





Article

Decoupling Energy, Water, and Food Resources Production from GHG Emissions: A Footprint Perspective Review of Africa from 1990 to 2017

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Abstract: Decoupling energy, water, and food (EWF) consumption and production from GHG emissions could be an important strategy for achieving the UN Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 7 (Clean and Affordable Energy) in Africa. This study applies Tapio's decoupling method to analyze the relationship between GHG emissions and EWF resources use in 15 African countries over the period 1990–2017. The results show a remarkable relationship, which includes the contamination of EWF by GHG emissions, that mostly exhibits unsatisfactory decoupling state to satisfactory decoupling over a period of several years. The decoupling of water and energy resources from GHG emissions in most countries of Africa has not been able to reach an excellent decoupling state or a strong positive decoupling state. This requires countries in Africa to support environmentally friendly water and energy infrastructures and to promote an integrated, mutually managed, whole resource interaction system. The study also highlights the importance of tracking sources of GHG emissions, whether within individual resource sector activities or across resources to each other.

Keywords: greenhouse gas; Africa; Tapio decoupling method; energy, water, food resource; economic growth

1. Introduction

The sustainable upkeep of EWF resources in Africa has raised new concerns, due to high population growth, increased economic development and climate change impacts [1]. As many African countries increase their demand for EWF resources to satisfy their populations and economies, it brings the necessity to understand the inevitable link between EWF resources and a failure to manage any one of them, leading to compromised sustainability of supply for the entire ecosystem. Unsustainable agricultural practices, for example, release large amounts of methane and nitrous oxide, two potent greenhouse gases (GHGs) that can overall affect the stability of other resources, i.e., pollution of water and food crops from acid rain [2]. Energy production is one of the main sources of CO₂ emissions and

is responsible for more than 80% of these emissions as a result of the strong reliance on traditional non-renewable energy resources [3]. While the use of fertilizers and pesticides in agriculture positively impacts food production, it increases the GHG footprint on soils, which poses significant risks to the overall EWF resource interaction system [4,5].

In fact, the African continent has experienced an increase in GHG effects, which has resulted in higher temperatures, increased rainfall, and changes in extreme weather conditions, making the continent more vulnerable to extreme human and natural disasters. The major disasters threatening development and resource security in the African region are floods, droughts, temperature rises, and storms [6]. Precipitation is primarily associated with catastrophic challenges to crops and hydropower infrastructure damage in several tropical African countries. Such extreme events put additional stress on already stressed and complex land use, watersheds, economic infrastructure, developed water systems and economic footprints [7–9]. The effect of this climate change is projected to cause an average agricultural yield loss of 13% in West and Central Africa, 11% in North Africa, and 8% in Eastern and Southern Africa by 2050 [10,11]. Yet, according to Maris, et al. [12], sustainable water resource management is critical for decreasing methane (CH₄), carbon dioxide (CO₂), and nitrous oxide (N₂O) emissions from rice fields.

During the mainstreaming of the sustainable development goals (SDG), it is widely recognized that the relevance of mutual and inclusive management of EWF resources in a nexus approach with the sharing of costs, minimizing the trade-offs and fostering the benefits of synergies in practice [13]. Over the years, much-needed descriptive studies have been carried out to improve our understanding of Africa's EWF resources interaction characteristics and their impact on sustainable development [14–16]. Nevertheless, studies that provide insight into assessing the relative shares of the GHG emissions footprint in the EWF's resources are limited in the current African research context, but their complexity poses relatively significant challenges to the overall benefits and management system of the EWF.

Literature Review

The previous literature has widely endorsed decoupling theories in various socio-economic contexts, such as population growth, urbanization, transport or other economic growth activities with single or two resources among EWF resources [17]. Many studies on decoupling analysis have been carried out, using the Tapio decoupling approach, a method developed based on the elastic coefficient [18]. Among its first applications by Tapio [19], the approach showed the potential to evaluate the relationship between the rate of carbon dioxide change in transportation activities. Eight categories were defined to better assess the degree of decoupling in the Tapio decoupling index, ranging from strongly negative to strongly positive decoupling [19]. Further, Li and Zhou [20] also classified the decoupling states in Tapio's elasticity approach into five resource utilization efficiency states ranging from unsatisfactory to excellent states. Many studies have been conducted based on Tapio's decoupling theory by many researchers to decouple the relationships between many variables such as energy, the economy, transportation, water, food, agriculture, GHG, CO₂ and other gases, and economic growth within countries, regions, and continents [12,18].

Indeed, decoupling states have been illustrated in energy use with economic development and GHG emissions in African countries, and research proposes that the continent develop energy from non-emitting sources [21]. This is due to the fact that energy use and economic evolution have a noteworthy long-term positive impact on GHG emissions, with real GDP showing a critical linkage with GHG emissions in Africa [22]. Some evidence in the literature has mostly shown decoupling for production-based emissions, but research gaps have been shown in decoupling evidence for consumption-based emissions [13].

Reviewing existing studies linking the EWF and climate change, Lahmouri, et al. [23] expressed concern about the polluting atmospheric function of climate change on EWF resources caused by the strong pressure of economic development. Moreover, Maji, et al. [24] examined renewable energy use in economic development and climate change resilience

in Western Africa. The findings illustrated that the use of renewable energy slows down development in Western Africa. They mentioned the challenges posed by the traditional use of non-renewable energy in West Africa, with impure and inefficient resource sources, such as forest biomass, as an energy source. Furthermore, Martin and Danielsson [25] mentioned the environmental implications of minimizing food waste and promoting food waste re-use as a critical solution for reducing the EWF GHG footprint for food resource emissions into land and water pollution. For decoupling GHG studies in Africa, many studies, such as that of Gabon, use non-renewable energy products to endorse economic development but compromise environmental quality, which is the case in Angola [26].

An interesting study by Pardoe, et al. [27] on managing EWF resources under the constraints of climate change in Tanzania called on Tanzanian policymakers to establish climate change policies, budgets, and plans, which are still relatively superficial. In South Africa, Mpandeli, Naidoo, Mabhaudhi, Nhemachena, Nhamo, Liphadzi, Hlahla and Modi [14] mentioned that increasing GHG has reduced agricultural yields, water and sanitation issues, and sustainable energy as the main areas of concern that have led to worsening of the human and economic health development situation in the region. Conway, et al. [28] presented the future projection impact of increased climate change anomalies on South Africa's EWF resources, which will decrease annual precipitation by 20% by the 2080s, reducing water availability and crop yields. Disequilibrium in energy and water resources management depressingly disturbs the country's demand for electricity in Ghana [29]. The findings indicate a need to develop a theory of nutritional transition and clean and renewable energy that can be used to reduce external diseases and challenges posed by the supply of EWF resources and pollution that can be associated with Uganda [30].

Using a random-effects panel model, Zaman, et al. [31] examined the non-linear interaction among environmental water supplies and air pollutants across 19 Sub-Saharan African (SSA) nations from 2000 to 2014. This research concluded that SSA countries should take effective measures to reduce the air pollution that compromises environmental water resources management. A study in Pakistan by Anser, et al. [32] analyzed the relationship between EWF resources and GHG-fossil-carbon emissions in Pakistan, using the Tapio elasticity model. The results showed a visible impact of GHG-fossil-carbon contamination of EWF resources and further suggested extending the analysis to several countries.

Our study particularly focuses on GHG emissions, which we classify into three categories: the GHG footprint of non-renewable energy sources, the GHG footprint of total energy sources, and the overall GHG footprint of human activities and natural systems. The findings of Maris, Teira-Esmatges and Català [12] suggested that reducing GHG emissions requires understanding the main sources of GHGs, underlying drivers within each country's economic sector, and policies to avoid dangerous climate change and minimize the growth of GHGs in the atmosphere. Therefore, the need to effectively and efficiently track GHGs emissions in Africa is the objective of this study. The paper specifically focuses on tracking different GHG sources emissions associated with EWF resources consumption and provides a comprehensive understanding of the interaction between GHG emissions and WEF resources production and consumption. It calculates the Tapio elasticity values of GHG pollution in EWF resources with eco-efficient decoupling states in 15 African countries over 27 years ago.

Following the introduction and review of the literature, the second part covers the materials and methods; the third focuses on the findings; the fourth analyzes the major findings; and the fifth ends the research with policy implications. Furthermore, the motivation for this article stems from several reasons. For instance, our research is among the few existing studies on decoupling GHG emissions from EWF resources. In addition, previous studies most often focused on the decoupling analysis of production-based emissions while ignoring the environmental impacts of consumption, which are more focused on in this work. Iteratively, this work analyzes GHG emissions by considering different sources—GHG from non-renewable energy, GHG from total energy consumption, and

GHG from all sectors (including land use, forestry, industrial processes, waste, agriculture, and energy)—and tracing the energy, water and food interdependence in GHG emissions.

2. Materials and Methods

2.1. Data and Study Areas Description

Data for different variables are taken in range of 1990–2017 and divided into three decades, namely 1990–1999, 2000–2009 and 2010–2017, and rationalized according to the growth rates in the decade (Table 1).

Table 1. Graphical table of data variable used.

Variable	Indication (Sub-Variables)	Source of Data
ENERGY	<ul style="list-style-type: none"> Energy supply from non-renewable sources (% of overall energy use) denoted as ENERG Total energy production (TEP) 	[33]
	<ul style="list-style-type: none"> Energy consumption from fuel types 	[34,35]
FOOD	<ul style="list-style-type: none"> Food imported (FI) in (%), Food exported (FE) in (%) Net food exported (FOODNEXP) in (%) = (FE (%)-FI (%)) 	[36]
WATER	<ul style="list-style-type: none"> Improved water source (% of people access) denoted as IWAT 	[37]
GHG	<ul style="list-style-type: none"> GHGs emissions from all sectors (GHG-AS), (Mt CO₂e) 	[38]
	<ul style="list-style-type: none"> GHG from all energy (GHG-TE) consumptions 	[38]
GHG proportion in water	<ul style="list-style-type: none"> GHG from non-renewable energy sources (fuel types) (GHG-NRE) 	Authors
	<ul style="list-style-type: none"> Calculated based on IWAT sub-variable over each GHG sub-variable 	Authors
GHG proportion in food	<ul style="list-style-type: none"> Calculated based on FOODNEXP (%) sub- variable over each GHG sub-variable 	Authors
	<ul style="list-style-type: none"> Calculated based on energy sub-variables over each GHG sub-variable 	Authors
GHG proportion in energy	<ul style="list-style-type: none"> Calculated based on energy sub-variables over each GHG sub-variable 	Authors
GDPpc	<ul style="list-style-type: none"> GDP per capita (constant 2010 USD) 	World bank

In the selection of variables for the analysis (Table 1), the energy consumption from non-renewable sources (% of overall energy demand) was collected from the International Energy Agency (EIA) Country Profiles database, the United Nations database. Additionally, energy consumed from types of fuel, such as liquefied petroleum gas (LPG), gasoline, kerosene, fuel oil, natural gas, coal, and diesel/gasoline was used to calculate GHG from fuels consumptions (Appendix Tables A2 and A3). Figure 1 below illustrates the diagram of research methodology.

In addition, this study was conducted in 15 African countries. The countries were selected based on data availability and distribution in five regions of the African continent: four from the northern region (Algeria, Tunisia, Egypt and Morocco), three from the southern region (South Africa, Angola and Zimbabwe), two from East Africa (Kenya and Tanzania), two from Central Africa (Republic of Congo and Cameroon) and four from West Africa (Ghana, Nigeria, Senegal and Benin). These countries accounted for 24.44% of the continent's total land area, 37.7% of the total population, and 48.14% of Africa's total GHG emissions from all sectors between 1990 and 2017 (Table A1). Countries such as Nigeria and Egypt are the most populous in Africa. The selected countries also occupy the top 10 countries with the highest annual GDP, as well as the largest and most urbanized cities in Africa [39]. Exploring energy consumption data from 1990 to 2017 shows that the selected countries are the largest consumers of conventional non-renewable energy sources (see Appendix Table A2). Algeria, for example, consumed 31.7% of total African

LPG consumption from 1990 to 2017. Morocco increased its consumption capacity from 18.2% in 1990 to 21.95% in 2017.

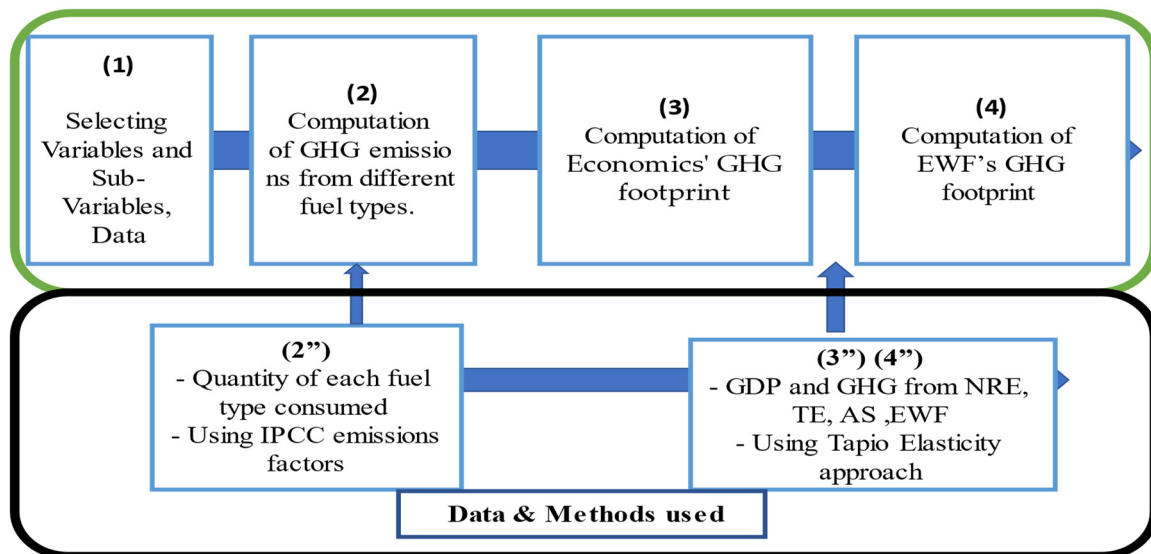


Figure 1. Diagram of research methodology.

Egypt was also the largest consumer, accounting for 31.7% of total LPG consumption in 1990 and 41.1% in 2017. Sub-Saharan Africa, Angola, Ghana, Kenya, Senegal, and South Africa accounted for 3% to 1.12% of the total consumed. Nigeria was the largest consumer of kerosene from 1990 to 2017, while South Africa was the largest consumer of gasoline, which is also similar to other countries selected, as shown in Table A2. Along with examining data on how the selected countries on GHG emissions were incorporated from three sources (GHG emissions from all sectors, GHG from total energy consumptions and GHG from non-renewable energy sources), many countries show a predominance of GHGs from non-renewable energy sources (Table A3). For example, during the period 1990–1999, Algeria, Egypt, Nigeria and Tunisia's GHG emissions from total energy consumption are more closely related to GHG emissions from non-renewable energy, 81.39/85.02 MtCO_{2e}, 87.06/99.38 MtCO_{2e}, 107.72/124.75 MtCO_{2e} and 12.9/16.3 MtCO_{2e} respectively, showing variation over the next decades. Nigeria varied by 85.2/170.35 between GHG from non-renewable energy sources (C) and GHG from total energy consumption (T) between 2010–2017. Algeria was able to maintain a balance between GHGs from these two resources (C, T) at a rate of 148.5/157.17, the same as Egypt with 198.4/211.83. Overall, embodied GHGs in non-renewable energy sources (C) decreased from 64.2% to 57% between 1990 and 2017, the same as total energy GHG emissions, which decreased from 33.04% to 28.9% from 1990 to 2017. However, non-renewable energy GHG emissions decreased but still had a high percentage of emissions (57%), which is critical and requires a policy to promote modern, clean energy from renewable energy resources. GHGs for all sectors in the selected countries showed different variations over the selected decades. For example, from 1990 to 1999, there were 1361.48 MtCO_{2e}, 1751.05 MtCO_{2e} from 2000 to 2009, and 2431.69 MtCO_{2e} from 2010 to 2017 (see Appendix Table A3).

The historical trend of GHG emissions from the main sectors of human activities (Figure 2) shows that the energy sector was the largest emitter of GHGs, followed by agriculture, land-use change and forestry, industrial processes, and waste in the selected countries during the period 1990–2017.

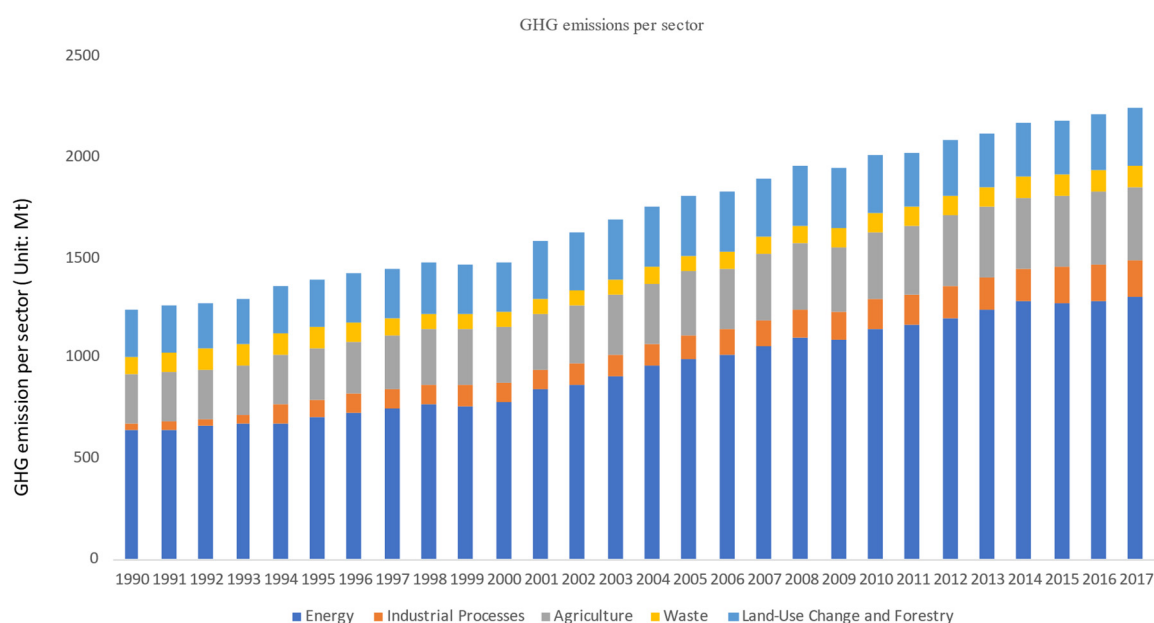


Figure 2. Historical GHG emissions by emitting sectors.

2.2. Methodology Description

2.2.1. Embodied GHG Emissions from Non-Renewable Fuels Energy Consumption

The World Resources Institute has defined different ways to measure GHG emissions, either by direct GHGs emissions from sources controlled by the country or by indirect GHG emissions from the export of purchased resources, with indirect emissions not produced or used inside the region but attributed to the region's emissions [40,41]. IPCC [40] has also calculated emission factors of fuel energy used in the global warming potential (GWP), a ratio of 1:21:310 for CO₂:CH₄:N₂O (Table 2).

Table 2. GHG emission factors in various fuels.

Fuel Energy	Emission Factors				Unit: tCO ₂ e./Tj
	CO ₂ ^a unit Kg/Tj	CH ₄ ^a	NO ₂ ^a	GWP ^b	
Gasoline	69,300	3	0.6	69.5	
Kerosene	71,900	3	0.6	72.1	
Gas oil and Diesel	74,100	3	0.6	74.3	
Fuel Oil	77,400	3	0.6	77.6	
LPG	63,100	1	0.1	63.2	
Traditional Fuel	112,000	1	1.5	112.5	
Natural Gas	56,100	1	0.1	56.2	

^a Source: Li and Chen [42] based on IPCC, [40], ^b GWP based ration calculation IPCC [40].

Calculating embodied GHG from energy consumption uses the following formula:

$$EGHGE = \sum_i EC_i \times EF_i \quad (1)$$

where EGHGE denotes embodied greenhouse gas emissions in energy consumption, EC_i presents energy use by fuel type i obtained from different databases, and EF_i presents embodied emission factors (Table 2) considered for each energy type.

2.2.2. Decoupling Index of GHG and Per Capita Income Growth

The analysis uses the Tapio elasticity approach to calculate the decoupling state of analysis among GHG emissions per capita income by a formula of Chen, et al. [43].

$$DI_{T-A} = \frac{\Delta C_{T-A\%}}{\Delta GDP_{T-A\%}} \quad (2)$$

where DI_{T-A} is the decoupling index in period from a base year A to a target year T between decades of 1990–1999, 2000–2009, and 2010–2017, and $\Delta C_{T-A\%}$ denotes the percentage change of the fiscal target, calculated as follows:

$$\Delta C_{T-A\%} = \frac{(GHG_T - GHG_A)}{GHG_A} \times 100\% \quad (3)$$

$\Delta GDP_{T-A\%}$ represents the percentage change of GDP per capita as follows:

$$\Delta GDP_{T-A\%} = \frac{(GDP_T - GDP_A)}{GDP_A} \times 100\% \quad (4)$$

Therefore, finally, we have the following:

$$DI_{T-A} = \left(\frac{GHG_T - GHG_A}{GHG_A} \right) / \left(\frac{GDP_T - GDP_A}{GDP_A} \right) \quad (5)$$

2.2.3. GHG Emissions Pollution in EWF Resources

The GHG emission contamination in EWF resources is calculated by using the method conceptualized by Anser, Yousaf, Usman, Nassani, Qazi Abro and Zaman [32], which states that the GHG share in water resources (WGHG) is equal to the percentage of people's access to improved water over the total amount of GHG emissions in water resources given by (IWAT/GHG). Similarly, in sharing GHGs in energy resources (EGHG), the total energy consumption and energy from non-renewable sources relative to total GHG emissions are used to calculate GHG emissions contamination in energy resources. Shared GHG in food resources (FGHG), Anser, Yousaf, Usman, Nassani, Qazi Abro and Zaman [32], also mentioned it as being equal to net food exports (FOODNEXP (%)) over total GHG emissions. The following equations (6, 7 and 8) further show the calculation of the decoupling state analysis indexes between WEF indicators and per capita income, using Tapio's elasticity approach as follows:

$$WGHG = \frac{(WGHG_T - WGHG_A)}{IWATGHG_A} / \frac{(GDP_T - GDP_A)}{GDP_A} \quad (6)$$

$$EGHG = \frac{(EGHG_T - EGGH_A)}{EGHG_A} / \frac{(GDP_T - GDP_A)}{GDP_A} \quad (7)$$

$$FGHG = \frac{(FGHG_T - FGGH_A)}{FGHG_A} / \frac{(GDP_T - GDP_A)}{GDP_A} \quad (8)$$

where A is the base year, T presents targeted years in three different decades (1990–1999; 2000–2009; and 2010–2017), and GDP shows GDP per capita.

2.3. Decoupling Approach Description

In calculating the decoupling of energy, water, and food resources from GHGs, there is concern about the critical link between these resources and economic growth, which may ultimately increase pressure on the ecosystem's capacity to provide these resources. In our study, the decoupling approach used is based on Tapio's decoupling methodology or Tapio's elasticity methodology, which pays considerable attention to the economic activities that can be associated with GHG emissions. GDP is taken as a reference point to present each country's economic development level during constructing an index presented in

Equations (5)–(8). Two different periods for each decade are considered and denoted by A as the “base year” and T as the “target years” to calculate the elasticity that evaluates the level of economic development of each country in terms of percentage change in economic growth and resource use in response to GHG emissions. The weighting of our index is based on the eco-efficient decoupling classification proposed Li and Zhou [20] based on Tapio’s decoupling standards, as shown in Table 3.

Table 3. Evaluation of eco-efficiency WEF’s GHG footprint.

Decoupling Trends	DEP	DED	DEI	Level	Trends
Strong-positive decoupling	<0	>0	<−0.5	excellent(E)	GDP increase is accompanied by a reduction in emissions by no less than 50% of the rate of economic increase.
Weak positive decoupling	<0	>0	>−0.5	Very good (VG)	GDP increase coupled with emissions declines at 50% of the rate of GDP increase.
Expansive decoupling	>0	>0	<1	satisfactory (S)	GDP tends to increase emissions as well, but not by more than the GDP growth rate.
Declining (Recessive) decoupling	<0	<0	<1.2	satisfactory (S)	Pollution decreases 1.2 times great than GDP declines.
Expansive negative > 0 decoupling		>0	>1	poor (P)	Emissions increase at a higher rate than the growth of the economic GDP.
Decline-negative decoupling	<0	<0	<1.2	poor (P)	Emissions are declining at a pace 1.2 times slower than GDP declines.
Strong-negative de-coupling	>0	<0	<0	unsatisfactory (U)	GDP is declining while emissions rise.

3. Results

3.1. The Decoupling between CO₂ Eq of GHG Sectors and Economic Growth

Africa’s economy is constantly growing. This progress is necessary to achieve the SDGs, particularly reducing poverty (SDG1), hunger (SDG2), promoting decent employment opportunities (SDG8) and increasing modern energy demand (SDG7). Our analysis of decoupling economic growth from GHGs in Africa shows unimpressive performance over three decades of analysis. Almost all countries selected had unsatisfactory or poor decoupling performances, which are presented in reddish colors. Figure 3 shows that the GHG footprint of non-renewable energy, total energy consumption, or the overall GHG footprint of almost selected countries is unsatisfactory or has poor decoupling relationships in all decades. This prevalence of poor and unsatisfactory decoupling means that economic growth increases or decreases while GHG emissions increase, or both increase simultaneously. However, over the last decade (2010–2017), three countries (Cameroon, Egypt and Ghana) have shown excellent decoupling, while four other countries (Nigeria, Senegal, Tanzania and Tunisia) have shown satisfactory decoupling; the remaining countries have shown unsatisfactory or poor decoupling. It is clear that economic activities coupled with GHG emissions and the quality and quantity of energy used by each country also play a key role in the acceleration [32]. In this regard, nations need to develop strategies for energy policies that help minimize ecosystem degradation through investments in social and economic sectors and help industries develop environmentally friendly production systems to support climate change mitigation initiatives [44].

Country	GHG NRE	GHG TE	GHG AS	GHG NRE	GHG TE	GHG AS	GHG NRE	GHG TE	GHG AS
	1990-1999			2000-2009			2010-2017		
Algeria	U	U	U	P	P	P	P	P	P
Angola	U	U	VP	P	P	P	U	G	U
Benin	P	P	P	P	P	P	P	P	P
Cameroon	U	U	U	S	P	P	P	S	E
Congo	U	U	U	P	P	P	U	G	U
Egypt	P	P	S	P	P	P	P	P	E
Ghana	P	P	P	P	P	P	P	P	E
Kenya	U	U	U	P	P	P	P	P	P
Morocco	P	P	P	S	G	G	S	P	P
Nigeria	U	U	U	VP	S	S	P	P	S
Senegal	P	P	P	P	P	P	P	P	S
South Africa	U	U	U	P	G	G	P	S	P
Tanzania	U	U	U	P	P	P	P	P	S
Tunisia	P	P	S	VP	S	S	U	P	S
Zimbabwe	P	U	P	VP	VP	VP	U	S	P
Unsatisfactory (U)	Very Poor (VP)	Poor (P)	Satisfactory (S)	Good (G)	Excellent (E)				
Strong negative decoupling	Weak negative decoupling	Expensive negative decoupling	Recessive decoupling	Expensive positive decoupling	Strong negative decoupling				

Figure 3. Decoupling GHG with economic growth.

3.2. Decoupling GHGs Share in EWF Resources

GHG emissions are widely observable in our findings. The EWF resources' GHG footprint in Figures 4–7 shows that the state of decoupling varies greatly among EWF resources.

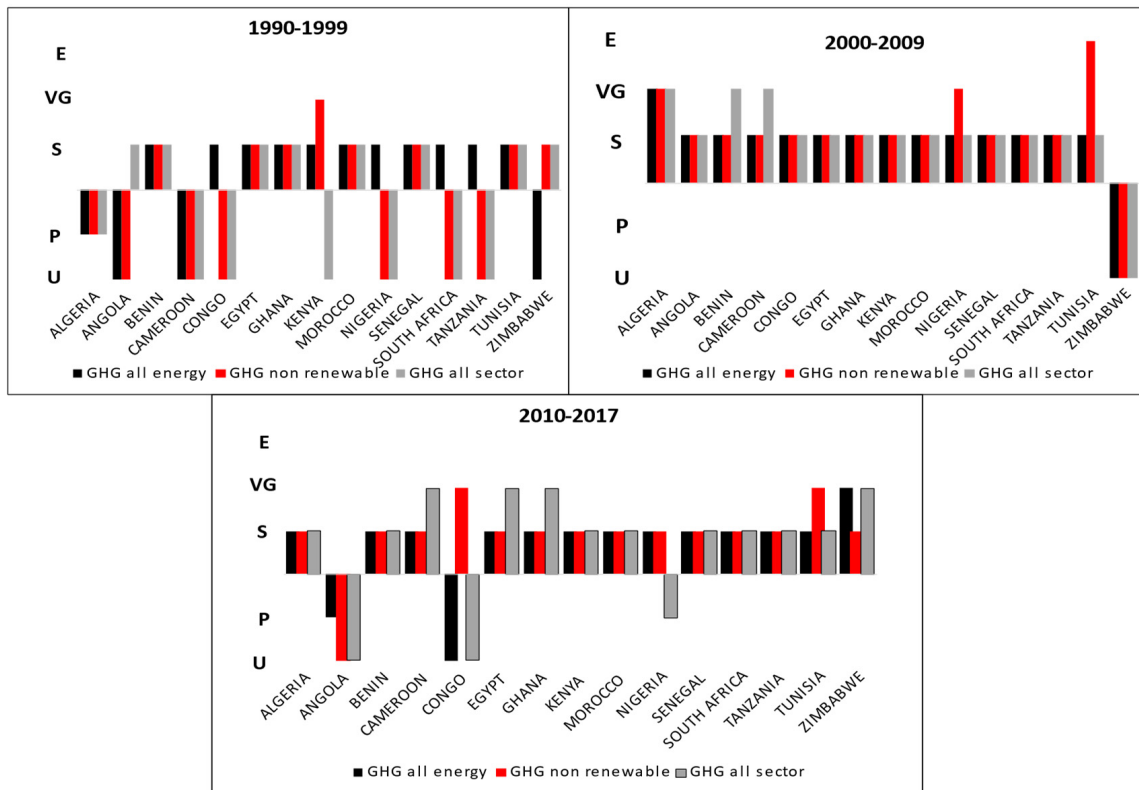


Figure 4. EWF's GHG footprint—waters GHG footprint.

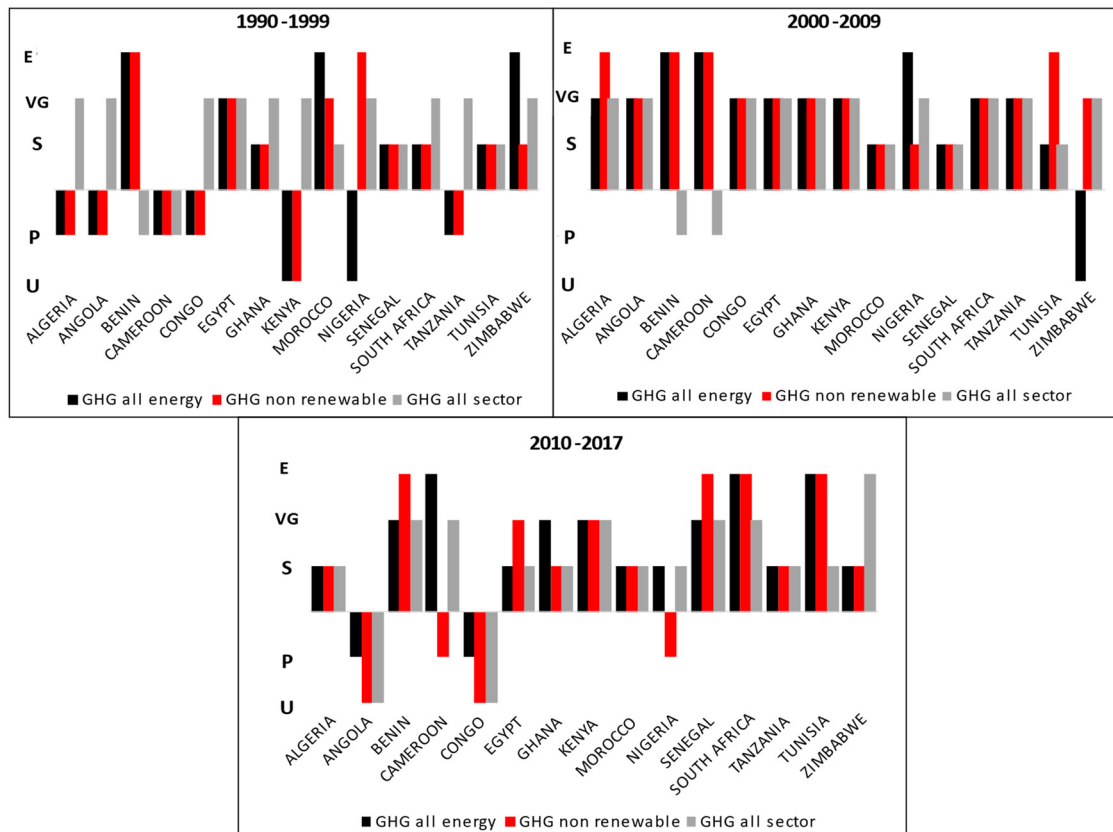


Figure 5. EWF's GHG footprint—food GHG footprint.

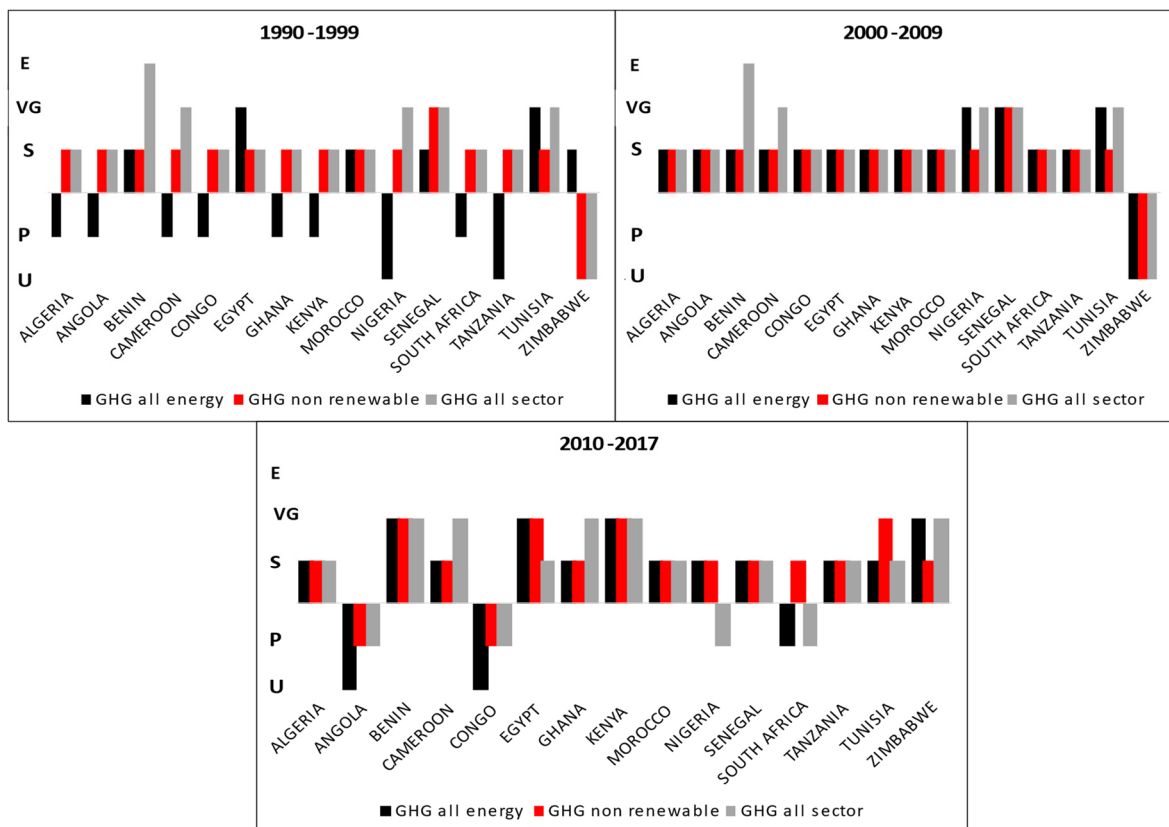


Figure 6. WEF's GHG footprint—non-renewable energy GHG footprint.

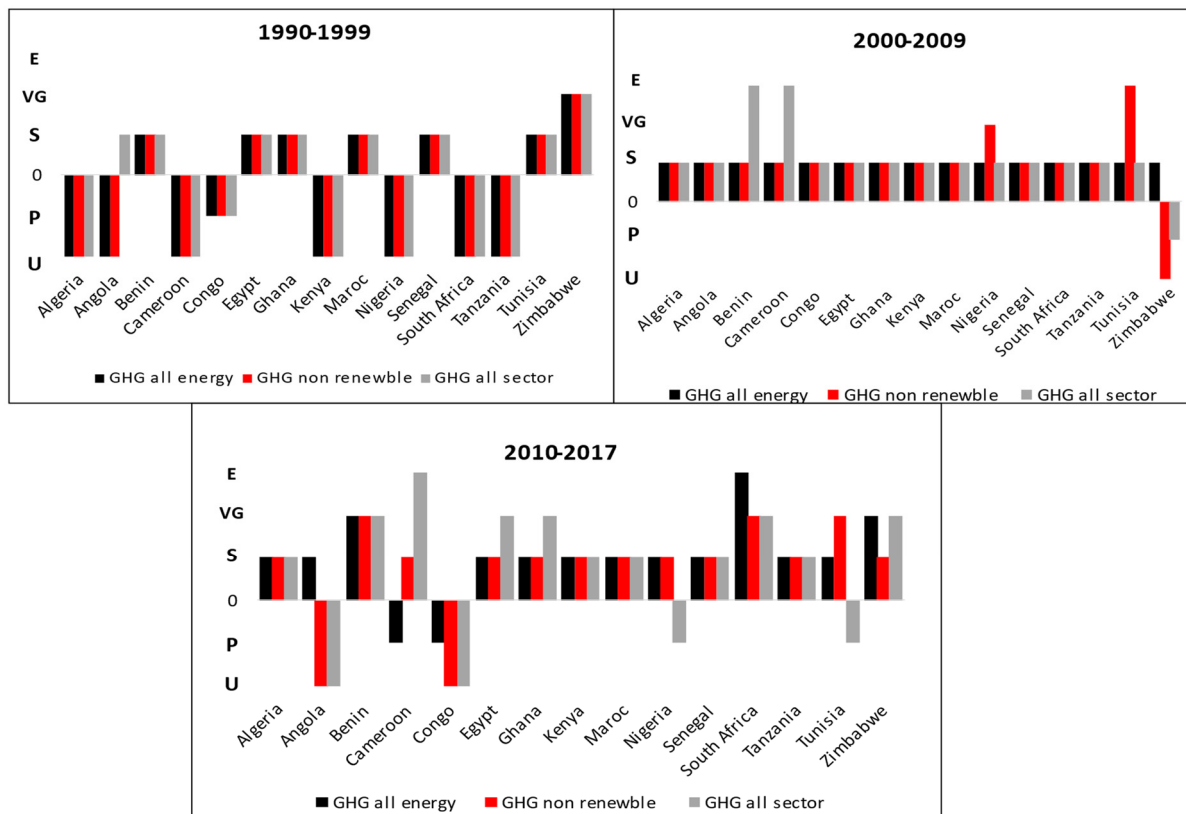


Figure 7. WEF's GHG footprint—total energy GHG footprint.

3.2.1. EWF's GHG Footprint—Water GHG Footprint

Figure 4 illustrates the decoupling share of GHGs in water resources during various stages of economic development under the three GHG emission sources. The results on the proportion of GHGs in water resources from 1990 to 1999 show that six countries (Benin, Egypt, Ghana, Morocco, Senegal and Tunisia) have a satisfactory decoupling between water use and GHGs shared from the three sources of per capita income analyzed. Other countries, such as Algeria and Cameroon, experienced poor or unsatisfactory decoupling. The remaining countries showed variation in GHG decoupling states, where GHGs from non-renewable fuel energy and total GHG emissions from all sectors showed poor or unsatisfactory decoupling in relation to the share of GHGs in water resources and per capita income, particularly in Congo, Kenya, South Africa, and Tanzania. During the decade 2000–2009, a widely visible change was observed. Subsequently, during the decade 2010–2017, the positive decoupling between the share of GHGs in water resources and per capita income was maintained in most countries, with satisfactory and very good decoupling, except for Angola, the Republic of Congo and Nigeria. Overall, there is a significant trend in the GHG emissions relationship with water resources and per capita income over the decades. Moreover, no country has yet achieved an excellent decoupling (strong negative decoupling) of GHG share in water resources and per capita income, which makes it imperative for the concerning policymakers to stimulate GHG emission reduction measures.

3.2.2. EWF's GHG Footprint—Food GHG Footprint

GHG emissions are also widely observable with different variations among the three categories sources of GHGs analyzed that share GHGs in food resources and per capita income. During the first decade (1990–1999), different decoupling states are presented, dominated by very good to excellent decoupling in one of the GHG emission sources. For example, the relationship between food resources and GHG emissions from all sectors

depicts very good decoupling states in Algeria, Angola, Egypt, Ghana, Kenya, Nigeria, South Africa, Tanzania, and Zimbabwe. Benin, Morocco, Nigeria, and Zimbabwe also show excellent decoupling between food resources and GHG emissions from either total energy consumption or non-renewable energy use. Regarding the source of GHG emissions analysis, for instance, Angola shows that overall GHG emissions from all sectors have a very good decoupling state, while GHG emissions from energy types show poor decoupling states. This implies a need to be aware of the need to reduce sources of GHG emissions from inputs.

On the contrary, in Benin, GHG emissions from non-renewable energy and total energy consumption shared in food resources show an excellent decoupling status, while overall GHG emissions from all sectors show a poor decoupling status. This implies a need to reduce sources of GHG emissions from activities other than energy inputs, such as agriculture, deforestation, and industries, which can lead to increased GHGs. Such observations of different decoupling states from three GHG emissions analyzed within the same country are observed among different countries over decades. In the following decade (2000–2009), positive changes in satisfactory, very good, and excellent decoupling of food GHG emissions footprint are observed. Satisfactory, very good, and excellent decoupling remain observable during the 2010–2017 decade, except for Angola, the Republic of Congo, and other countries, such as Cameroon and Nigeria, which experienced poor decoupling. The overall relationship between the share of GHGs in food resources and per capita income shows an interesting improvement in excellent and very good decoupling states in some countries, such as Benin, Senegal and South Africa (see Figure 5).

3.2.3. EWF's GHG Footprint-Energy's GHG Footprint

In this study, results are presented for the share of GHGs in energy resources for both electricity generation from conventional non-renewable sources (Figure 6) and for total electricity generation from all sources (non-renewable and renewable) (Figure 7). The results for non-renewable electricity generation from 1990 through 1999 show that most countries range from unsatisfactory to satisfactory decoupling states. In the following decades, 2000–2009, energy's GHG footprint showed satisfactory, very good, and excellent decoupling and unsatisfactory decoupling in Zimbabwe only. In the most recent period of 2010–2017, many countries showed satisfactory and very good decoupling, but no country showed excellent decoupling status for GHG share of energy resources and per capita income. Countries such as Angola and Congo showed poor and unsatisfactory decoupling status. At the same time, Nigeria and South Africa also had poor decoupling of GHG emissions in some sectors, especially from total GHG emissions in all sectors. Similar to the water resources analysis, this suggests that efforts are needed to change policies in the energy sector to address the problem of restoring the negative decoupling between GHG emissions and national economic growth.

Apart from analyzing the GHG footprint—non-renewable energy, the following results show the GHG footprint in total energy generation (from non-renewable and renewable resources). In the decade 1990–1999, most countries experienced decoupling ranging from unsatisfactory to very good. Countries such as Algeria, Cameroon, Kenya, Nigeria, South Africa, and Tanzania had completely unsatisfactory decoupling, which is not the case for non-renewable resources. This can also be explained by the fact that, although the countries concerned consumed some renewable energy resources, they have mostly used traditional biomass fuels, which have the highest greenhouse gas emissions. In the decade 2000–2009, the GHG footprint of energy showed a similar range to that of non-renewable resources, with unsatisfactory, satisfactory, very good, and excellent decoupling, with a predominance of the satisfactory state. Zimbabwe showed its uniqueness of unsatisfactory and poor decoupling, compared to others. In the most recent period from 2010 through 2017, many countries showed different decoupling states, such as unsatisfactory, poor, satisfactory, and very good to excellent decoupling states in some countries such as Benin and South Africa. Likewise, countries such as Angola and Congo showed poor and unsatisfactory decoupling.

At the same time, Nigeria Tunisia and other countries also showed poor decoupling states in one of the sources of GHG analyzed. The same as the water resources analysis suggests, efforts are needed to change policies and the technologies used in the energy production and consumption sectors to achieve the excellent decoupling needed to sustain resource productivity in the countries concerned while also achieving the SDGs.

3.3. Tracing Energy Water Food Inter-Dependence in GHG Emissions

A special relationship between GHG emissions and water, energy and food individual or resources interdependence is noticed in the above analysis and Figure 8. In fact, the production of EWF resources is interdependent in a complex system with other socio-economic sectors, contributing more GHG emissions from one sector to another. Figure 8 illustrates how industries, agriculture, livestock, forestry and land management, waste production, and other resources' (transportation, urbanization, construction, natural decomposition, etc.) sectors or their concerned stockholders act as interfaces of supplying or consuming GHG emissions with EWFs' interactions.

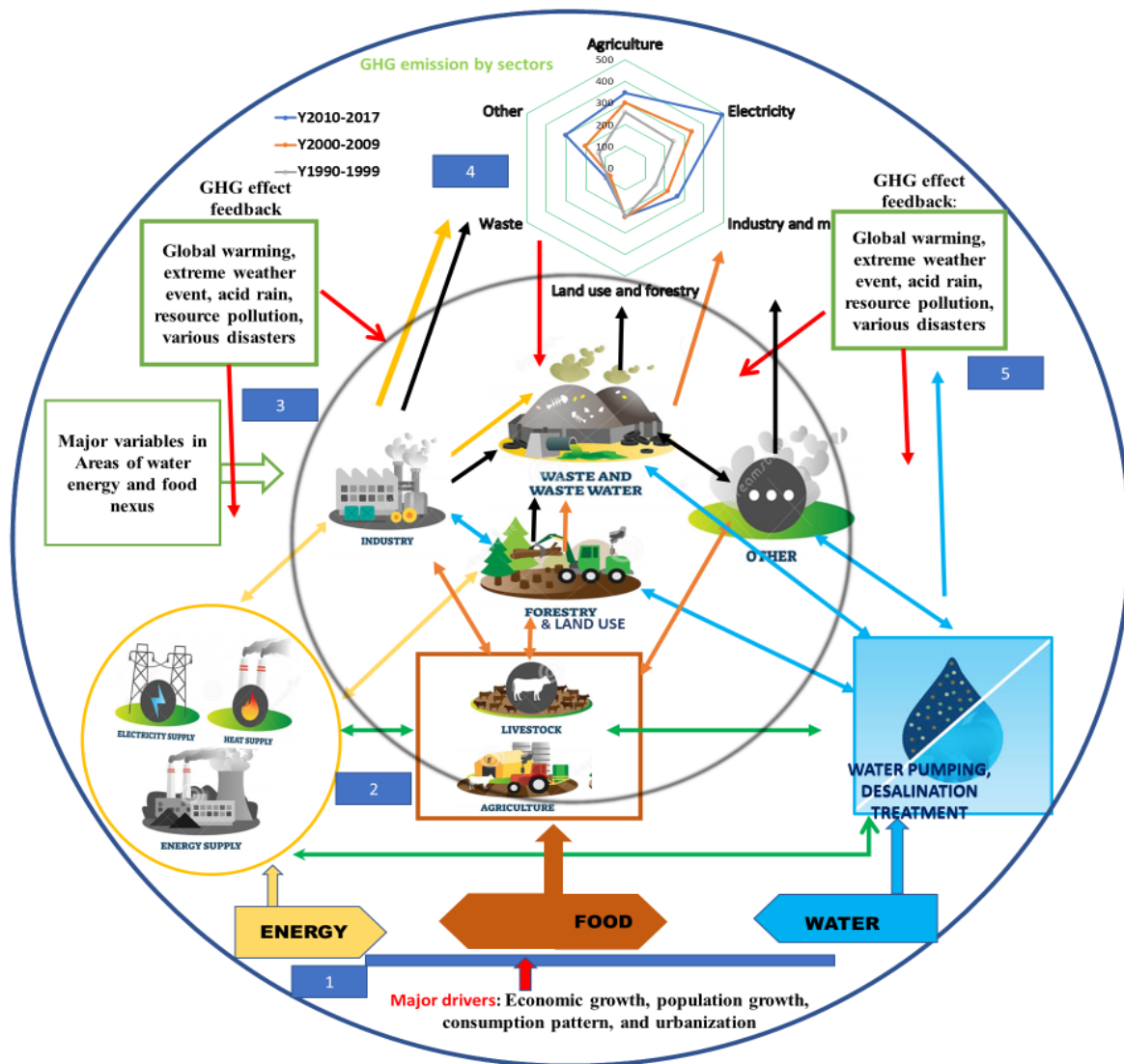


Figure 8. EWF nexus in GHG emissions cycle.

This figure illustrates the interaction of EWF resources in production and consumption that contributes to an enormous amount of GHGs emitted into the atmosphere, either individually or collectively, which is important for policymakers to recognize and trace

the different sources of GHG emissions for effective decoupling measures. Figure 8 is composed of different categories from 1 to 5. The first category shows the main drivers involved in GHG emissions; the second shows three resources (EWF resource sectors); the third exhibits the interaction areas of EWF resource sectors, with the main socio-economic and natural variables, such as agriculture, livestock, industries, forest and land use, waste and other categories; the fourth category depicts GHG emissions from EWF activities; and the fifth category mentions the feedback reactions of GHG emissions on resources, natural systems, and other socio-economic activities. In terms of interaction, the green arrow shows the direct interaction between the three EWF resources. The yellow arrow shows the interaction of energy resources with other resources in different categories 2–4. The brown arrow denotes the food resources at all stages. The blue arrow shows the interaction of water; the black arrow shows the interaction between the variables of interest in the nexus areas; and the red arrow shows the feedback effects of GHG emissions.

In more detail, the interaction between EWFs and GHG emissions is classified into two dimensions: the first is based on the independent contribution of each resource to GHG emissions. The energy sector (electricity), for example, is the largest contributor to GHG emissions in Africa, accounting for 243.8 Mt CO₂e, 337.5 Mt CO₂e, and 492.1 Mt CO₂e, respectively, from 1990 to 1999, 2000 to 2009, and 2010 to 2017. Food production contributed 257.2 Mt CO₂e, 300.6 Mt CO₂e, and 347.3 Mt CO₂e of total GHG emissions from 1990 to 1999, 2000 to 2009, and 2010 to 2017, respectively. Additionally, in line with the literature, 31% of food-related GHG emissions come from livestock and fishing, 27% from crop production, 24% from land use (i.e., 16% from livestock and 8% from crops for human consumption), and 18% from the food chain [44]. In water resources, GHG emissions are accumulated from land activities and the aquatic system, particularly through decomposition, fermentation, and denitrification.

Furthermore, the second dimension looked at the interaction of EWF resources in generating or contaminating GHG from common socio-economic and natural activities or resources that each resource sector needs, with others in demand or supply. Consider agriculture, for example, which emitted 347.3 Mt CO₂e, 300.6 Mt CO₂e, and 257.2 Mt CO₂e of CO₂e between 2010–2017, 2000–2009, and 1990–1999, respectively. This agricultural sector consumes 80% of the continent's total water withdrawals and accounts for more than 75% of Africa's direct food dependence, but it also accounts for 15% of total energy production. In Africa, food agriculture also contributes to annual biofuel production, with over 5.6 million liters of ethanol and 4.04 million liters of biodiesel [45]. Vice versa, energy resources play a role in agricultural production systems, with 8.6% of continental energy used to pump irrigation water for food production. Thus, without a doubt, this interconnected system can allow each sector to partner in the GHG emission portion to one another.

Additionally, EWF resources may contribute to the GHG emissions emitted through industries' processing, as the majority of them are obtained as raw materials that require industrial technology to be processed (see Figure 6). Similarly, EWF resources can interact themselves through waste-generated GHGs, which accounted for 94.5 Mt CO₂e, 75.3 Mt CO₂e, and 89 Mt CO₂e in 2010–2017, 2000–2009, 1990–1999, respectively, on a continental scale. The other notable interaction can be seen on each resource's different land and forest uses, such as firewood for energy production, agricultural land for food production, and vegetation cover for water resource management. The remaining variables are classified as (other) transportation, infrastructure, and housing, which are also critical in terms of GHG emissions from one resource to another, which also needs critical consideration.

4. Discussion

This research explores the historical relationship between EWF resources and the share of GHG emissions from different GHG sources in 15 African countries selected over 27 years ago to ensure the sustainability of these resources. In this analysis, decoupling food, energy, and water from GHG emissions requires policymakers and researchers to

comprehensively identify the sources of GHG emissions and their interactions between these resources production, consumption, and possible mitigation pathways. Within Tapio's decoupling index analysis, our study shows that in many countries, particularly Angola and the Congo Republic, the economic growth system exposes energy, water, and food resources to greater vulnerability to GHG emissions, which exhibit unsatisfactory decoupling, poor decoupling states to excellent decoupling states.

Concerning energy consumption, being dominated by traditional biomass and non-renewable fuels that emit large amounts of N₂O is critical. Both types of energy have higher GHG emissions than other sources of energy (see Table 2). The results show that it is much more difficult to decouple economic growth from GHG emissions from energy resources than from resource sectors and socio-economic activities. To overcome such a challenge, the Oyedepo [46] study on sustainable energy use in Nigeria mentioned the need to diversify energy sources and adopt newly available technology that may reduce the future crises of energy and minimize GHG-related non-renewable energy heavily used in Africa by promoting renewable resources and efficient energy use.

In line with the literature, Anser, Yousaf, Usman, Nassani, Qazi Abro and Zaman [32] used the same methodology of the Tapio decoupling state analysis in decoupling WEF resource production from carbon-fossil and GHG emissions in Pakistan and found remarkable pollution of these gases' emissions into water-energy-food resources that present weak decoupling, expensive negative decoupling, and strong decoupling. Wei, et al. [47] studied the decoupling of energy resources on GHGs and recommended adopting green economic policies in parallel with the increase in the national economy and the implementation of the SDGs.

In addition, many different analyses have been conducted on the link between water production and greenhouse gas emissions. For instance, Hao, et al. [48] showed the critical GHG emissions from water basins that strongly contribute to the worldwide CO₂ and NO₂ cycle. Further study of Ran, et al. [49] showed that water obtains GHG emissions from two sources: land, with different drivers from human activities, and the other from the natural process of sea or other water resource microorganism decomposition. Hao, Ruihong, Zhuangzhuang, Zhen, Xixi, Tingxi and Ruizhong [48] also mentioned that GHG emissions from wastewater is more significant in cities than in rural areas. In these pathways, reducing GHG emissions from land activities should be preferable to reducing GHG emissions in water resources rather than focusing on GHG produced from the natural decomposition of microorganisms in oceans, lakes, and rivers.

Food productivity shares one-quarter of GHG emissions worldwide, while the same fertilizer production accounts for up to 575 megatons of GHG emissions [50]. These emissions can alter natural ecosystem species composition, reducing biodiversity and land ecological resilience, and can compromise future food product safety. The pollution in the energy–water–food quality pollution system may also directly affect end-users, increasing out-of-pocket healthcare costs [32]. In addition, research shows that the decoupling analysis method should be a sustainable approach to combat climate change and control sustainable economic growth worldwide [51]. In proposing scenarios for decoupling food energy production from GHG, the study of Heller, et al. [52] recommended using individual behaviors rather than generalization means. Thus, generally, the scholars' abovementioned insights on decoupling EWF resource production from GHG emissions support this finding of EWF production and consumption decoupling from GHG in Africa. This is a complex task requiring many sectors and stakeholders to collaborate in terms of interdependence, as shown in Figure 8.

The application of the Tapio decoupling method to the research results has increased in various policy agendas to decouple the economy from resource sustainability and to decouple human activities from the increase in GHG emissions [19]. However, this Tapio decoupling method has shown some limitations in identifying the influence of the interaction on the level of economic growth and GHG emissions with decoupling with other variables [18]. In the face of these shortcomings, this study makes a traceability

analysis of the energy–water–food interdependence in the GHG emissions and economic growth parts. Furthermore, despite the usefulness of Tapio’s methodology to analyze the different levels of decoupling relationships, from unsatisfactory to excellent decoupling, sometimes, within a data set, the magnitude and direction of variables may not fit into one of the standard categories of decoupling states, which then requires further investigation in the estimation procedure [32]. Despite the above challenge, this study was faced with data availability limitations to conduct a continent-wide analysis. Indeed, the study focused on three major resource sectors that are managed separately, even in terms of data collection, making it difficult to obtain trade data from the same year across all sectors and countries in Africa. However, in order to fill these gaps, the research took nearly a third of the continent’s countries in different regions of Africa to provide an overview of the state of the relationship between resource use, GHG emissions, and economic growth in Africa.

5. Conclusions and Policy Implications

Decoupling energy, water, and food resources from GHG emissions was calculated from 1990 to 2017. It showed unsatisfactory to satisfactory decoupling states in many countries, especially in the periods from 1990 to 1999 and 2010 to 2017, compared to 2000 to 2009. This can be explained by the fact that in the first decade, technology was limited, and consumption of non-renewable resources was high. The economic growth was hardly more decoupled from GHG emissions from non-renewable energy than it was decoupled from overall GHG emissions, which is critical and shows the significant impact of energy resources on economic growth and GHG emissions in Africa. Tracing the sources of GHG emissions in the EWF resources is essential to help policymakers define common initiatives that should greatly reduce pollution emissions from resource production or economic activities oriented to increase GHG emissions. The African population is expected to surpass 2 billion by 2030; the demand for water, energy, and food is expected to increase by 283%, 70%, and 60%, respectively. Resources are expected to be a major pillar in achieving the SDGs in Africa, which is accompanied by an increase in GHG emissions and climate change impacts. Thus, promoting green industrialization, waste minimization and re-use, sustainable land and forest conservation, renewable energy, and water resource conservation are essential parts of the policy-making agenda. Mutual collaboration of all sectors involved with EWF resources is also essential to monitor and track every source of GHG emissions, from the most basic production and consumption activities to the most significant. Research in the future should focus on developing approaches that promote EWF integration and multi-sector collaboration via GHG monitoring and minimizing decoupling costs, such as incorporating the nexus perspective.

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Appendix A

Table A1. Description of 15 selected countries in Africa.

Country Name	Areas Km ²	Population/2020	Population Growth %	Urbanization %	REC Per Capita (2019)	GHG (Mt CO ₂ e) 1990–2018	CCI 2000–2019	Employment Rate in Agriculture 2019 (%)
Algeria	2,381,741	43,851,044	0.56	72.9	15.9	149.9	92.8	9.6
Angola	227,540	31,735,462	0.4	56.7	86.8	107.1	84	50.7
Benin	112,760	12,123,200	0.16	48.4	0.3	22.9	139.8	38.2
Cameroon	472,710	26,545,863	0.34	56.3	28.8	123.5	128	43.4
Congo Rep	341,500	5,518,087	0.07	69.9	39.9	17.8	148.6	33.5
Egypt	995,450	102,334,404	1.31	43	59.5	228.3	142	20.6
Ghana	227,540	31,072,940	0.4	56.7	54.4	50.4	101.3	29.7
Kenya	569,140	53,771,296	0.69	27.8	41.4	57.6	52	54.3
Morocco	446,300	36,910,560	0.47	63.8	89.6	61.7	96	33.2
Nigeria	910,770	206,139,589	2.64	52	10.7	289.0	104.3	34.9
Senegal	192,530	16,743,927	0.21	49.4	12.8	27.6	123	30.1
South Africa	1,213,090	59,308,690	0.76	66.7	N/A	437.8	76	5.2
Tanzania	885,800	59,734,218	0.77	37	11.7	129.6	111.3	65
Tunisia	155,360	11,818,619	0.15	70.1	31.9	32.1	114.5	13.8
Zimbabwe	386,850	14,862,924	0.19	38.4	81.5	47.8	37.3	66.1
Total	7,566,561	506,331,234				1783.2		
Share % at continent	24.4	37.7				48.1%		

Table A2. Non-renewable energy consumption from different fuel.

	TEC/TJ	ALG	ANG	BEN	CAM	CD	EG	GH	KEN	MOR	NIG	SEN	SA	TZD	TUN	ZIM	Tot % Δ	
Year range	LPG				Country%													
1990–1999	230187	31.7	0.69	0.02	0.5	0.08	31.7	0.55	0.671	18.2	1.957	1.09	6	0.12	6.5	0.2		
2000–2009	404610	22.2	1.28	0.1	0.54	0.07	43.2	1.03	0.582	18.6	0.948	1.51	4.2	0.07	5.6	0	76.0	
2000–2017	522493	19.8	2.17	0.14	0.78	0.09	41.1	2.4	1.24	21.9	0.4	1.12	3.2	0.63	4.9	0.2	127.0	
	Gasoline																	
1990–1999	830984	10.9	0.48	0.77	1.64	0.44	11.7	1.79	1.988	2.22	22.67	0.6	40	1.71	0.6	1.9		
2000–2009	1227026	7.43	1.34	1.41	1.21	0.26	23.6	2.24	1.411	1.57	24.99	0.42	31	1.6	0.7	0.8	47.6	
2000–2017	1655462	10.7	2.61	2.26	1.23	0.44	17.5	2.95	2.526	1.71	29.94	0.34	24	1.51	1.8	1	99.2	
	Kerosene																	
1990–1999	102084	0.67	0.21	0.24	0.66	0.21	7.17	0.55	0.976	0.26	85	0.06	2.8	0.7	0.3	0.2		
2000–2009	17380	0.21	2.5	6.81	3.16	0.47	12.5	2.57	7.465	1.39	39.02	0.36	15	4.12	3.6	1.2	−83	
2000–2017	140543	0.22	1.75	4.06	2.77	0.63	1.21	1.5	11.08	0	56.84	0.08	15	1.59	2.2	1.4	−86	
	Fuel oil																	
1990–1999	723010	15.2	1.98	0.05	1.67	0.53	35.6	1.51	2.237	7.75	8.754	1.26	19	1	3.6	0.2		
2000–2009	1141840	19.9	2.16	0.09	1.24	1.09	37.2	0.62	1.953	7.51	7.46	0.84	17	0.65	2.2	0.1	57.9	
2000–2017	938680	26.1	3.3	0.12	1.18	1.24	36.8	0.27	1.308	6.79	4.235	0.79	15	0.87	1.9	0.1	29.8	
	Natural gas																	
1990–1999	2204058	35.9	0.98	0	0	0.22	39	0	0	0.06	17.17	0.06	3	0	3.6	0		
2000–2009	3031035	31.7	0.78	0	0.03	0.27	42.1	0	0	0.44	11	0.06	8.2	0.36	5.1	0	37.5	
2000–2017	4317429	33.25	0.60	0.04	0.42	1.21	40.17	0.66	0.00	1.00	14.20	0.04	4.28	0.75	3.37	0	96	
	Coal																	
1990–1999	6459313.8	2.5	0.0	0.0	0.0	0.0	2.7	0.0	0.5	3.0	0.1	0.0	86.3	0.1	0.0	4.9		
2010–2010	7385394.5	2.4	0.0	0.0	0.0	0.0	1.5	0.0	0.3	3.2	0.1	0.5	88.2	0.1	0.0	3.7	14.3	
2011–2017	5002472.9	1.1	0.0	0.2	0.0	0.0	3.6	0.0	1.6	0.6	0.2	1.7	88.2	0.8	0.0	2.0	−22.5	
	Gas oil																	
1990–1999	851400	16.05	2.55	0.41	1.28	0.26	24.17	2.71	2.75	11.45	9.17	1.06	17.56	6.35	1.10	3.14		
2010–2010	1413900.2	16.63	3.03	0.58	1.11	0.46	27.03	2.65	2.39	10.43	5.34	1.13	20.78	5.35	1.78	1.29	66.06	
2011–2017	1727653.845	18.39	4.90	1.16	1.07	0.71	23.68	3.22	3.19	10.21	4.25	1.33	21.09	3.65	1.83	1.31	36.80	

In general, TJ means Terajoule, ALG = Algeria, ANG = Angola, BEN = Benin, CAM = Cameroon, CD = Congo Republic, EG = Egypt, KEN = Kenya, MOR = Morocco, NIG = Nigeria, SEN = Senegal, SA = South Africa, TZD = Tanzania, TUN = Tunisia, ZIM = Zimbabwe, TEC=Total Energy Consumed in TJ. Source of data: [34,35].

Table A3. Shows the results of the comparison of GHGs embodied by non-renewable energy consumption (MtCO₂e).

Country	1990–1999	1990–1990	1990–1999	2000–2009	2000–2009	2000–2009	2010–2017	2010–2017	2010–2017
	C	T	O	C	T	O	C	T	O
Algeria	81.39	85.025	103.807	102.99	131.897	143.724	148.5	157.17	224.45
Angola	4.46	15.633	70.507	8.31	35.923	109.923	15.59	49.98	155.32
Benin	0.9	1.57	21.523	2.76	4.908	20.631	5.17	7.53	28.12
Cameroon	3.24	7.501	109.478	3.84	11.3	126.591	5.57	12.12	139.08
Congo	1.01	3.175	15.368	2.2	5.298	17.079	5.57	5.2	22.4
Egypt	87.06	99.383	150.123	166.6	172.387	227.301	198.47	211.83	341.34
Ghana	4.08	6.381	26.039	5.81	13.475	65.777	11.29	22.92	63.25
Kenya	5.28	11.783	33.553	6.79	17.648	61.129	11.74	24.23	87.1
Morocco	17.93	27.72	40.165	27.14	46.424	59.262	33.28	59.09	95.99
Nigeria	107.72	124.757	264.181	57.31	161.171	264.068	85.26	170.35	360.17
Senegal	1.98	4.307	21.821	3.26	7.704	27.329	4.77	9.77	36.3
South Africa	113.12	269.674	335.839	152.99	411.315	436.869	146.45	431.8	584.93
Tanzania	1.92	8.586	103.549	4.19	16.731	121.18	8.12	31.74	178.71
Tunisia	12.93	16.351	23.13	19.48	24.995	31.754	19.21	26.6	45.59
Zimbabwe	6.88	18.661	42.406	5.31	14.258	38.388	4.89	14.32	68.92
Total	449.9	200.507	1361.489	568.98	1075.434	1751.005	703.8	1234.6	2431.69
	GHGs emitted by sources (%)								
Percentage	C-T	T-O	C-O	C-T	T-O	C-O	C-T	T-O	C-O
	64.2	51.45	33.04	52.9	61.42	32.49	57	50.77	28.94

In Table A3, C-T is the percentage of GHGs calculated from the GHGs of non-renewable energy sources as a percent-age of the GHGs of total energy consumption. T-O is the percentage of GHGs calculated from the GHGs of total energy consumption as a percentage of the overall GHG emissions from all sectors. C-O is the percentage of GHGs from non-renewable energy sources as a percentage of the overall GHG emissions.

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