus through an SDG lens for the big 5 African countries

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Abstract
The misallocation and scarcity of food, energy and water resources have been a challenge for African countries, mainly as they try to achieve long-term future sustainable development. This study explores the dynamic relationship between water, energy, food and economic conditions in Angola, Ethiopia, Kenya, Nigeria and South Africa. Since the water-energy-food nexus underpins the Sustainable Development Goals (SDG 6, 7 and 2), respectively the study uses SDG indicators to proxy food, energy and water. To do so, the study employs a Generalised Methods of Moments panel data technique for the period from 2000 to 2015. For the whole group of countries, a sub-nexus was concluded from Food to Water, Water to Food and Water to Energy for Ethiopia was confirmed, Energy to Water for Kenya and Water to Food for Angola. This study explains these important interlinkages appreciating the growing demand for the three resources as population in the continent keeps growing. The findings indicate synergies between the three sustainability demonstrations for the five countries that have important policy implications for the continent's current and future developmental conditions.

Keywords Sustainable development goals (SDGS) · African countries · Energy–water–food nexus · Sustainable development

1 Introduction

Sustainable development is considerably dependent on food, energy and water security. This phenomenon is considered valid for the global community; however, certain regions cannot witness sustainable growth due to scarcity, misallocation and mismanagement of resources (Costanza et al., 2016; Ozturk, 2015, UN Water, 2003). The continuously growing population places a more significant burden on the limited food, energy and water sources, further delaying economic prosperity. In addition to the growing population, lack of infrastructure, inadequate investment, irregular growth patterns in industries, unemployment and others place a more significant constraint on sufficiently balancing food, energy and water production without depleting natural resources (Ozturk, 2015). The indivisible food–energy–water nexus

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increases the need for integrated policies to ensure sustainability. The United Nations (UN) Sustainable Development Goals (SDGs) consider this growing demand within the targets 2, 6 and 7:

- SDG 2—“End hunger, achieve food security and improved nutrition and promote sustainable agriculture”.
- SDG 6—“Ensure availability and sustainable management of water and sanitation for all”.
- SDG 7—“Ensure access to affordable, reliable, sustainable and modern energy for all”.

The national policies are encouraged to be integrated with the UN’s SDGs (Costanza et al., 2016). To address the Millennium Development Goals’ shortfalls (Kaivo-oja et al., 2018), the SDGs are of significant importance for developed and developing countries to achieve economic prosperity while ending all forms of poverty and inequality, preserving the climate and developing the quality of health and education (United Nations, 2015).

Considering that the African continent is faced with the challenges mentioned above, the journey towards economic prosperity proves to be considered troublesome. Furthermore, the present deficit in the region’s food, energy and water balance, in addition to political instability, raises concerns about whether sustainable development can be achieved within the approaching decades (Endo et al., 2017). Finally, potential synergies between achieving energy–water–food targets might provide saving opportunities from investment by governments and in Research and Development (R&D).

This study examines the dynamic relationship between food, energy and water and economic indicators relevant to the challenges confronted by African countries. The purpose of the study is to understand the interlinkages and trade-offs between the three resources as they are continuously under pressure due to the continent’s growing population, industrialisation and urbanisation rates. Comprehending their synergies will assist policymakers to appropriately and efficiently allocate financial, human and capital resources.

Aligning the SDGs with the FEW nexus has been proposed and discussed before by the UN; however, this study contributes to the food–energy–water nexus discussion of the literature by taking into consideration the socio-economic conditions of the big five sub-Saharan African countries. These countries are chosen because they generate the highest income in sub-Saharan Africa for the past two decades: Angola, Ethiopia, Kenya, Nigeria and South Africa, with the assumption that these countries have the potential and willingness to ensure sustainable growth, relative to the rest of the African continent.

The study adopts a Generalised Method of Moments (GMM) panel data economic technique to obtain valid estimates considering the differences in the countries of interest. The dependent variables are proxies for the food–energy–water nexus, selected from indicators as specified by SDG 2, 6 and 7. These indicators are generally used to monitor national and global progress towards securing sustainable development (Kaivo-oja et al., 2018). The study is organised as follows: Sect. 2 consists of the literature review, Sect. 3 discusses the theoretical framework, data and methodology followed in the study, Sect. 4 consists of results, and Sect. 5 concludes the study.

2 Literature review

Numerous academic disciplines and industries have had an escalating interest in the food–energy–water nexus. Evidence is presented in several studies conducted on the topic. The motivation for these studies is generally driven by issues related to the environment, economy, scarce resources and endeavours to formulate operative solutions to overcome current burdensome constraints hindering sustainable development.

Recently, studies concur that evaluating food, energy and water resources separately underestimates the joint influence these resources have on sustainability (Al-Saidi & Elagib, 2017; Alfstad et al., 2013; Bhaduri et al., 2013; Epstein et al., 2015; Mabhaudhi et al., 2018). When these interlinkages between the three get acknowledged as the WEF nexus and managed appropriately, then the benefits spread to the broader socio-economic environment. That approach of resource management has emerged only post-2008 and has been established as a necessary management model of resources due to the current and expected rise in global demand.

Additionally, the same sentiment holds for SDGs (Costa et al., 2017; Kaivo-oja et al., 2018). Sector-oriented policies have failed to neither accelerate economic prosperity nor lead to optimal resources (Arent et al., 2011; Epstein et al., 2015). Al-Saidi and Elagib (2017) further indicate that interest in sub-nexus (water–energy, food–water, etc.)-related research dates back to the 1980s. Synergy evaluations on SDGs attest to cross-sectional policies potentially having a more considerable impact than the sum of sector-oriented policies (Arent et al., 2011; Epstein et al., 2015).

On the other hand, it has been somewhat challenging for policymakers to formulate integrated policies that address the food–energy–water nexus. Arent et al. (2011) and Chang et al. (2019) are of the view that this is borne by the lack of coordinated models which address the food–energy–water nexus and the notable effort required for the government to consider systems thinking when formulating policies.

Additionally, Epstein et al. (2015) integrate the Institutional Analysis and Development (IAD) and the Network of Action Situations (NAS) frameworks, where the authors study the effect of institutions on social and environmental outcomes which influence food, energy and water management. Epstein et al. (2015) conclude that it is difficult (if not impossible) to formulate adequate policies without considering geographic and political restrictions. Institutions have a significant role in limiting or promoting the effectiveness of the food–energy–water nexus on a nation's (Epstein et al., 2015; Mabhaudhi et al., 2018).

On a different note, most quantitative studies examining the food–energy–water nexus are motivated by the increasing demand for resource interconnections created by scarce resources. These studies also note that social, economic and climate fluctuations make shocks that accelerate the demand for food, energy and water resources (Al-Saidi & Elagib, 2017; Arent et al., 2011; De Fraiture & Wichelns, 2010; Freitas, 2015; Bartram et al., 2009). On a social note, Bartram et al. (2009) find that in addition to health issues, the demand–supply shortfall for sustainable water and sanitation services in sub-Saharan Africa is linked to a significant volume of preventable deaths. Drastic climate changes, in addition to endeavours to increase economic income, further strain the water stress in sub-Saharan Africa (De Fraiture & Wichelns, 2010; Freitas, 2015). More than 70% of the region's water resources are attributed to eight river basins (Freitas, 2015).

Overall, from a food point of view, the literature reveals that water, energy and other resources are intermediate resources for food production (De Fraiture & Wichelns, 2010; Hanjra & Khan, 2009; Hafeez et al., 2009; Bhaduri et al., 2013). Comparably, from an energy point of view, researchers find that water, food (biofuels) and other resources are intermediate resources for energy supply (Bhaduri et al., 2013; Gu et al., 2016; Jacobson et al., 2017; Okadera et al., 2015). Lastly, from a water point of view, the literature indicates that food, energy and other variables utilise water resources for crop and livestock husbandry, hydropower generation, etc. (Alfstad et al., 2013; Fricko et al., 2016; Conway & Rothausen, 2011; Karp & Richter, 2011).

Noteworthy extensions have been made on the food–energy–water nexus. These studies take into account climate change, other scarce resources such as land, economic challenges such as health expenditure, investments, etc. (Bellomi et al., 2016; Bhaduri et al., 2013; De Dalila & Fabiola, 2016; Finley & Seiber, 2014; Howarth & Monasterolo, 2017; Mabhaudhi et al., 2018; Ozturk, 2015; Rasul & Sharma, 2016). Land is considered in some studies stressing that while WEF improves, land degradation is present—land availability is limited (De Dalila & Fabiola, 2016). Bhaduri et al. (2013) highlight that fluctuating food, energy and water resource prices trouble land prices. Additionally, De Dalila and Fabiola (2016) and Bhaduri et al. (2013) highlight the relationship between energy, water and health; these studies find a significant association between resource insecurity and land degradation, malnutrition and low life expectancy. De Dalila and Fabiola (2016) and Bhaduri et al. (2013) also encourage the consideration of SDGs when studying the food–energy–water nexus.

The impact of climatic volatility is felt mainly by water resources (Freitas, 2015; Mabhaudhi et al., 2018) which translates to trouble for energy and food resources. Rainfall has been projected to decrease, predominantly for the SADC (Southern African Development Community) region (Mabhaudhi et al., 2018). This will burden water resources, reduce the production of rain-fed agricultural sectors (crop yield reduced) and decrease hydropower generation. On this account, adapting to climate change is of the essence. However, the relationship between climate change and food, energy and water is rather complex. Howarth and Monasterolo (2017) and Rasul and Sharma (2016) emphasise that interdisciplinary models/frameworks and policy formulation optimise the relationship between climate change and food, energy and water nexus, resulting in more efficient use of resources.

3 Methodology and data

3.1 Theoretical framework

This study examines the food–energy–water nexus in association with sustainable development. Therefore, how the models are structured indicates how economic prosperity delays or accelerates food, energy and water security in the big five countries. The three dependent variables representing the energy–water–food nexus each will be regressed against the other two controlling for the economic conditions of the countries (gross domestic product (GDP), gross capital formation (GCF), industry value-added (INDVAL) and labour force participation rate).

The study uses three simultaneous models to capture the interrelated demand for food, energy and water resources concerning the increasing need for sustainable development.

Energy

$$\text{renergy}_{it} = \beta_0 + \beta_1 \text{renergy}_{it-1} + \beta_2 \text{gdp}_{it} + \beta_3 \text{gcf}_{it} + \beta_4 \text{indval}_{it} + \beta_5 \text{lfpr}_{it} + u_{it} \quad (1)$$

$$\text{renergy}_{it} = \beta_0 + \beta_1 \text{renergy}_{it-1} + \beta_2 \text{food}_{it-1} + \beta_3 \text{drnkwater}_{it-1} + \beta_4 \text{gdp}_{it} + \beta_5 \text{gcf}_{it} + \beta_6 \text{indval}_{it} + \beta_7 \text{lfpr}_{it} + u_{it} \tag{2}$$

Food

$$\text{food}_{it} = \beta_0 + \beta_1 \text{food}_{it-1} + \beta_2 \text{gdp}_{it} + \beta_3 \text{gcf}_{it} + \beta_4 \text{indval}_{it} + \beta_5 \text{lfpr}_{it} + u_{it} \tag{3}$$

$$\text{food}_{it} = \beta_0 + \beta_1 \text{renergy}_{it-1} + \beta_2 \text{food}_{it-1} + \beta_3 \text{drnkwater}_{it-1} + \beta_4 \text{gdp}_{it} + \beta_5 \text{gcf}_{it} + \beta_6 \text{indval}_{it} + \beta_7 \text{lfpr}_{it} + u_{it} \tag{4}$$

Water

$$\text{drnkwater}_{it} = \beta_0 + \beta_1 \text{drnkwater}_{it-1} + \beta_2 \text{gdp}_{it} + \beta_3 \text{gcf}_{it} + \beta_4 \text{indval}_{it} + \beta_5 \text{lfpr}_{it} + u_{it} \tag{5}$$

$$\text{drnkwater}_{it} = \beta_0 + \beta_1 \text{renergy}_{it-1} + \beta_2 \text{food}_{it-1} + \beta_3 \text{drnkwater}_{it-1} + \beta_4 \text{gdp}_{it} + \beta_5 \text{gcf}_{it} + \beta_6 \text{indval}_{it} + \beta_7 \text{lfpr}_{it} + u_{it} \tag{6}$$

Equations (2), (4) and (6) include dependent variables of Eqs. (1), (3) and (5) in order to account for the food–energy–water nexus. The lagged dependent variable is included in the equations above in order to account for the dynamic adjustments, this assists in minimising heterogeneity.

In the literature, the signs indicating the effect the selected independent variables have on the dependent variables vary based on the econometric methodology followed attributes of the countries of interest, etc. (Ercantan et al., 2017). The following independent variables (Gross domestic product (GDP), gross capital formation (GCF), industry value added (INDVAL) and labour force participation rate) are expected to have a positive impact on the chosen dependent variables. Due to the big five countries being developing countries—economic growth improves food, energy and water security (World Resource Institute, 2019). Ideally, growth in GDP and domestic investments implies room for improving current production capacity through infrastructure, etc. Therefore, energy and water consumption and food production will increase since the production and distribution process has improved. Industrialisation demands a significant volume of energy and water resources. Generally, industries require electricity to operate, and water is used to cool off machinery. Hence, industrialisation increases energy and water consumption. Furthermore, industrialisation improves the agricultural production process by introducing innovative equipment allowing farmers for product diversification (John Hopkins Centre for a Livable Future, 2018) and increased food production. Lastly, most of the population in the countries of interest consists of individuals of working age, predominantly individuals aged between 15 and 24 (World Bank, 2019).

3.2 Econometric methodology

The study uses a dynamic general method of moments (GMM) model to examine the dynamic relationship between food, energy and water and selected explanatory variables. In econometric estimations where there are more moment conditions than model parameters or in other words the problem of endogeneity is implicit, the GMM estimation procedure provides a straightforward way to test the specification. Intuitively the way that the model is specified, the problem of endogeneity is expected, and thus, we directly consider the GMM specification before any other.

Equation (7) is the partial adjustment model, where y^* is the optimal value of y. To be precise, consider Eqs. (7) and (8).

$$y*_{it} = \beta_0 + \beta_1 X_{it} + u_{it} \tag{7}$$

$$y_{it} - y_{it-1} = \lambda\left(y* - y_{it-1}\right) \tag{8}$$

The following equation is obtained when substituting y^* into Eq. (8):

$$y_{it} = \beta_0\lambda + (1-\lambda)y_{it-1} + \lambda\beta_1 X_{it} + \lambda u_{it} \tag{9}$$

Equation (9) indicates a structure in which Eqs. (1)–(6) should follow, where the lagged explanatory variables may serve as instrumental variables for the GMM models. Appropriate diagnostic tests were conducted in addition to the instrumental GMM estimation used. Furthermore, the following panel data techniques were used:

It determines each variable's order of integration through testing for unit roots in each variable, following the Fisher-PP panel unit root test. The significance of the diagnostic tests encourages the use of the Fisher-PP test since the Fisher-PP test follows the assumption that unit roots are different for each cross section (Maddala & Wu, 1999).

Due to the lack of stationarity, the Pedroni (1999) test was used to test for panel cointegration. The Pedroni (1999) test was preferred because it is a residual-based cointegration test with a procedure similar to the traditional Engle–Granger cointegration test. Secondly, it allows for heterogeneous intercepts for the cross sections. The number of cointegrating vectors was determined using the Johansen Fisher panel cointegration test (Maddala & Wu, 1999).

3.3 Data

The study is conducted on a panel of annual data from 2000 to 2015 for the following countries: Angola, Ethiopia, Kenya, Nigeria and South Africa. The reason behind selecting these countries is based on real GDP ranks; the selected countries have managed to generate the highest real GDP in sub-Saharan Africa for the past two decades (World Bank, 2019). South Africa held the first position while Nigeria held the second position from 1990 to 2011; these two countries then switched places from 2012 to the present (World Bank, 2019). Angola maintained the third position from 1990 to the present, while Sudan maintained the fourth position from 1992. On the other hand, Kenya held the fifth position from 1990 to 2016; Ethiopia took over Kenya's fifth position from 2017 to the present (World Bank, 2019). Due to data constraints, Sudan is excluded from the study and Kenya is kept even though it is currently generating the sixth-highest real GDP in sub-Saharan Africa.

Data used in this study are sourced from the World Development Indicators, published by The World Bank (World Bank, 2019). Table 1 provides information on (1) the variables of interest, (2) how these variables are measured and (3) the variables' representation in the studied models.

Food production, people using at least essential drinking water services (water consumption) and renewable energy consumption are indicators of SDG 2, 6 and 7, respectively, proxying food, water and energy. Renewable energy consumption serves as a suitable proxy since it provides a precise outline of SDG 7 (affordable, modern, reliable). It also helps measure how sustainable the energy supply in the big five countries is.

Table 1 Variables and measurements

Variable	Measurement	Model representation
Food production	Food production index (2004–2006 = 100)	Food
Gross domestic product (GDP)	Constant 2010 US$	Gdp
Gross capital formation	% of GDP	Gcf
Industry, value-added	% of GDP	Indval
Labour force participation rate for ages 15–24	% modelled ILO estimate	Lfpr
People using at least essential drinking water services	% of population	Drnkwater
Renewable energy consumption	% of total final energy consumption	Renergy

Table 2 Pairwise correlation matrix

	food	gdp	gcf	Indval	lfpr	drnkwater	renergy
food	1						
gdp	0.1278	1					
Gcf	0.3166**	0.2801**	1				
indval	0.0652	0.2007*	0.5131***	1			
lfpr	0.1156	−0.8096***	−0.1631	−0.0358	1		
drnkwater	0.1072	0.8444***	0.1952*	0.1303	−0.849***	1	
renergy	−0.1520	−0.5950***	−0.1727	−0.3263**	0.5001	−0.8511***	1

*(**)[***] Statistically significant at a 10(5)[1] % level

Table 2 presents the pairwise correlation matrix. There exists a positive correlation between the food production index and water consumption ($\rho = 0.107$). However, a negative correlation exists between the food production index and renewable energy consumption ($\rho = -0.152$). A greater negative relationship exists between water consumption (drinking water) and renewable energy consumption ($\rho = -0.851$). Moreover, renewable energy consumption negatively correlates with all explanatory variables (gdp, gcf, indval) except for the labour force participation rate ($\rho = 0.500$). Table 2 reveals a positive correlation between water consumption and explanatory variables except for the labour force participation rate ($\rho = -0.850$). Furthermore, a positive correlation exists between the food production index and all explanatory variables.

4 Results and discussion

Table 3 indicates the results of the Fisher-PP unit root test, which considers the null hypothesis of non-stationarity (no unit root). The null hypothesis is not rejected for the drnkwater variable from the results below. Therefore, drnkwater is a stationary variable (I(0)) while all the others contain unit roots, or in other words, they are non-stationary or I(1) except lfpr that is I(2).

The varied orders of integration observed above lead to the long-run cointegration results presented in Table 4, where the number of cointegrating vectors is determined using the Johansen Fisher test. Results in Table 4 indicate that the null hypothesis of no cointegration is rejected for the food, energy and water model. Furthermore, four cointegrating vectors are identified between renewable energy consumption and the explanatory variables. Similarly, there are four cointegrating vectors between water consumption and the explanatory variables. On the other hand, there are three cointegrating vectors between the food production index and the explanatory variables.

Consequently, a long-run relationship is confirmed between the food–energy–water nexus and the explanatory variables for the big five countries. This also demonstrates the synergy between SDG 2, 6 and 7. Therefore, policymakers are encouraged to jointly prioritise policies that address food, energy and water security. Rather than having separate policies for energy security, food security and water security.

Next, dynamic panel models were estimated (following the GMM method). Endogeneity is absent in the parameters estimated below. Each of the three nexus variables is first

Table 3 Panel unit root test: Fisher-PP

Variables	Level intercept term only	Trend & intercept term	1st difference intercept term only	Trend & intercept term	2nd difference intercept term only	Trend & intercept term
food	7.727	17.946	143.273***	124.804***	–	–
gdp	9.064	4.018	24.947***	42.0756***	–	–
gcf	9.651	14.086	77.760***	58.270***	–	–
indval	12.9	8.79	31.301***	18.87**	–	–
lfpr	14.436	5.847	13.368	7.107	58.907***	47.813***
drnkwater	260.132***	99.002***	–	–	–	–
renergy	4.195	5.876	57.319***	49.342***	–	–

***, **, * denote 1%, 5% and 10% level of statistical significance

Table 4 Johansen Fisher panel cointegration test: unrestricted cointegration rank test (trace and maximum eigenvalue)

Energy model					Food model					Water model				
Hypoth-esised No. of CE(s)	Fisher stat* (from trace test)	Prob	Fisher stat* (from max-eigen	Prob. test)	Hypoth-esised No. of CE(s)	Fisher stat* (from trace test)	Prob	Fisher stat* (from max-eigen test)	Prob	Hypoth-esised	Fisher stat* (from trace test)	Prob	Fisher stat* (from max-eigen test)	Prob
None	23.97	0.0077	23.97	0.0077	None	58.03	0	58.03	0	None	23.97	0.0077	23.97	0.0077
At most 1	92.1	0	92.1	0	At most 1	141.3	0	115.3	0	At most 1	75.07	0	75.07	0
At most 2	233	0	86.24	0	At most 2	54.2	0	45.3	0	At most 2	352.1	0	109.4	0
At most 3	54.5	0	42.18	0	At most 3	21.6	0.0173	22.57	0.0124	At most 3	78.49	0	54.47	0
At most 4	26.09	0.0036	26.09	0.0036	At most 4	7.081	0.7178	7.081	0.7178	At most 4	40.16	0	40.16	0

Probabilities are computed using asymptotic Chi-square distribution

Table 5 GMM system results (all countries)

	renergy		food		drnkwater	
	GMM1	GMM2	GMM1	GMM2	GMM1	GMM2
$renergy_{i,t-1}$	0.912***	0.961***	–	−0.00704[c]	–	0.0107[c]
$food_{i,t-1}$	–	−0.410[a]	0.889***	0.603**	–	−0.363***[a]
$drnkwater_{i,t-1}$	–	−0.0866[b]	–	0.00583[b]	0.966***	0.996***
$gdp_{i,t}$	−0.704	0.623	0.0173	0.104	0.401***	0.339***
$gcf_{i,t}$	0.00112	−0.00271	0.00108	0.000483	−0.00683***	−0.00655***
$indval_{i,t}$	−0.0737*	−0.0511*	0.000176	0.000331	−0.00305***	0.000181
$lfpr_{i,t}$	0.0169	−0.0312	0.00211**	0.00166	−0.00395**	0.014
cons	24.48	−3.916	–	–	−6.865***	−6.888***
N	75	75	75	70	75	75

*(**)[***] Statistically significant at a 10(5)[1] % level a, b & c indicate f $ood_{i,t}$, $drnkwater_{i,t}$ & $renergy_{i,t}$; respectively

regressed against only the other two and subsequently the other two and the economic control variables.

From a bird's eye view (Table 5), the big five countries' food production significantly decreases water consumption, ceteris paribus. This is due to the large volumes of water needed for growing crops and animals. A 1% increase in food production reduces water consumption by 0.363%, ceteris paribus. This indicates the water stress witnessed in these countries and emphasises the urgent need for efficient water use. Another major consumer of water resources, that is the industrial sector, has a negative impact on the drinking water resources: the higher the industrial share, the higher the water volumes to operate and distribute products (cooling, processing, transporting, etc.), the lower the available resources for drinking purposes. However, at a much lower rate, a 1% growth in industries leads to a 0.003% decrease in water consumption, ceteris paribus.

Results in Table 5 indicate that renewable energy consumption in the big five countries is significantly decreased by industrialisation, ceteris paribus. This indicates that current energy resources do not adequately meet the requirements for industries to secure economies of scale. Despite the relatively small coefficients, the results show the absence of green initiatives.

Moreover, food production increases significantly due to the labour force participation rate, ceteris paribus. A 1% increase in the labour force participation rate leads to a 0.002% increase in food production, ceteris paribus. The more people get absorbed in the production processes, the higher the demand for food and hence food production. The nation's productivity improves food security in the big five countries; this bodes well since the agricultural sector is generally one of the leading employers in developing countries.

Water consumption is affected by gross domestic product, gross capital formation, industry value-added and labour force participation rate. GDP increases water consumption, while industry value-added, gross capital formation and the labour force participation rate decrease water consumption. These results indicate sustainable development issues in the big five countries; ideally, the growth of industries, investments and productivity leads to good use of water resources.

Overall, the results in Table 5 highlight the urgent need for policy reforms that encourage a green sustainable economy. The study further traces the relationship between food, energy, water and sustainability in the big five countries. Since literature has highlighted the significance of institutions, geopolitics, etc., and the panel modelling techniques have confirmed the heterogeneity of the big five countries—[The results and analysis of each of the countries separately are presented in the "Appendix"].

5 Conclusion and discussion

The study simultaneously used three models to examine the food–energy–water nexus concerning sustainability in an annual panel between 2000 and 2015 for sub-Saharan Africa's big five countries (Angola, Ethiopia, Kenya, Nigeria, South Africa). The study made use of a GMM panel estimation appreciating that by specification endogeneity issues need to be accounted for. Results indicate a strong sub-nexus (food–energy, energy–water, food–water) in the countries of interest. Therefore, the food–energy–water nexus is present in these countries, and policymakers should implement systems thinking to ease the journey towards sustainable development. The big five countries have been listed amongst the top ten populous countries in sub-Saharan Africa for the past two decades (Angola became part of this list in 2011) (World Bank, 2019). Overall, the challenge in these countries is that efficient use and management of food, energy and water resources have to a great extent been neglected by policymakers. In addition to the capital potential that the big 5 countries hold, these countries have a significant energy potential since the primary energy source is hydropower (except for South Africa). Such potential in these countries oftentimes comes in competition with drinking water requirements for the growing population of these countries. However, it is encouraged that these countries invest efforts towards diversifying their energy mix. In doing so, less pressure will be placed on the already stressed water resources. Furthermore, food insecurity in these countries is aggravated by the failure to align food production with the growing population.

The findings of this study for the whole group of countries, a sub-nexus was concluded from Food to Water, Water to Food and Water to Energy for Ethiopia was confirmed, Energy to Water for Kenya and Water to Food for Angola; the big five countries primarily consume water for agricultural production. Analysing these countries individually reveals that water is also used for energy production and industrial cooling purposes. Meanwhile, the water sector uses energy to pump and distribute water. Agricultural production also requires significant power for purposes such as electricity to operate equipment and produce fertilisers/chemicals off the farm. Lastly, there is no significant food-energy sub-nexus.

Overall, food, energy and water resources have a rapidly increasing demand while the supply for these resources is notably limited. In line with the literature, climate change, geographic regions and politics, the supply of these resources is irresistibly influenced. They also bear these resources' security issues are central to society's daily functions. Therefore, policymakers are advised to consider these facts when implementing systems thinking. Mainly, sustainable development should encourage green economies (for example, through green industries), which translates to efficient use of energy and water resources. Ideally, this will result in less land degradation and increased food security.

Appendix

According to Table 6, GDP significantly decreases energy consumption in Angola. A 1% increase in GDP results in a 15.45% decrease in renewable energy consumption, ceteris paribus. Economic growth places considerable pressure on available renewable energy resources, considering that approximately 58% of the energy mix in this oil-dependent economy is attributed to hydropower (US AID, 2019). On the other hand, food security increases with economic growth. Food production increases by 0.881% due to a 1% increase in GDP, ceteris paribus. Amongst other reasons, this is attributed to the country adopting a growth strategy that prioritises the agricultural and private sectors to diversify economic growth (International Fund for Agricultural Development, 2019).

Water consumption is affected by GDP and the labour force participation rate. Meanwhile, water consumption decreases by 0.78% and increases by 0.264% due to a 1% increase in GDP and the labour force participation rate, respectively. Economic growth for middle-income countries such as Angola usually strains water resources, causing

Table 6 GMM system results: Angola

	renergy		Food		drnkwater	
	GMM1	GMM2	GMM1	GMM2	GMM1	GMM2
$renergy_{i,t-1}$	0.256	0.000827	–	−0.00795[c]	–	0.0176*[c]
$food_{i,t-1}$	–	−2.804[a]	0.0033	−0.124	–	0.0118[a]
$drnkwater_{i,t-1}$	–	−1.573[b]	–	0.0374[b]	1.050***	1.080***
$gdp_{i,t}$	−15.45*	−3.737	0.881*	0.469	−0.840*	−0.780*
$gcf_{i,t}$	0.136	−0.00717	−0.00432	−0.00221	0.00381	0.00393
$indval_{i,t}$	0.316	0.161	−0.0109	−0.006	0.00323	0.000121
$lfpr_{i,t}$	−9.51	−10.19	0.318	0.284	0.0574	0.264*
N	14	14	14	14	14	15

*(**)[***] Statistically significant at a 10(5)[1] % level a, b & c indicate $food_{i,t}$, $drnkwater_{i,t}$ & $renergy_{i,t}$; respectively

Table 7 GMM system results: Ethiopia

	renergy		Food		drnkwater	
	GMM1	GMM2	GMM1	GMM2	GMM1	GMM2
$renergy_{i,t-1}$	0.644**	0.209	–	0.0658[c]	–	−0.00218[c]
$food_{i,t-1}$	–	6.063[a]	0.785***	−0.204	–	−0.0419[a]
$drnkwater_{i,t-1}$	–	−0.390*[b]	–	0.0603*[b]	0.968***	0.995***
$gdp_{i,t}$	0.118	1.207	0.131	−0.0649	0.152**	−0.268
$gcf_{i,t}$	−0.0147	−0.0147	−0.00149	0.00126	−0.00109	−0.00111
$indval_{i,t}$	0.0327	−0.0778	−0.00289	0.00977	−0.0133**	−0.0218*
$lfpr_{i,t}$	0.403	0.392	−0.0268	−0.0116	−0.0156	−0.0680
N	15	15	15	15	15	14

*(**)[***] Statistically significant at a 10(5)[1] % level a, b & c indicate $food_{i,t}$, $drnkwater_{i,t}$ & $renergy_{i,t}$; respectively

water shortages in some country regions (International Fund for Agricultural Development, 2019). The majority of the country's population is working-age individuals (World Development Indicators, 2019). Hence, an increase in the labour force participation rate increases water consumption.

Table 7 presents results for Ethiopia where water consumption decreases renewable energy consumption and increases food security in this agricultural-based economy. A 1% increase in water consumption results in a 0.39% decrease in renewable energy consumption, ceteris paribus. Ethiopia has significant renewable energy potential, with approximately 89% and 8% of power attributed to hydropower and wind, respectively (US AID, 2019). However, water consumption (predominantly by the country's huge population) leaves little room for hydropower generation. The inelastic relationship in Table 6 between water consumption and food production is unsatisfactory for food security.

Moreover, water consumption increases with GDP and decreases due to industrialisation. Water consumption increases by 0.152% due to a 1% increase in GDP, ceteris paribus. Recently, the country has invested in water-related infrastructure developments (World Economic Forum, 2018a). Major industrial activities in the country compete for the same water resources used to provide for water consumption. Also, these industries have been rapidly growing in the past decade. Hence, the decrease in water consumption is caused by growth in industries.

Kenya's GMM results are presented in Table 8. These results reveal that water consumption increases with renewable energy consumption. Kenya's energy mix is reasonably diverse, with a mere 36% of power being attributed to hydropower (US AID, 2019). Therefore, there is more room for water resources for other purposes than power generation.

Furthermore, renewable energy consumption in Kenya increases with the labour force participation rate. A 1% increase in the labour force participation rate leads to a rise in renewable energy consumption of 0.424%, ceteris paribus. Similarly, food security increases with economic growth. A 1% increase in GDP leads to a 0.135% increase in food production, ceteris paribus. Kenya's power capacity from renewable energy is above the world's average renewable energy power capacity; while achieving this, the country prioritised job creation (World Economic Forum, 2018b). Kenya engaged in policy reforms that resulted in good economic growth during the past decade, translating to improved food security for the agricultural-led economy (The World Bank, 2019b).

Table 8 GMM system results: Kenya

	renergy		Food		drnkwater	
	GMM1	GMM2	GMM1	GMM2	GMM1	GMM2
$\text{renergy}_{i,t-1}$	0.853*	0.691	–	−0.00518[c]	–	0.000458**[c]
$\text{food}_{i,t-1}$	–	−17.39[a]	0.361	−0.182	–	−0.00328[a]
$\text{drnkwater}_{i,t-1}$	–	0.0257[b]	–	0.0349[b]	0.987***	0.988***
$\text{gdp}_{i,t}$	−0.429	3.692	0.135*	0.152	0.0568***	0.0538***
$\text{gcf}_{i,t}$	0.0382	−0.0230	0.00364	−0.0104	−0.000764*	−0.000651**
$\text{indval}_{i,t}$	0.213	0.764	0.014	0.0458	0.0000274	−0.0000125
$\text{lfpr}_{i,t}$	0.424*	0.0322	−0.0151	−0.00522	−0.000470	−0.000285
N	15	15	15	15	15	15

*(**)[***] Statistically significant at a 10(5)[1] % level a, b & c indicate $\text{food}_{i,t}$, $\text{drnkwater}_{i,t}$ & $\text{renergy}_{i,t}$; respectively

Table 9 GMM system results: Nigeria

	renergy		Food		drnkwater	
	GMM1	GMM2	GMM1	GMM2	GMM1	GMM2
$renergy_{i,t-1}$	0.293	0.158	–	−0.00103[c]	–	−0.00226[c]
$food_{i,t-1}$	–	0.0219[a]	0.357	−0.143	–	−0.118[a]
$drnkwater_{i,t-1}$	–	−1.200[b]	–	0.0545[b]	1.025***	1.030***
$gdp_{i,t}$	2.484**	19.37	0.118*	0.0325	−0.0358	−0.0223
$gcf_{i,t}$	0.0828	0.172	−0.000932	0.00536	−0.0181	−0.0176
$indval_{i,t}$	−0.165	−0.224	0.00231	0.00331	−0.00558	−0.00564
$lfpr_{i,t}$	−0.0829	−0.662	−0.00584	0.0359	0.0455*	0.0485
N	15	14	15	15	15	15

*(**)[***] Statistically significant at a 10(5)[1] % level a, b & c indicate $food_{i,t}$, $drnkwater_{i,t}$ & $renergy_{i,t}$; respectively

Table 10 GMM system results: South Africa

	renergy		Food		drnkwater	
	GMM1	GMM2	GMM1	GMM2	GMM1	GMM2
$renergy_{i,t-1}$	0.216	−0.0233	–	−0.0365[c]	–	0.000366[c]
$food_{i,t-1}$	–	−13.45[a]	0.245	−0.105	–	0.176*[f]
$drnkwater_{i,t-1}$	–	1.040*[b]	–	0.0799[b]	0.974***	0.966***
$gdp_{i,t}$	6.433	−1.122	0.0992	−0.352	0.108***	0.109***
$gcf_{i,t}$	−0.509	−0.289	0.0319**	0.00337	0.000607	−0.00239
$indval_{i,t}$	0.322	0.830*	0.0360*	0.0485**	−0.00277	−0.00933*
$lfpr_{i,t}$	0.114	0.0325	−0.0245*	−0.00540	−0.000570	0.00114
N	14	15	15	15	15	15

*(**)[***] Statistically significant at a 10(5)[1] % level a, b & c indicate $food_{i,t}$, $drnkwater_{i,t}$ & $renergy_{i,t}$; respectively

Water consumption increases with economic growth, while it minutely decreases when investments increase. Policymakers in this agricultural-led economy have worked towards a market and digital economy (The World Bank, 2019a). Ideally, resource management tends to improve as the economy grows, hence the positive relationship between water consumption and economic growth. The minute decrease in water consumption due to an increase in investments indicates the limited resources which the country has for domestic investment purposes. This also highlights the country's dependence on international financial assistance to improve infrastructure.

Table 9 presents GMM results for Nigeria; these results reveal that renewable energy consumption and food security increase with GDP, while water consumption increases with the labour force participation rate. Renewable energy consumption and food production increase by 2.484% and 0.118%, respectively, due to a 1% increase in GDP. Meanwhile, water consumption increases by 0.046% due to a 1% increase in the labour force participation rate, ceteris paribus. Considering Nigeria's current hydro and solar resources, this oil-dependent economy has the potential to increase renewable power generation with its existing plants (US AID, 2019). Therefore, GDP growth provides Nigeria with the necessary capital to diversify its energy mix and kick start using hydro and solar resources by the country's present power plants.

Diminutive development strategies have been directed towards the country's agricultural sector, hence the relentless food security challenges faced by the government (Elegbede & Matemilola, 2014). The positive relationship between food production and GDP in Table 10 indicates the country's potential to improve its current state of food insecurity, given the country's significant economic growth. Comparably, this populous country has abundant water resources; however, these resources are poorly managed (Ezeabasili et al., 2014). Hence, a negative relationship between water consumption and labour force participation rate.

Table 10 shows South Africa's GMM results. The country's renewable energy consumption is significantly increased by water consumption, while food production increases water consumption. The government is highly dependent on thermal power (US AID, 2019). Therefore, renewable energy infrastructure is still in its early stages. Hence, the absence of intense competition for water resources between renewable energy generation and other water resource consumers is observed. Given the recent drought witnessed by the country, the positive relationship between food production and water consumption indicates the country's efforts towards implementing strategies that encourage the efficient use of water resources in the agricultural sector (World Wide Fund for Nature, 2018).

Industries in South Africa have been overgrowing, and the country consists of a diverse manufacturing base. On the other hand, there have been reasonable efforts towards becoming a green economy; hence, industrialisation increases the consumption of renewable energy (Gungor & Simon, 2017). Furthermore, this agricultural-led economy continuously grows and improves its agricultural sector. Thus food security improves as domestic investment and industries increase. Digital agriculture (often called precision agriculture) is moderately growing in South Africa (AFGRI, 2019), hence the inverse relationship between food security and the labour force participation rate.

Water consumption increases with GDP growth; this is true for most developing countries since the economy's growth is accompanied by numerous uses for water resources (Katz, 2015). The inverse relationship between water consumption and industrialisation indicates that current water resources and the management of these resources cannot provide for the rapidly growing industries.

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