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DOI:
10.1016/j.apenergy.2023.122494

Applied Energy 357 (2024) 122494

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Investigating the fast energy-related carbon emissions growth in African countries and its drivers

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HIGHLIGHTS

- We provide energy-related emission inventories for 19 African countries from 2010 to 2019.
- African countries experienced rapid growth in CO2 emissions.
- Two countries achieved strong decoupling of GDP from CO2 emissions.
- Economic and population growth are the most important drivers of emissions.

ARTICLE INFO

Keywords:
Africa
CO_2 emissions
Climate change mitigation
Drivers
Decoupling

ABSTRACT

Efforts to avoid the acceleration of global warming have tended to focus on countries with high CO_2 emissions levels and large populations, with a high level of economic development or industrialization. African countries, which often do not conform to such criteria, are more vulnerable to climate change due to their dependence on climate-sensitive industries and their limited infrastructure and technological capacity to cope with its impacts. The long-term economic growth rates projected for Africa's rapid development period will, further, make Africa a potential emission hotspot in the near future. Here, for the first time, we built an energy-related emissions inventory for 19 African countries for 2010–2019, which addresses emissions from 47 economic sectors and 5 energy types, making it the most comprehensive of its kind. The degree of decoupling of economy and emissions, and drivers of CO_2 emission changes are also examined. Most African countries experienced rapid growth in CO_2 emissions, with an average annual growth rate of 5.5% for fossil fuel-related CO_2 emissions and 6.0% for unsustainable biomass-related CO_2 emissions. Only two countries, South Africa and Tanzania, have achieved a strong decoupling of economic growth from CO_2 emissions. Economic and population are the most important drivers of emissions, while energy intensity has been identified as a key factor in mitigating CO_2 emissions, especially for those countries that have reached strong or weak decoupling. The findings from this study provide essential insights that could guide the development of low-carbon policies and strategies in Africa.

1. Introduction

Climate change affects all countries around the globally, with Africa being particularly vulnerable [1]. The region is warming faster than the global average [2] and is at the forefront of climate change shocks. According to one Climate Change Vulnerability Index study, the top 10 countries most vulnerable to climate change are all from sub-Saharan Africa [3]. Climate change exacerbates food insecurity and increases the risk of conflict and civil unrest [4]. The African Union and the international community must reduce energy-related emissions to address these threats. However, the urgency of the situation in Africa must not be misconstrued as a product of the continent's historical contribution to

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https://doi.org/10.1016/j.apenergy.2023.122494
Received 14 September 2023; Received in revised form 26 November 2023; Accepted 11 December 2023
Available online 21 December 2023

global greenhouse gas emissions. Historically, Africa's contribution to global greenhouse gas emissions has been relatively small, estimated at approximately 3–6%. Despite this, Africa's share has been slowly, yet steadily, increasing. According to calculations by IEA and EDGAR, Africa's carbon emissions accounted for 4.5% (2511.4Mt) of the global total in 1970 and rose to 6.6% (3021.0Mt) by 2020. Furthermore, the continent's carbon emissions growth rate outpaces the global average - between 2010 and 2019, Africa's annual carbon emissions growth rate was 2.1%, notably higher than the global average of 1.2%. And Africa's economic and social development has led to alarming rates of energy consumption and CO_2 emissions [5,6]. Despite abundant renewable energy sources, the region's energy production sources are heavily reliant on fossil fuels. The projected rate of long-term economic growth, coupled with rapid population growth, ambitious industrial development plans, and rocketing energy demand in many countries will make lead to a growth in emissions from Africa that will not be able to be ignored in the future [7].

Despite the serious nature of this situation, there is limited research on the carbon emissions generated in African countries [8]. Existing studies have focused on a limited number of African countries, such as South Africa [9–11], Egypt [12], Ghana [7], West African countries [13,14], SSA region [15]. While global datasets such as the International Energy Agency (IEA), the Global Carbon Budget (GCB) and the Emissions Database for Global Atmospheric Research (EDGAR) provide carbon emissions data for African countries, but their scope and detail can often be limited. For example, the data for fossil CO_2 emissions in EDGAR do not provide explicit categorization for energy types such as coal, crude oil, and natural gas. Furthermore, EDGAR's fossil carbon emission inventory is partitioned into five broad sectors: Power Industry, Other Industrial Combustion, Buildings, Transport, and Other Sectors. These broad categories, while useful for some analyses, can oversimplify the situation in Africa due to a lack of sectoral granularity. Similarly, other datasets like IEA and GCB, tend to use generalized industry and energy type classifications which, while understandable given their global scope, might not fully capture the nuances of the situation in African countries [4,16]. This level of aggregation not only hinders the accurate identification of high emission sectors and energy types, but also inhibits the fine-tuning of decarbonization policies, which are most effective when they target specific, high-impact areas. In addition, such broad categories pose challenges when attempting to connect with multisectoral economic models for analysis. Without the ability to delve into the sector-specific and energy type-specific details, it becomes exceedingly difficult to trace emission drivers and accurately forecast future trends, which are crucial for planning effective interventions.

It is worth noting that traditional datasets, such as those produced by the IEA and GCB, include only fossil fuels (coal, oil, and natural gas) in their data on energy-related emissions, excluding biomass emissions. Biomass, however, serves as the primary energy source in rural areas of less-developed countries. It has been left out of energy-related CO_2 emissions in both the datasets produced by these research institutions and some national accounts, under the presumption that it is "carbon neutral." However, this assumption doesn't hold for unsustainable practices, such as deforestation.

A detailed, up-to-date, and uniformly formatted CO_2 emission inventory is the basis for revealing a country's emission patterns and determining its environmental responsibility. The lack of relevant data has become a major obstacle to in-depth research on the characteristics of CO_2 emissions in Africa, and to a certain extent has limited research and policy explorations on low-carbon development pathways in Africa. Recently, Sun et al., (2022) [17] provided a 45-sector carbon emission inventory of eight African countries; this study, however, only considered East African countries and used data updated to 2017. Given the large number of countries in Africa and the regional heterogeneity that is present in Africa in terms of the economic development, population size, and energy mix at work in different countries, more detailed and updated data on sectoral emissions from as many countries as possible should be used to study their emission patterns.

To sum up, previous accounting of carbon emissions has hardly focused on Africa, with only a few countries like South Africa, and Egypt receiving attention. Moreover, the scope of available data on carbon emissions in Africa is confined to certain energy types and a limited array of sectors, thereby failing to provide a comprehensive picture of the continent's emissions patterns. Recognizing these gaps, our study presents a breakthrough in this regard, carving out several significant contributions. Initially, our paper pioneers in building a comprehensive 47-sector and 5-energy type carbon emission inventory for 19 African countries spanning from 2000 to 2019, setting a new standard for inclusivity and depth in emission research; this uniform methodology across countries facilitates robust and nuanced comparisons. Additionally, our research dives deep to analyze the degree of economic and emission decoupling, providing a layered understanding of the intricate emission drivers unique to each country. Moreover, the study lays the foundation for future scholarly explorations, offering a robust framework that can influence policy crafting towards sustainable trajectories.

2. Method

2.1. Emission accounting

This study uses the administrative-territorial GHG accounting methodology outlined by the IPCC to compile an emission inventory for 19 African countries. We focus on territorial CO_2 emissions from fuel combustion, specifically energy-related emissions associated with 47 socioeconomic sectors and 5 fossil fuels (i.e., coal, crude, natural gas, oil products and unsustainable biomass). In accounting for territorial emissions and to avoid double accounting, emissions related to electricity/heat use were assigned to the power sector based on fossil fuel inputs for electricity/heat generation.

In accordance with the IPCC guidelines, fossil fuel-related carbon emissions are calculated as follows:

$$CE_{ij} = AD_{ij} \times NCV_i \times CC_i \times O_{ij} \tag{1}$$

where CE_{ij} stands for the CO_2 emissions from burning fossil fuel *j*; AD_{ij} refers to the fossil fuel consumption for the corresponding fossil fuel type *j* and sector *i*; NCV_i represents the net caloric value, i.e., the heating value produced per physical unit of fossil fuel combustion; CC_i is the carbon content, i.e., carbon dioxide emissions per net calorific value produced by fossil fuel j; and O_{ij} denotes the oxidation efficiency, which refers to the oxidation rate of fossil fuels when they are burned.

2.2. Decoupling index

At the beginning of the 21st century, the OECD began using *decoupling theory* to describe the interdependence between economic growth and environmental degradation [18]. Decoupling occurs when the growth rate of environmental stress is lower than the growth rate of its economic driver over a certain period of time. However, the widely used OECD methodology has poor stability and imprecise decoupling index calculations [19,20]. To address this, Tapio (2005) [21] defined an alternative decoupling method that divides the decoupling index into eight categories according to the range of elasticities. Currently, the Tapio decoupling method has been widely used to study the relationship between ecological and environmental factors and economic growth. Therefore, we introduce the Tapio decoupling method to study the decoupling relationship between CO_2 emissions and economic development in African countries (Fig. 1). The mathematical formula is as follows:

$$DI_{Tapio} = \frac{(CE_t - CE_0)/CE_0}{(GDP_t - GDP_0)/GDP_0} = \frac{\Delta CE/CE_0}{\Delta GDP/GDP_0} \tag{2}$$

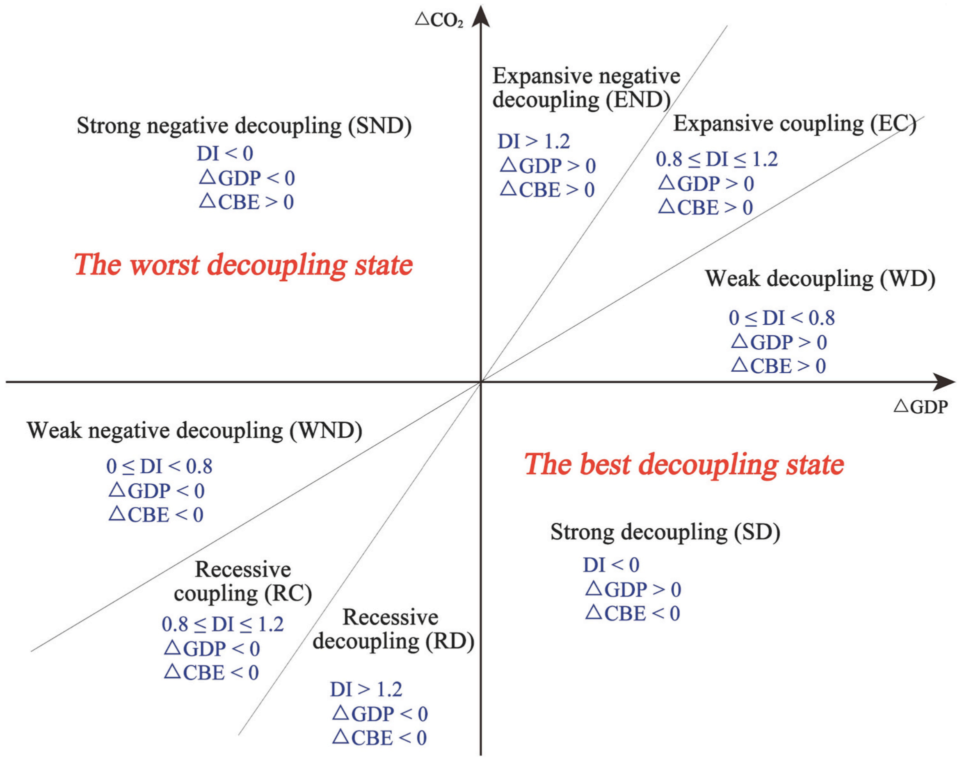

Fig. 1. The determination of Tapio decoupling states.

Where DI_{Tapio} stands for the decoupling index, ΔCE and ΔGDP denote the change values of CO_2 emissions; GDP is measured at the base year 0 to the target year *t*. Depending on the value of the decoupling index and the change in GDP, countries can be classified into eight categories.

2.3. Index decomposition analysis

Understanding the drivers of CO_2 emissions changes in Africa is crucial for developing effective mitigation policies. We undertook an Index Decomposition Analysis (IDA) to evaluate the contributing factors. IDA is a widely used, adaptable, and simpler method than other decomposition models [22]. Various IDA methods have been developed, of which the Logarithmic Mean Divisa Index (LMDI) method is the most popular one because it passes some basic tests for a good index [23]. The LMDI method, which has proven to be technically mature, computationally convenient, and path independent, was chosen for this study due to its perfect decomposition and ability to handle zero values [24–27]. We used LMDI to decompose carbon emissions into five drivers based on Kaya characteristics, as shown in Eq. (3).

$$CO_2 = int_C \times str_{en} \times int_{en} \times Eco \times Pop = \Sigma_j \frac{C_j}{En_j} \times \frac{En_j}{En} \times \frac{En}{GDP} \times \frac{GDP}{Pop} \times Pop \quad (3)$$

where $int_C = C_j/En_j$ stands for carbon intensity effect in sector j, $str_{en} = En_j/En$ measures the proportion of energy in total energy use of sector *j* and represents the energy structure effect, $int_{en} = En/GDP$ measures energy use per GDP and represents energy intensity effect, $Eco = GDP/Pop$ stands for the economic change effect, and *Pop* denotes the population of each country.

2.4. Data sources

The energy consumption data was obtained from the Energy Balance Table (EBT) published by the National Statistical Bureau and the African Energy Commission (see Table S2). The energy types for all countries are integrated into five energy types: coal, crude, oil products, natural gas, biomass and renewable energy (including hydropower, wind, geothermal, and solar PV). We used the emission factors that are given in the 2006 IPCC Guidelines for National GHG Inventories (NCV_i, CC_i, and O_{ij}). The emission factors for oil products were obtained by weighting the consumption of oil subcategories in the EIA.

Due to the disparities in how different countries report their energy consumption statistics across various industries, we initiated a standardization process, consolidating sector definitions into 47 distinct categories. We then employed sector mapping indicators to distribute emissions among these 47 sectors (as detailed in Table S1). These indicators embrace a range of sector data, including energy consumption, production, output, and employment, ensuring comparability across analogous sectors.

In the context of metal production, both ferrous and non-ferrous metals fall under the same raw material sector. Distinguishing between these two sectors necessitates the application of consistent mapping indicators. One viable approach involves using the product of each metal's output and its corresponding average energy intensity as the industrial mapping criterion. In the absence of energy intensity data, economic indices, such as value-added metrics, could facilitate this differentiation.

However, the sector mapping indicators may vary for sectors not tied to a single primary department. For instance, employment figures can serve as mapping indicators for the service industry. Conversely, when apportioning emissions from residential sectors to urban and rural divisions, the mapping criteria could rely on urban-rural population distributions instead of production or economic markers akin to those used in manufacturing.

The hierarchy of preferred data sources for sector mapping indicators is as follows: energy consumption, energy intensity, value-added, output, employment, and population data. These metrics are procured from national statistical bodies, economic reports, industry-specific documents, and continental or regional statistical compilations. A comprehensive listing of these data sources by country is provided in

Supplementary Material Table S2. This methodological rigor enhances the granularity and accuracy of our emissions inventory, accounting for the diverse economic activities and energy practices across different nations.

In addition, socioeconomic data (i.e., GDP and population) was obtained from the World Bank dataset.

2.5. Technical validation

2.5.1. Comparisons with major emission datasets

In this study, we juxtaposed our data on carbon emissions related to both biomass and non-biomass sources against figures from major international carbon emission databases, including EDGAR(Emissions Database for Global Atmospheric Research), IEA(International Energy Agency), GCB(Global Carbon Budget), and EIA(U.S. Energy Information Administration). Our findings revealed a consistent trend in emissions without biomass calculations verses other entities' CO_2 statistics (Fig. 2). For instance, countries like Tanzania exhibited minimal discrepancies, with less than a 1% gap between the figures from GCB and EIA and a marginal 8% variance with EDGAR and IEA. Egypt's data aligned closer with GCB and EIA, showing no more than a 4% difference, while diverging up to 9% from IEA's statistics and 13% from EDGAR's metrics.

Conversely, more significant disparities emerged in other instances, such as with Liberia (Fig. 2). Although the initial data points commenced similarly, the gap widened over the years, with IEA reports suggesting a rapid escalation in Liberia's carbon emissions, contradicting our findings that indicated a more tempered growth in the nation's fossil fuel-derived emissions.

Two primary factors contribute to these discrepancies between our data and that of other databases. Firstly, our methodological approach to energy categorization is more nuanced. For example, we further subdivide petroleum products into categories like motor gasoline, diesel, fuel oil, and other derivatives, each with its corresponding emission factors. In contrast, the IEA does not employ the same sub-categories of energy and utilizes different emission factors, resulting in variations in the emitted data. Additionally, our energy consumption data sources differ from those of the IEA. We derive our data from national and regional statistical bodies via transparent and publicly accessible platforms, while the IEA gathers its data through a blend of online sources, publications, and direct communications. The latter approach, though more versatile, offers limited verifiability for data users. Simultaneously, databases like GCB and EDGAR synthesize their information from

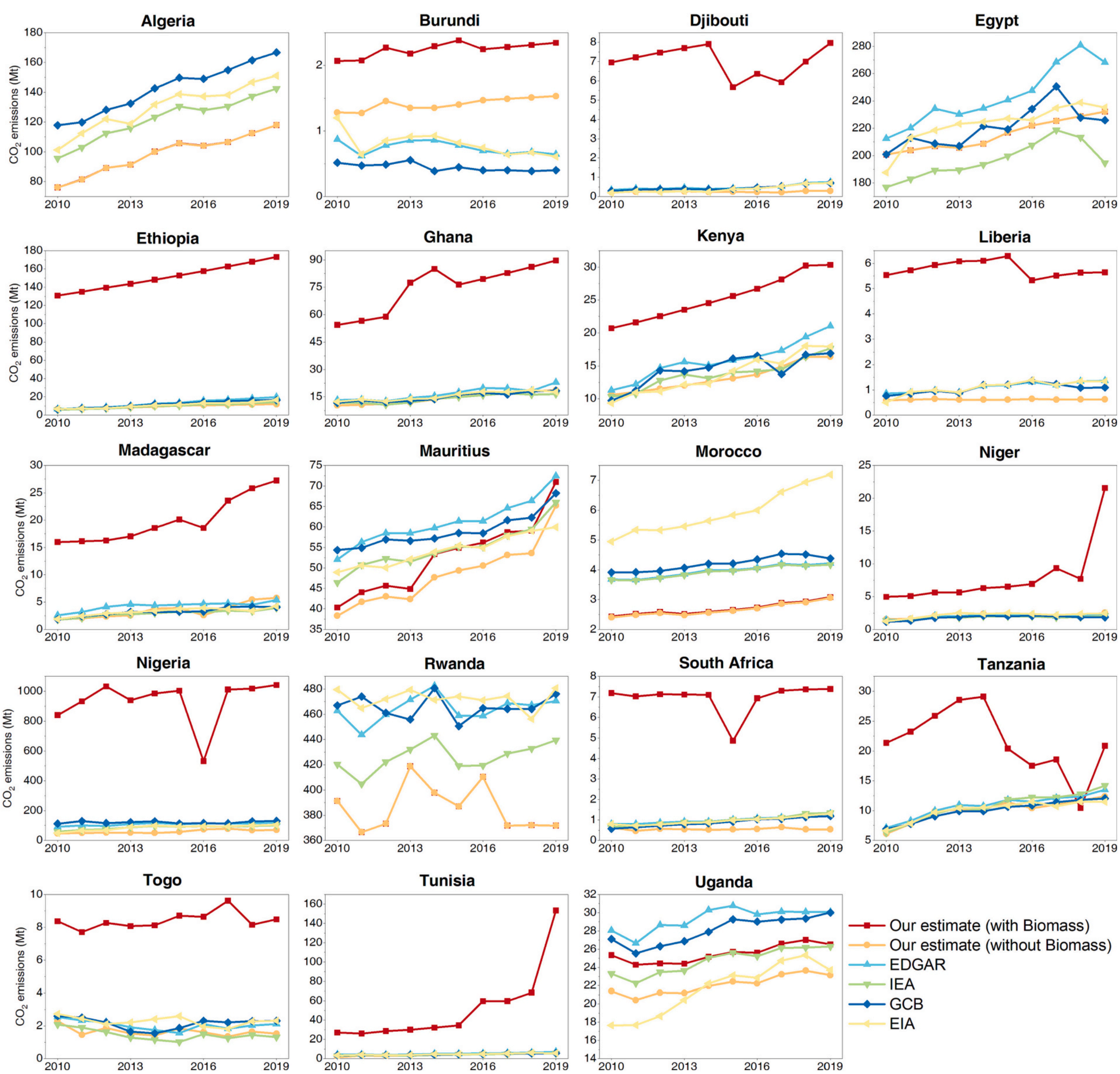

Fig. 2. Comparison of CO_2 emissions of African countries with other international institutions, 2010–2019.

multiple sources, including BP, the IEA, and the United Nations, inheriting the innate discrepancies between these primary sources and our dataset.

When incorporating emissions with biomass-related emissions, our calculated total carbon emissions are considerably higher than those from other databases that exclude biomass-related emissions. This disparity underscores the significant role of biomass in certain economies' energy matrices, often overlooked in mainstream emissions databases, hence influencing the interpretation and policy implications of such emission statistics.

2.5.2. Uncertainty

Incomplete or inaccurate data collection can introduce uncertainty into both activity data and emission factor data, consequently affecting the precision of emission accounting. To address this issue, our study employs Monte Carlo simulations to assess the uncertainty in emission calculations. These methods simulate the uncertainties by randomly selecting values for both the emission factor and activity data, each drawn from their respective normal probability density functions.

The methodology unfolds in three critical steps:

Initially, we establish the probability distributions of activity volume and emission factor data. These distributions are anchored in the quality and uncertainty ranges recommended by the IPCC National Greenhouse Gas Inventory Guidelines, ensuring methodological robustness. For emission factors, the distributions are simulated considering the specific energy types and categories unique to each country.

Upon this foundation, the study progresses by performing random samplings from the meticulously established activity level and emission factor distributions. Utilizing these sampled values, we compute the corresponding CO_2 emissions, adhering to a predefined formula that underpins the consistency and repeatability of our calculations.

The above step is replicated across 20,000 simulations, a scale that ensures statistical significance and depth. This repetition furnishes us with a comprehensive distribution of CO_2 emissions. And the results show that the average uncertainty in the total CO_2 emissions range from −7.1% to 7.3% at a 97.5% confidence level.

3. Results

3.1. CO_2 emissions of the African countries

African countries vary greatly in their emission levels, which fossil energy CO2 emissions ranged between 0.3 and 372 million tons in the year 2019 (Fig. 3); Many African nations derive energy from biomass sources like firewood and charcoal, which are linked to excessive deforestation and consequent forest degradation. Given the

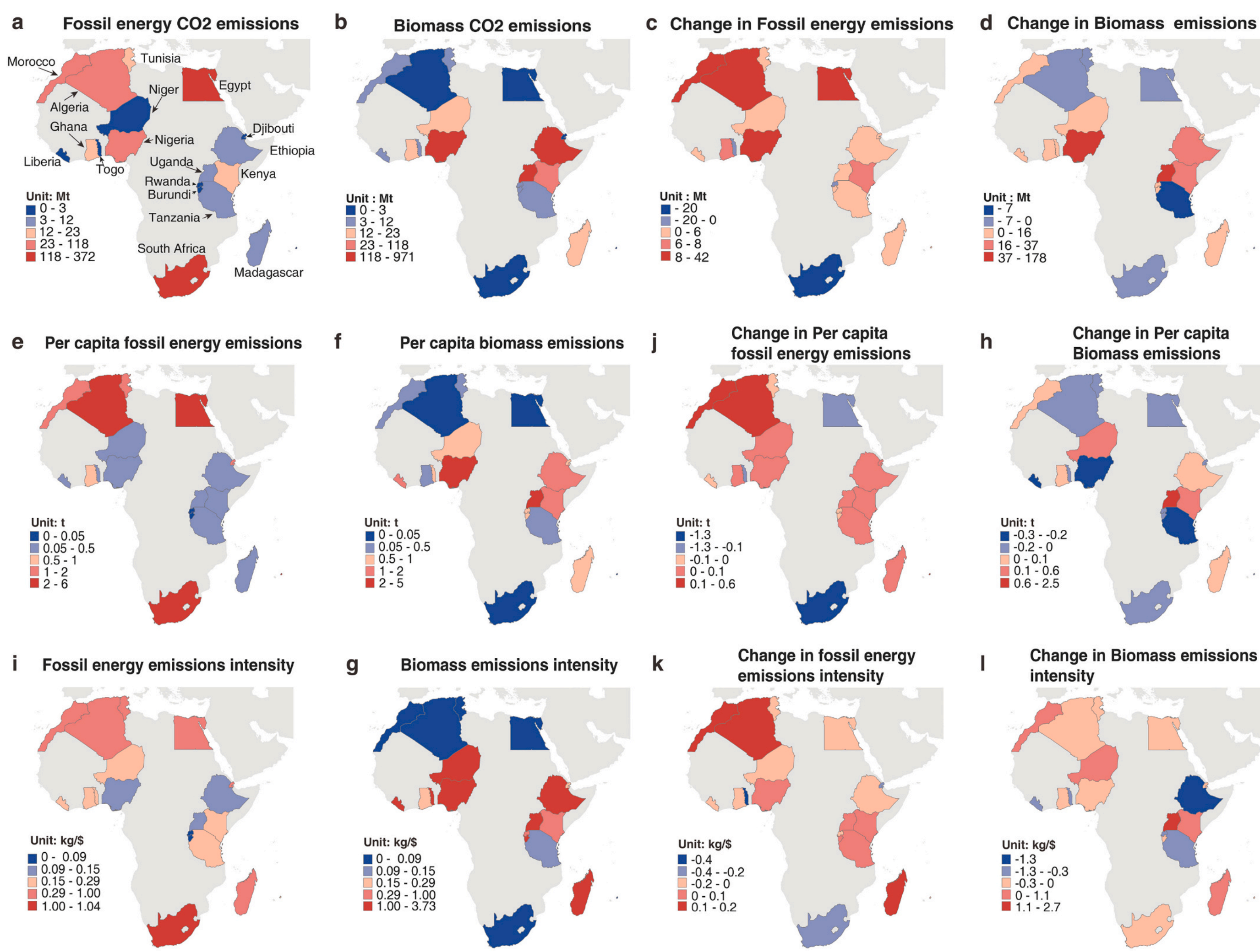

Fig. 3. CO_2 emissions in nineteen African countries. a-b) Fossil energy and biomass CO_2 emissions in 2019; c-d) Change in fossil energy and biomass CO_2 emission from 2010 to 2019; e-f) per capita fossil energy emissions and per capita biomass emissions in 2019; j-h) Change in per capita fossil energy emissions and biomass emissions in 2019; i-g)Fossil energy emissions intensity and biomass emissions intensity in 2019; k-l)Chang in fossil energy emissions intensity and biomass emissions intensity from 2010 to 2019.

unsustainable nature of this biomass utilization, it is imperative to account for such emissions. In this context, 2019 saw negligible biomass emissions from Egypt and South Africa, with Nigeria leading at 971.2 Mt. biomass CO2 emission.

Of the 19 countries studied, all but 3 (South Africa, Togo, and Rwanda) experienced varying degrees of fossil energy carbon emission increases between 2010 and 2019, with Algeria, Egypt, and Morocco showing the largest increases. The annual growth rate of fossil energy CO_2 emissions 2010–2019 ranged from 0.5% in Liberia to 15.3% in Uganda. In terms of Biomass CO2 emissions, 12 countries have seen their biomass grow between 2010 and 2019, with annual growth rates ranging from 0.2% in Liberia to 21.5% in Uganda. Uganda is one of the fastest growing economies in Africa and the world, and the development of the construction and manufacturing sectors in recent has been an important factor in both the economic growth of the country and the rapid growth in Uganda's carbon emissions. Excluding the three countries with decreasing carbon emissions, the remaining nations sustained an average annual growth rate of 5.5% for fossil fuel-related carbon emissions and 6.0% for unsustainable biomass-related carbon emissions between 2010 and 2019, exceeding both the world average of 2.0% and the 4.5% annual growth rate of similarly situated countries, revealing the growing fossil energy and unsustainable biomass demands associated with economic development in these African countries.

The countries with the highest total emissions were those with a strong industrial and economic activity base (e.g., South Africa, Egypt, Algeria, and Nigeria). In contrast, the bottom-ranked countries in terms of emissions levels (e.g., Burundi, Rwanda, and Djibouti) have relatively poor natural resources and low levels of industrialization—here, industrial value added as a share of GDP has largely not exceeded 20% for decades, placing them below the accepted ratio for the early stages of industrialization—and are among the least developed countries in United Nations' rankings.

In 2019, per capita fossil energy CO_2 emissions in African countries exhibited significant disparities, ranging from a minimal 0.02 t in Burundi to a substantial 6.3 t in South Africa. Simultaneously, biomass CO_2 emissions per capita were equally variable, with no significant emissions in countries like Egypt and South Africa, contrasting sharply with Nigeria's 4.8 t. These figures indicate a heavy dependence on biomass energy in less developed areas, often correlating with limited access to alternative energy sources. The absence of biomass emissions in Egypt and South Africa likely results from their urbanized economies and broader access to energy infrastructure.

Between 2010 and 2019, Algeria experienced the most significant increase in per capita fossil energy CO_2 emissions, with a rise of 0.6 t. This escalation can be attributed to several factors, including increased domestic energy consumption due to economic growth, and perhaps more critically, the expansion of the country's oil and gas sectors. These developments, while boosting the national economy, have had consequential environmental impacts, emphasizing the need for a more sustainable energy framework. In the same period, Uganda's per capita biomass emissions saw the largest upsurge at 2.5 tons, among seven countries recording an increase. This trend is indicative of a growing population's escalating energy needs, primarily met through traditional biomass sources due to the absence of affordable or accessible alternatives. This overreliance on biomass contributes to various environmental issues, including deforestation and the consequent release of greenhouse gases.

Interestingly, a shift in energy reliance is observable in countries such as Djibouti, Mauritius, Nigeria, and Tanzania, where increases in fossil fuel emissions coincide with decreases in unsustainable biomass emissions. This pattern suggests a gradual energy transition from traditional biomass to more modern energy sources, driven by economic development, urbanization, and efforts to curb deforestation and health issues associated with biomass use. However, this shift necessitates careful management to prevent a consequent surge in fossil fuel-based emissions.

In 2019, the fossil energy emission intensity ranging from 0.05 kg/$ in Rwanda to 1.0 kg/$ in South Africa. Such variation can be attributed to the economic structure and energy consumption habits of individual countries. For instance, South Africa's high emission intensity is linked to its coal-dependent energy sector and its energy-intensive industries. Conversely, Rwanda's low intensity may be due to its smaller industrial base, greater energy efficiency, or a combination of these factors.

Similarly, biomass emission intensities showed stark disparities, with Algeria at the lower end with 0.0001 kg/$ and Uganda at the higher end with 3.7 kg/$. Algeria's low biomass emission intensity can be attributed to its reliance on natural gas and limited use of biomass for energy. On the other hand, Uganda's high intensity indicates a significant dependence on biomass for energy, potentially due to limited access to other energy sources or prevailing agricultural practices.

From 2010 to 2019, the fossil energy emission intensity decreased in 12 countries, suggesting a reduction in fossil energy emissions relative to economic output. Among them, Togo, Djibouti, and South Africa recorded the most significant declines. Contrarily, some countries, notably Madagascar and Algeria, witnessed a rise in fossil fuel carbon emission intensity. This uptick might be due to increased industrial activities without corresponding improvements in energy efficiency or the adoption of carbon-intensive industries.

In terms of biomass emission intensity, 12 countries recorded a decrease between 2010 and 2019, with Ethiopia leading the way. This reduction can be linked to efforts to diversify energy sources, introduce efficient cooking stoves, reforestation projects, or policy measures to reduce reliance on traditional biomass fuels.

The researched African nations display a significant reliance on unsustainable biomass, including charcoal and firewood, for their energy needs. Remarkably, 10 out of the 19 countries sourced over 59% of their energy consumption from biomass. Among these, Nigeria and Rwanda stand out with an overwhelming dependency, where biomass accounts for more than 90% of their energy utilization. These observations echo the work of Iiyama et al. (2014), which indicated that biomass energy satisfies approximately 80–90% of low-income households' energy demands in Africa [28]. Similarly, research by Shi et al. (2020) corroborates Africa's position as the largest contributor to CO2 emissions from biomass burning [29].This high dependency underlines the region's challenges in diversifying energy sources and its continued dependence on forest resources, which can have long-term implications on environmental sustainability and local livelihoods.

The structure of fossil energy consumption in the African countries studied was relatively homogeneous, with oil products being the main or even the only type of fossil energy consumed in most of the countries studied (Fig. 4a). In 15 of the 19 countries studied, more than 50% of fossil energy consumption took the form of oil products, and 6 countries relied exclusively on oil products for their fossil energy consumption.

Coal consumption was relatively low or non-existent in most African countries, with South Africa and Morocco being exceptions. In South Africa, the highest carbon-emitting country in Africa, about 71% of the total fossil energy consumed in 2019 was in the form of coal. In addition, we note that as a percentage of fossil energy consumption, coal consumption increased in many countries between 2010 and 2019, mainly as a result of economic development and changes in national industrial structures. For example, due to rising demand from non-metal manufacturing and construction, Ethiopia's coal consumption increased from 1% of fossil energy consumption in 2010 to 9% in 2019. The share of coal consumption in fossil energy consumption in Morocco increased from 26% in 2010 to 39% in 2019, which can be attributed to the implementation of the National Plan for Industrial Emergence in 2009 and the National Industrial Acceleration Plan in 2014, which raised industrial development levels in Morocco.

In terms of natural gas consumption, in five countries (Algeria, Egypt, Nigeria, Ghana, and Tunisia) natural gas consumption made up more than 30% of total fossil fuel consumption. These five countries are all important gas producers in Africa—especially Algeria, where the

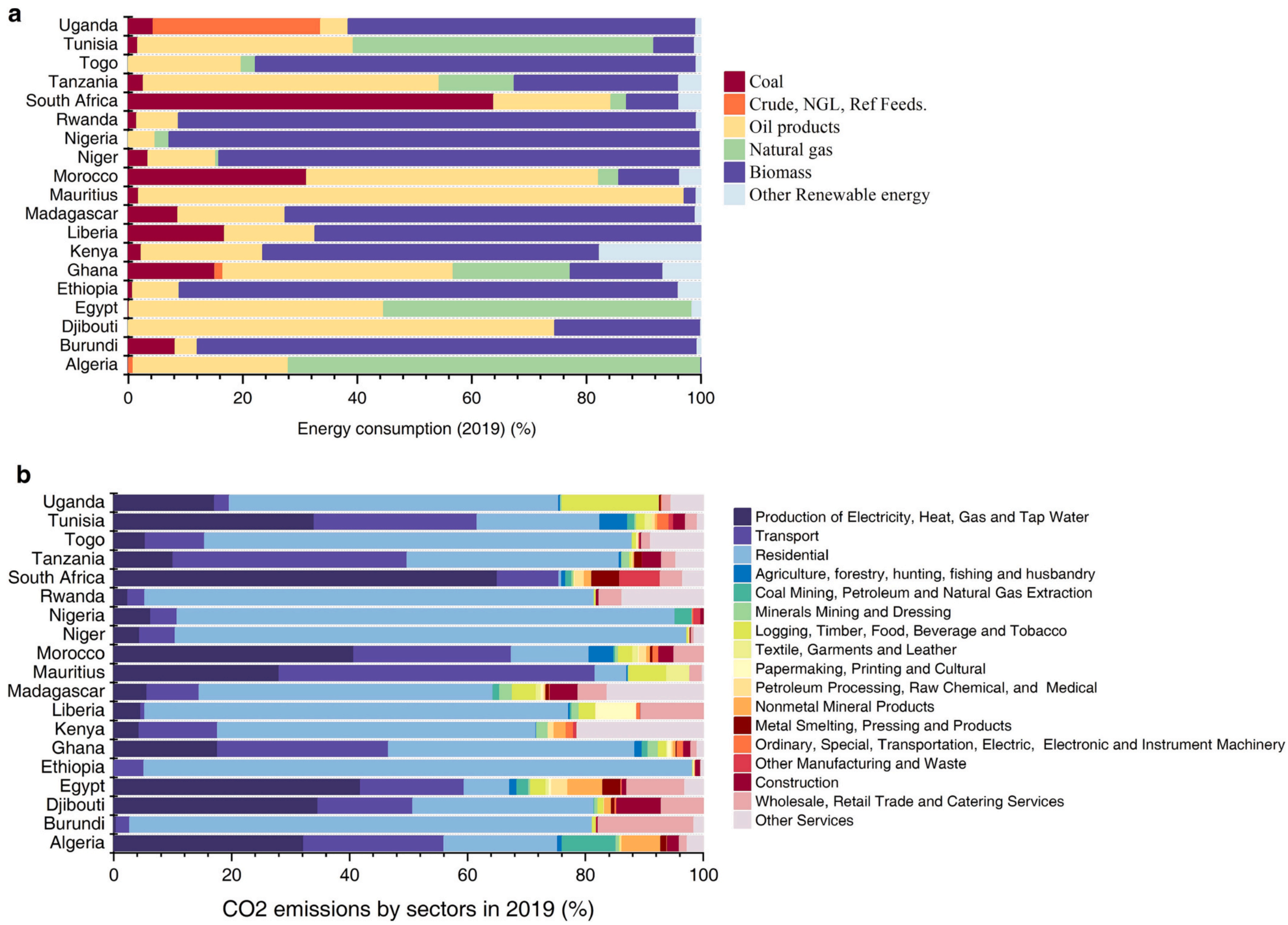

Fig. 4. Structure of energy consumption and emissions in nineteen African countries, 2019. (a) energy consumption (%); (b) CO_2 emissions by economic sector (%).

share off fossil fuel consumption attributed to gas reached 75%, which has the tenth largest nature gas reserves in the world and is the largest gas producer in Africa. This indicates that these five countries have cleaner energy options than other African countries.

In many African nations, domestic sectors stand out as primary contributors to carbon dioxide emissions. In 9 of the studied countries, household emissions accounted for over 50% of the total CO2 emissions. A significant driver behind these high household emissions is the widespread use of biomass fuels for daily consumption. As rural electrification remains a challenge and many off-grid households continue to rely on traditional cooking methods, biomass consumption remains high.

Transport is the main sector emitting CO2 from fossil fuels in many African countries. Across the 19 nations, emissions from the transport sector averaged 16% of the total CO2 footprint. From 2010 to 2019, most African countries witnessed a surge in transportation emissions. Nigeria particularly exhibited a steep rise, escalating from 3.3% (or 28.5Mt) in 2010 to 4.4% (or 46.3Mt) in 2019. To accelerate the development of transport infrastructure, the Nigerian government has developed a National Integrated Infrastructure Master Plan for 2014–2043, which sets transport as a priority development area and invests $25 billion (7% of annual GDP) per year in infrastructure development in the first five years (2014–2018).

The power sector is another hotspot of carbon emissions in African countries due to the strong demand for electricity resulting from industrialization, urbanization, and electrification. In South Africa, for example—which has a developed power industry that generates two thirds of all Africa's electricity, about 92% of which is thermal—the power sector accounted for 65% of total CO_2 emissions in 2019. Compared to other countries, the power sectors of Uganda and Kenya are shown to maintain a smaller share of emissions due to cleaner power generation systems. Uganda is rich in hydropower resources, with 89% of its electricity supply coming from hydroelectric plants. Kenya has been encouraging the development of clean energy and has a high share of renewable energy generation, at 48.3% [30]. Burundi also has a smaller share of electricity emissions (10%); unlike Uganda and Kenya, though, the country has a low electrification rate, with almost 90% of the population without access to electricity [30].

3.2. *Decoupling of CO_2 emissions from economic growth*

All evaluated African countries achieved economic growth from 2010 to 2019 and can be characterized into four decoupling types, namely: (1) strong decoupling, where economic growth is accompanied by a decline in emissions; (2) weak decoupling, where emissions grow at a lower rate than the economy; (3) expansive decoupling, where the economy and emissions grow at similar rates; and (4) expansive negative decoupling, where emissions grow at a higher rate than the economy.

Fig. 5 shows that South Africa and Tanzania strongly decoupled economic growth from emissions during study period, and ten countries achieved weak decoupling. Among the countries that achieved strong decoupling, South Africa decoupled its emissions at a relatively high level of GDP and high per capita emissions, which is consistent with most countries in the world that have achieved decoupling, such as most

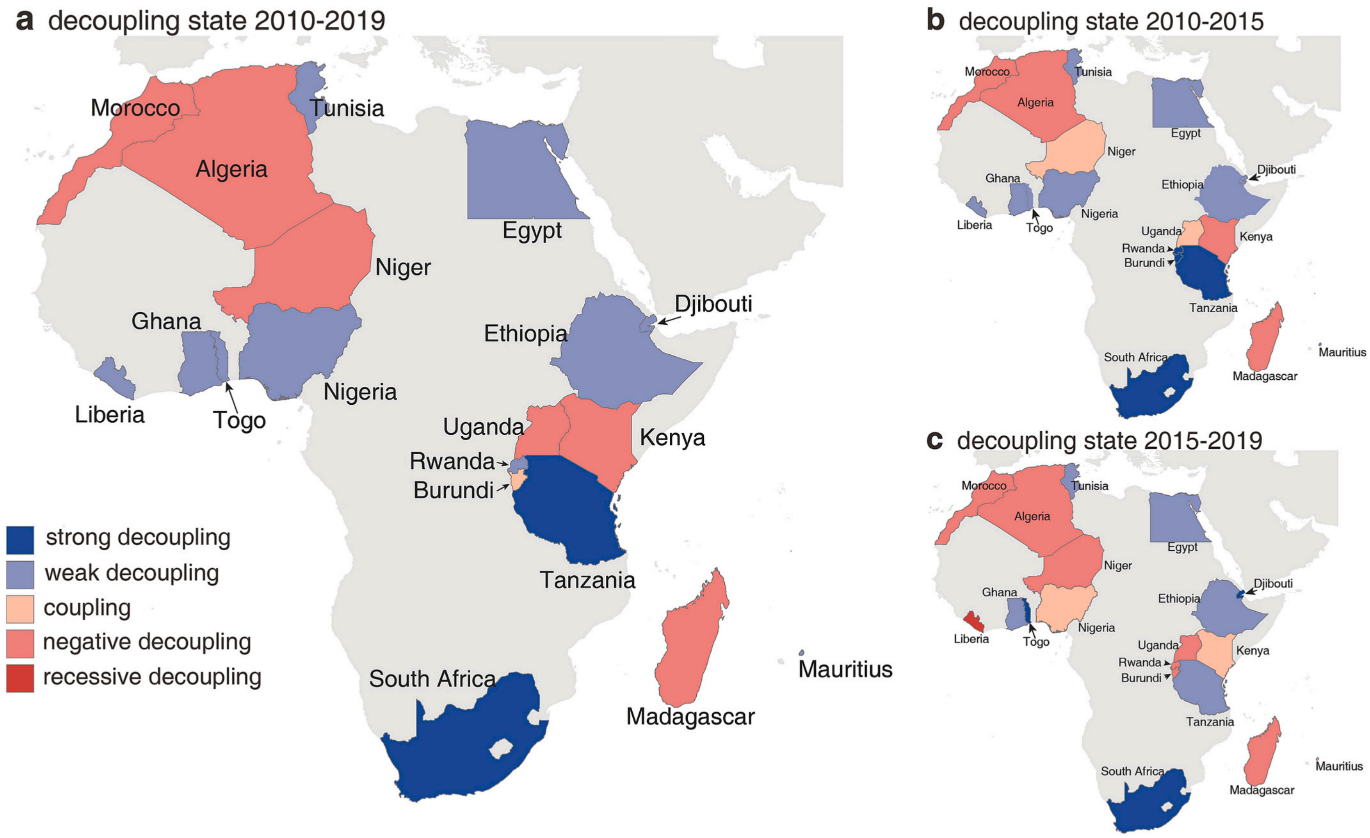

Fig. 5. Decoupling states of countries in Africa from 2010 to 2019.

EU and North American countries [31,32]. A study of China also found that wealthy cities tend to be more likely to decouple economic growth from emissions [22].We have observed instances of strong decoupling between emissions and GDP in Tanzania, characterized by low income and low emissions. However, such phenomena in low-income countries should be interpreted with caution. Decoupling trends in these countries could be seen as exceptions rather than the rule, often influenced by external factors such as political instability, economic downturns, and data quality [33]. Furthermore, the volatility of these countries' socio-economic conditions often results in fluctuating decoupling statuses. As such, it is not uncommon for them to transition back-and-forth between different decoupling stages such as absolute decoupling, weak decoupling, and expansive negative decoupling over relatively short timeframes, like the past decade (2010 to 2019). Consequently, while it's important to recognize these instances of decoupling in Tanzania, generalizing its experiences to other regions may not be feasible or accurate.

It is worth noting that the degree of decoupling varies over time. If we divide the period 2010–2019 in two (as shown in Fig. 4b and c), we find that eight countries achieved weak decoupling from 2010 to 2015, but only four maintaining it in the following years. The number of countries not showing decoupling (i.e., coupling, negative decoupling, and recessive decoupling) between GDP growth and emissions increased from 6 in the period 2010–2015 to 9 from 2015 to 2019, indicating a closer link between economic growth and emission-intensive products. Continued GDP growth in these countries may lead to increased emissions.

3.3. Driving forces of CO_2 emissions in Africa

It can be seen from Fig. 6 that population is the major driver in increasing emissions, accounting for 23.2% of all emissions increases in the African countries studied. Economic growth (11.4%) and the increase in energy consumption share in secondary sector (1.1%) are the other two factors that increase emissions. On the other hand, the main driver of emissions reduction was decreasing carbon intensity (−4.2%), followed by the decline in energy intensity (−2.2%).

The impact of the drivers varied considerably between countries. Population growth was the most important driving factor in 6 countries, while growth in GDP per capita was the most important factor in 7 countries. Energy intensity differs significantly between countries that have achieved strong or weak decoupling and those that are not showing decoupling (i.e., coupling, and negative decoupling). For strong or weak decoupling countries like South Africa, Egypt and Djibouti, lower energy intensity leads to significant reductions in carbon emissions due to the use of low-carbon technologies. For example, in 2005, South Africa released its first national energy efficiency strategy, and in 2008 the South Africa Energy Development Institute was established to improve climate mitigation programs, energy efficiency, and the promotion of renewable energy use [34]. In non-decoupled countries such as Algeria and Madagascar, the positive effect of energy intensity on emissions is significant because the growth rate of emissions is much higher than the economic growth rate, mainly due to rapid development and an increasing reliance on non-renewable energy sources.

In addition, we note that the energy mix varies considerably from country to country. The primary sector has a small contribution to emissions, except for Burundi where it offsets 10% of emissions growth. The secondary sector significantly increase CO_2 emissions in Liberia, Morocco, and Rwanda due to increased coal consumption in the electricity and heat sectors. Liberia, for example, has been developing significantly in power generation and transmission in recent years with the assistance of the EU, World Bank, etc. But for some countries, the secondary sector has reduced its emissions. For example, Niger's secondary sector has contributed to a 19.5% drop in emissions, which is closely linked to the increase in the share of renewable energy generation.

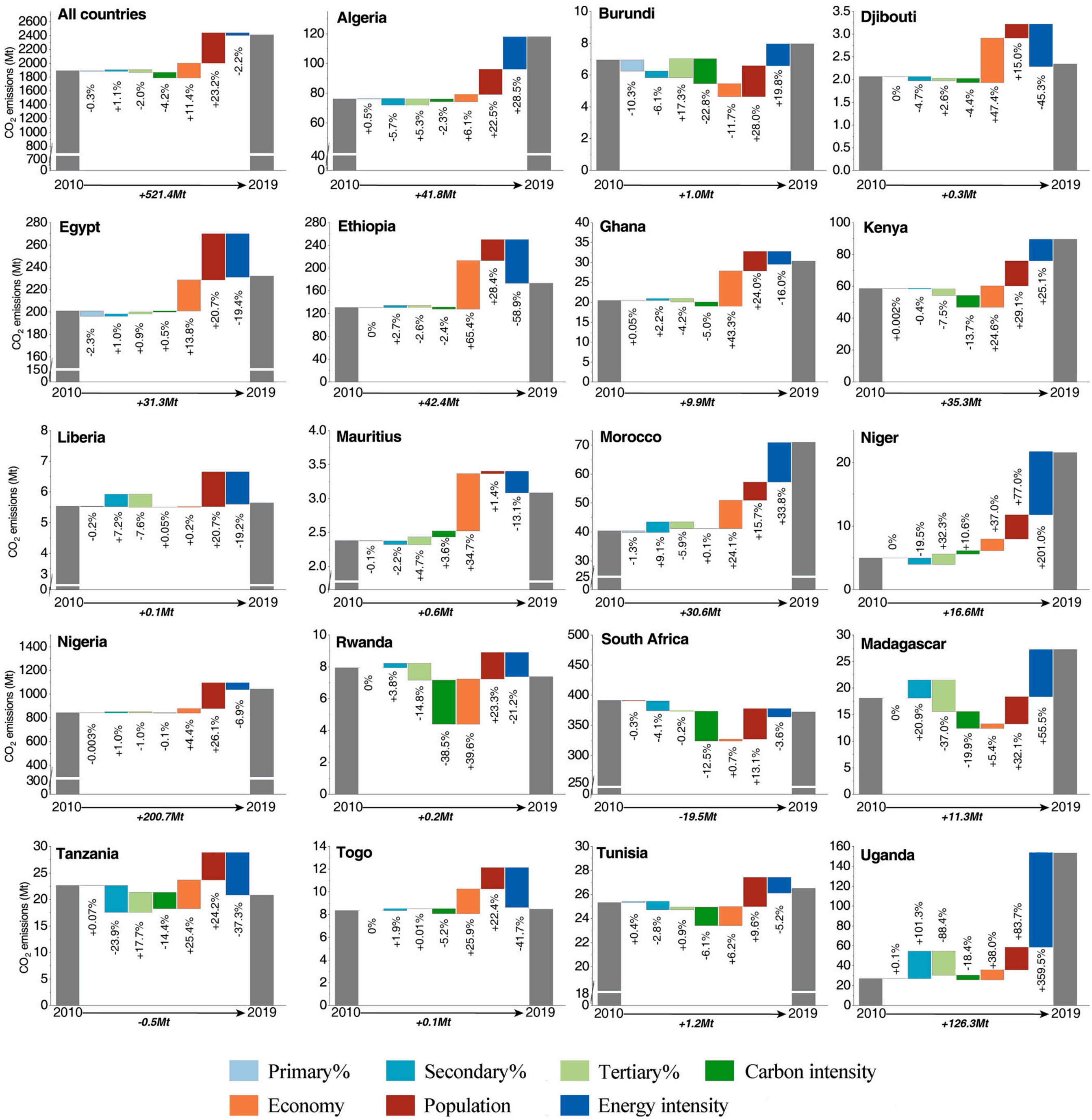

Fig. 6. Drivers of emissions change in African countries from 2010 to 2019.

4. Discussion and conclusions

Carbon accounting and analysis for African countries is currently insufficient and lacks multi-source statistics and detailed sectoral mapping. Addressing this gap, we here provide the most comprehensive and long-reaching time-series analysis of emission inventories for 19 African countries from 2010 to 2019. The inventories include energy-related emissions from four types of fossil fuels and unsustainable biomass, and have been compiled for 47 economic sectors. We have further also analyzed the degree of decoupling between emissions and economic development, and the key drivers of CO_2 emission changes.

Here are the main findings: firstly, regarding the overall CO_2 emissions situation, our study indicates significant inequality in emissions levels among African countries, the fossil fuel-related CO_2 emissions ranging from 0.3 to 372 Mt. in 2019, and the biomass-related CO2 emissions ranging from 0 to 971Mt. Most of the African countries studied experienced rapid growth in CO_2 emissions in the last decade, with an average annual growth rate of 5.5% for fossil fuel-related carbon emissions and 6.0% for unsustainable biomass-related carbon emissions. The potential for future growth in CO_2 emissions in Africa is, as a result, huge and cannot be ignored.

Second, as for the emission drives, our findings indicate that in most countries studied, economic and population growth are the main drivers of CO2 emissions, while energy intensity is the main factor inhibiting emissions in some countries, particularly those with strong or weak decoupling. The reduction of energy consumption in the tertiary sector is the second most important driver of emissions reductions.

In African countries, economic development has been a major policy focus to increase incomes and reduce poverty, especially in the face of projected population growth; sustained economic growth will, however, also continue to drive the growth of CO_2 emissions in these countries. Starting from a relatively low base concerning per capita income and energy use, Africa can significantly influence global emissions, dependent on its path of growth. Research has shown that even under a medium economic and population growth scenario, Africa's share of global CO2 emissions could potentially increase to around 20% by 2100 [35]. Therefore, the emission reduction strategies in African countries should not only focus on the current state but also on the potential future influence of these countries on global emissions. Considering the diversity of energy mixes and economic structures that could power African growth, the critical role of policy in guiding towards a low-carbon economy is underscored. Thus, the path towards sustainable economic growth in Africa calls for a delicate balance between development goals and climate change mitigation.

Drawing upon the comprehensive analysis and insights garnered from our research, we outline the principal policy recommendations below, designed to address the multifaceted challenges of CO2 emissions and pave the way for sustainable, environmentally responsible growth across the African continent.

First, it is imperative to confront the unsustainable use of biomass. Addressing the extensive reliance on unsustainable biomass, such as firewood and charcoal, by many African countries is paramount due to the associated environmental challenges of deforestation and forest degradation. To mitigate biomass carbon emissions, a holistic approach is essential. Tapping into alternative energy sources, like solar, wind, and hydropower, can reduce biomass dependency. Public awareness campaigns are pivotal, enlightening communities on the repercussions of unchecked biomass consumption and the virtues of eco-friendly alternatives. Sustainable agriculture models, such as agroforestry, can be encouraged, providing both carbon sequestration and alternative fuel sources. Offering incentives for dedicated biomass plantations can ensure a consistent, sustainable biomass source without depleting natural forests.

Second, the urgent need to mitigate CO2 emissions in Africa necessitates transformative changes in the continent's energy sector, particularly a significant shift from fossil fuel-based power consumption to renewable electricity generation. Economic development, although crucial for raising income levels and alleviating poverty, can spur on future emissions growth if not accompanied by offsetting declines in the carbon intensity of these countries' economies [36].

The production and supply of electricity is a major source of carbon emissions in Africa, mainly due to the reliance on fossil fuels in electricity generation. South Africa, generating two-thirds of Africa's electricity with 92% of it produced through coal-based thermal power, exemplifies this reliance. Additionally, half of Africa's population still lacks access to electricity. If electricity continues to be produced in the current manner, future development in Africa will result in significant CO_2 emissions from the power sector. However, African countries have significant potential for renewable energy development, including solar and wind energy. Switching from non-renewable to renewable energy sources is an important pathway for low-carbon development in Africa.

Thirdly, leveraging investments and public-private partnerships is critical: The energy sector's investment challenge can potentially be addressed through private investments and public-private partnerships (PPPs). Initiatives like South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPP) have demonstrated success in raising capital, along with generating the necessary technical and financial expertise for renewable energy projects. Enhancing governance, lowering financing costs, and international agencies' support are crucial for boosting these efforts [37]. African governments' role in enhancing governance for better credit ratings, lowering financing costs, and improving local financial markets is vital to boost domestic funding capacity. Simultaneously, given the current state of domestic funding capacity, international funding agencies need to supplement these efforts by increasing their investment volumes [38].

Fourthly, there is a pressing need to enhance energy efficiency. Improving energy efficiency is an important aspect of emission reduction policies. This is particularly important for the industry and transportation sectors, which are key drivers of economic development in many African countries. These sectors are also energy-intensive and contribute significantly to CO_2 emissions. Therefore, enhancing energy efficiency in the power, industry, and transportation sectors should be a major focus for reducing emissions in African countries.

Lastly, considering alternative development trajectories is essential. The traditional economic development model of vigorous industrialization may not be the only way to develop Africa. African countries can explore alternative development trajectories that are relatively less carbon-intensive, as conditions in the global economy are different for the "late industrializers" of today. Brazil, for example, reaps both environmental and economic benefits from its predominantly agricultural economy, which generates fewer CO_2 emissions than industrialized economies [39]. Opportunities exist for late industrializers to develop in different, relatively less carbon-intensive forms such as commercial agriculture, tourism, information and communication technologies, other services, and food processing and horticulture. These industries are often referred to as "industries without smokestacks" and could offer new opportunities for Africa's development in the coming decades.

We acknowledge a limitation of our methodology regarding the use of constant emission factors for each fossil fuel type. Due to data constraints, our study employs average emission factors, which may not capture the specific carbon intensity of every fuel sub-type. This is a commonly accepted practice in large-scale emission inventories when detailed information about specific fuel types is not available. Nonetheless, this simplification could lead to minor inaccuracies in the absolute emission values reported. Future work should strive to refine these estimates as more detailed data become available.

It is important to acknowledge certain inherent data limitations. The varied nature of the African nations in terms of their economic and developmental stages means that there is a high degree of variation in the quality, reliability, and completeness of data. For instance, some nations may have robust data collection and reporting mechanisms in place, resulting in high-quality, comprehensive datasets. Others, particularly those in the early stages of development or with less established infrastructures, may have more limited or less reliable data. This data variability, along with the potential for unreported or underreported data in these countries, could impact the overall quality of our analysis and the precision of our conclusions. For example, disparities in data quality could lead to either over- or under-estimation of certain parameters, thereby influencing the resultant insights and recommendations. Moreover, although we have made every effort to use the most credible data sources, it is worth noting that these sources are not immune to potential errors or inconsistencies. This is a common challenge in research, especially in complex fields like energy economics, which involve diverse data sets and variables. In light of these challenges, we are committed to transparently reporting these limitations, reinforcing the importance of interpreting our findings within the context of these acknowledged data limitations.

In this study, we meticulously quantified carbon emissions from various sectors and fuel types across 19 African countries, crafting a comprehensive inventory that serves as a foundational reference for more exhaustive future research in Africa. Our analysis touches upon critical areas such as the driving forces behind CO2 emissions, opportunities for emission reduction, efficiency enhancements, mitigation costs, and forward-looking emission projections. Recognizing the diversity and heterogeneity of the African continent, we acknowledge that this research represents only a fraction of the broader narrative. The countries included in this study were selected based on various criteria, including data availability and national energy dynamics, yet we understand the scope is somewhat limited in capturing the full spectrum of Africa's carbon emissions. Thus, future studies are encouraged to broaden this scope by incorporating more African nations. Moreover, the data presented here can be a valuable asset for exploring under-researched areas, such as consumption-based emissions in Africa, a critical perspective for comprehensive climate strategies. Through these expanded inquiries, subsequent research can significantly enrich our understanding, leading to more robust, informed, and region-specific climate policies that consider the diverse economic, cultural, and geographical contexts of African countries.

CRediT authorship contribution statement

Jieyu Wang: Writing – original draft, Methodology. **Yuli Shan:** Writing – review & editing, Supervision, Conceptualization. **Can Cui:** Methodology, Data curation. **Congyu Zhao:** Data curation. **Jing Meng:** Conceptualization. **Shaojian Wang:** Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This study is supported by the National Natural Science Foundation of China (Grant No. 42371207), and the China Scholarship Council Visiting Ph.D. program (J. Wang, C. Zhao).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2023.122494.

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