Energy for Sustainable Development 76 (2023) 101288

Contents lists available at ScienceDirect

Energy for Sustainable Development

journal homepage: www.journals.elsevier.com/energy-for-sustainable-development

Factors affecting household air pollutants in West Africa: Evidence from Ghana and Nigeria

Kwame Adjei-Mantey [a], Ken'ichi Matsumoto [b,*], Yosuke Shigetomi [c], Yuki Yamamoto [d], Tomoki Nakayama [c]

[a] Department of Applied Economics, University of Environment and Sustainable Development, PMB, Somanya, Ghana
[b] Faculty of Economics, Toyo University, 5-28-20 Hakusan, Bunkyo-ku, Tokyo 112-8606, Japan
[c] Graduate School of Fisheries and Environmental Sciences, Nagasaki University, 1-14 Bunkyo-machi, Nagasaki 852-8521, Japan
[d] Faculty of Economics, Kansai University, 3-3-35 Yamate-cho, Suita, Osaka 564-8680, Japan

ARTICLE INFO

JEL classification:
C6
Q4
Q5
R2

Keywords:
Index decomposition analysis
Air pollutants
Residential sector
Sub-Saharan Africa

ABSTRACT

In sub-Saharan African countries, exposure to air pollutants, such as fine particulate matter ($PM_{2.5}$), in the residential sector is a serious environmental issue which causes health problems. Identifying the driving factors of such air pollutants is significant to formulate policies to reduce emissions and achieve a sustainable society. This study examined five socioeconomic drivers (emission intensity, the share of each energy source, energy intensity, household size, and the number of households) for energy-related air pollutants ($PM_{2.5}$, nitrogen oxide, and non-methane volatile organic compounds) from the residential sector in Ghana and Nigeria from 1990 to 2018 using index decomposition analysis. Furthermore, we compared the similarities and differences in the driving factors of the two countries that showed different emission trends. We identified factors contributing to increasing/decreasing emissions in the two countries. In particular, the household effect is an increasing factor for both countries, while the household size effect is a decreasing factor. By contrast, the emission intensity, energy type, and energy intensity factors affect differently for the two countries. This finding suggests that energy-related policy considerably impacts the trends of air pollutant emissions from the residential sector.

Introduction

In recent times, issues about the environment have been pivotal to research and policy due to the global goals to achieve sustainability. The school of thought that economic growth and the pursuit of other economic goals should not come at the expense of the environment and the natural resources needed for achieving economic and welfare goals has become popular; thus, prompting actions in favor of environmental sustainability. The Paris Agreement of 2015, for instance, set the goal to hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels and aims for net zero emissions by 2050.[1] To this end, there is a focus on reducing greenhouse gas (GHG) emissions, and increasingly, researchers and policymakers are paying attention to global and territorial air quality. Several studies have focused on carbon dioxide (CO_2) emissions and their association with economic growth, other macro-level economic variables, and household welfare indicators. These studies have revealed important relationships between CO_2 emissions on one hand and on the other hand, economic growth (Pata, 2018; Sarkodie & Strezov, 2018); industrialization (Kwakwa et al., 2021; Li & Lin, 2015; Sharif, 2011); urbanization (Chen et al., 2019; Kwakwa et al., 2022; Sharma, 2011); energy consumption (Adams et al., 2020); foreign direct investment (Minh, 2020; Opoku et al., 2021); and institutional quality (Bokpin, 2017; Zakaria & Bibi, 2019). These studies have mainly focused on effects and associations at the macro level.

Besides CO_2, however, there are other pollutant emissions, particularly at the household level, but have received little attention in the literature compared to the attention received by CO_2. One of the common emissions at the household level, especially in developing economies, is fine particulate matter ($PM_{2.5}$). Recently, air pollution, mainly by $PM_{2.5}$ is recognized as the second most significant risk factor for death in Africa after malnutrition and more than 63% of premature deaths were estimated to be linked to exposure to household air

---

* Corresponding author: Faculty of Economics, Toyo University, 5-28-20 Hakusan, Bunkyo-ku, Tokyo 112-8606, Japan.
E-mail address: matsumoto1005@toyo.jp (K. Matsumoto).

[1] https://unfccc.int/process-and-meetings/the-paris-agreement

https://doi.org/10.1016/j.esd.2023.101288
Received 22 May 2023; Received in revised form 10 July 2023; Accepted 24 July 2023

pollution (Health Effects Institute, 2022). Even though observations of $PM_{2.5}$ are still very limited, the West African region experienced one of the highest ambient and indoor $PM_{2.5}$ pollution in Africa (Agbo et al., 2021; Health Effects Institute, 2022). It is commonly observed at the household level since it often results from the incomplete combustion of traditional solid biomass, including firewood and charcoal (Ali et al., 2021). Therefore, households that use these solid fuels for cooking or heating commonly emit this pollutant. Recent statistics published by the Ghana Statistical Service, Ghana's National Statistics Bureau, show that as of 2021, more than 50% of the population of households across the country relied on firewood or charcoal as their primary cooking fuel with a severe situation in many of the administrative regions away from the capital (Ghana Statistical Service, 2022). At least six in every ten households in 11 out of Ghana's 16 administrative regions use these fuels as their primary sources of cooking energy. The situation is not any different in Nigeria, where the National Bureau of Statistics of Nigeria reported that 68.3% of all households in Nigeria use biomass for cooking (Eleri, 2021; National Bureau of Statistics, 2020) with significant disparities which reveal more troubling statistics in some states (Danlami, 2019). These statistics indicate that the considerably large proportion of residential energy in Ghana and Nigeria sourced from biomass opens these two countries up for high pollutant emission levels from the residential sector.

Studies have observed adverse effects of exposure to $PM_{2.5}$ on household members who are exposed to these pollutants (Adjei-Mantey & Takeuchi, 2021; Kurata et al., 2020; Upadhyay et al., 2015). These studies have often examined the relationships between exposures to the pollutant and observed effects on the health of household members. While knowledge on the effects of these pollutant emissions on household welfare or macroeconomic variables is increasing due to previous research, there is a dearth of knowledge and literature on the constituting sources of these pollutant emissions, particularly the household or residential sector emissions in developing countries. Furthermore, more could be done concerning empirical literature on pollutant emissions from the residential sector with regard to pollutants other than $PM_{2.5}$ (see below for the literature review). This study aims to decompose energy-related air pollutant emissions from the residential sector in Ghana and Nigeria, focusing on $PM_{2.5}$, nitrogen oxide (NO_X), and non-methane volatile organic compounds (NMVOC). Among air pollutants, $PM_{2.5}$ has the largest impact on human health, especially in developing countries. Ozone is also known to greatly influence human health and is generated from photochemical reactions involving NO_X and NMVOC in the troposphere. Furthermore, the study aims to conduct a comparative decomposition analysis of these pollutant emissions for Ghana and Nigeria. Previous studies that have conducted a decomposition analysis of air pollutants have conducted such studies in countries outside sub-Saharan Africa (SSA), including China (Hu et al., 2022; Shen & Wang, 2017; Xu et al., 2017; Yang et al., 2019), the Czech Republic (Ščasný, Ang, & Rečka, 2021), Sweden (Ustyuzhanina, 2022), the United Kingdom (Shimamoto, 2017) and the United States (Wang et al., 2020), and the focus for these studies have not been on residential sector emissions. Following a thorough literature review, no study was found focusing on the residential sector in countries in SSA, including Ghana and Nigeria, where households have a relatively high dependence on heavily polluting cooking fuels.

Besides, this study fills the gaps in the literature on the sources of residential sector emissions and for countries in SSA by conducting a decomposition analysis of the residential pollutant emissions for Ghana and Nigeria. Decomposition analysis is a well-known tool used to quantify how much changes in the socioeconomic drivers contribute to changes in economy-wide environmental impacts, such as CO_2 emissions (Matsumoto et al., 2019), chemical toxicity (Fujii et al., 2017), water consumption (Zhao & Chen, 2014), coal consumption (Wei et al., 2020), material use (Weinzettel & Kovanda, 2011), and air pollutant emissions (Meng et al., 2019) between two periods. For changes in direct impact, index decomposition analysis (IDA) can be adopted. Since the first application of IDA to changes in energy consumption appeared before 1980, those in sectoral energy consumption and energy-related CO_2 emissions have been investigated in various nations and regions (Ang & Goh, 2016; Xu & Ang, 2013). For African countries, Inglesi-Lotz and Blignaut (2011) quantified the contribution of factors to energy consumption in South Africa from 1993 to 2006 and underpinned that their trends vary substantially among the sectors. Beidari, Lin, and Lewis (2017) also focused on South Africa, investigating the drivers of CO_2 emissions generated by the electricity sector from 1990 to 2013. Ebohon and Ikeme (2006) conducted IDA to understand the characteristics of key drivers of CO_2 emission intensity between oil-producing (including Nigeria) and non-oil-producing countries (including Ghana) in SSA from 1971 to 1998. Their results showed that the contributions of changes in economic scale, CO_2 emissions per unit of energy consumption, and energy consumption per unit of output differed between Nigeria and Ghana. Other than CO_2 emissions, Okorie and Lin (2022) explored the driving forces of agricultural GHG (focusing on methane and nitrous oxide) emissions from 1990 to 2019 in Nigeria and found that growth in the per-capita output was the largest increasing driver of the emissions, followed by the number of people employed in the agricultural sector and the reciprocal ratio of employment to the total population. Sun et al. (2022) compared the patterns and driving forces of GHG emissions across eight African countries. Although their analysis does not consider the emission drivers for Nigeria and Ghana, the results indicate the impact of large-scale foreign investment and the rapid development of the transport and infrastructure sectors on the emission growth in the analyzed countries after 2010.

Focusing on the residential sector, however, studies analyzing the drivers of environmental impact have been limited in economically developed nations and China. O'Mahony et al. (2012) disaggregated residential CO_2 emissions in Ireland for the period 1990–2007 and found that the total emissions would be reduced by improvements in energy intensity and the emission coefficient in contrast to an increase in the number of households. Berrill et al. (2021) examined the key drivers of changes in both residential energy use and GHG emissions in the United States from 1990 to 2015 and summarized that improvements in energy efficiency would not outweigh the increase in the number of households from population growth and further reductions in household size if the age distribution, type mix, or average size of dwellings do not change. In addition to these studies, other studies analyzed the breakdown of trends in residential CO_2 emissions across the subnational regions to understand the regional differences in the key drivers. Shigetomi et al. (2018) provided a detailed breakdown of the changes in residential CO_2 emissions in 47 prefectures in Japan from 1990 to 2015, and Yuan et al. (2019) demonstrated the decomposition analysis of the residential CO_2 emissions in 30 provinces of China between 2007 and 2012. Both studies identified the importance of population and income growth as the main drivers of increasing emissions across the regions. Nevertheless, to our best knowledge, no study identified the drivers of air pollutants directly generated from the residential sector in both Ghana and Nigeria, nor in other countries in SSA. Therefore, the main contribution of this study is to clarify the driving factors of multiple air pollutant emissions in the residential sector and in SSA, where residential air pollution is a severe environmental and health issue. We focus on Ghana and Nigeria for our analysis because they are among the largest economies in West Africa, from which other countries in the sub-region could draw lessons to reduce energy-related air pollutant emissions at the national scale (Fig. 1).

The remainder of the paper is organized as follows: the Methods section details the methodology adopted for the study, the Results section explains the findings, which are discussed in the Discussion section, and Conclusion section concludes.

Methods

This study applied the logarithm mean Divisia index (LMDI)

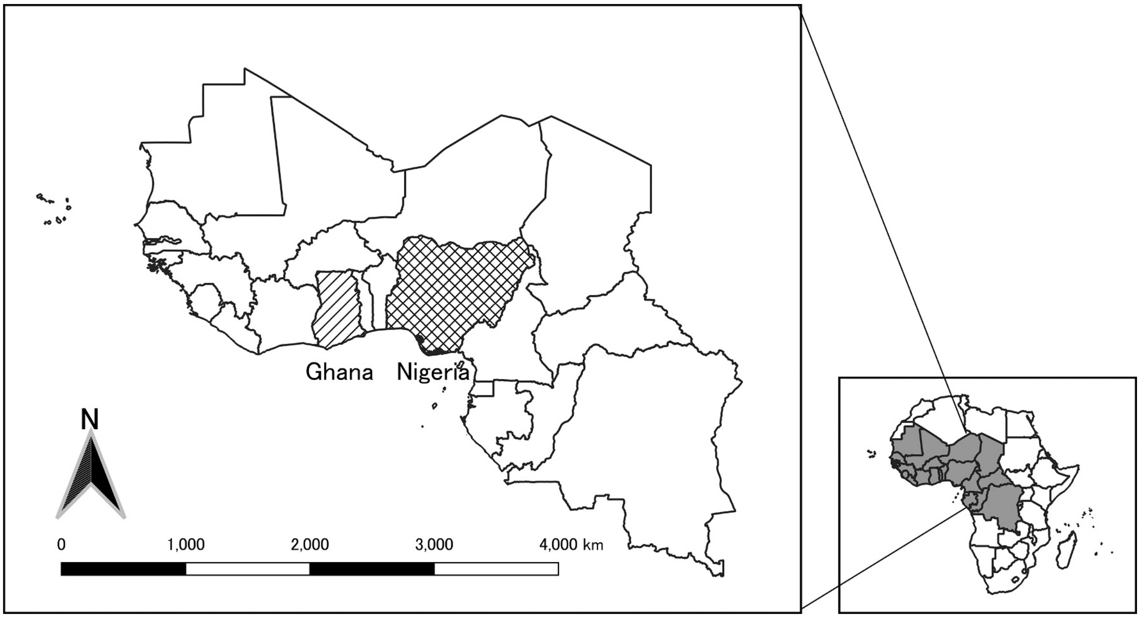

Fig. 1. Locations of Ghana and Nigeria.

approach of IDA (Ang, 2015) to decompose several types of energy-related air pollutant emissions from the residential sector in Ghana and Nigeria. This study focuses on $PM_{2.5}$, NO_X, and NMVOC as air pollutants. The study period is from 1990 to 2018 and is informed by data availability. Source Apportionment is another way to clarify factors of pollutant emissions. However, it is a tool for providing information about source contributions (Adeyemi et al., 2021) using data with fine special and/or temporal resolutions compared with the decomposition approach. Although both techniques can be used to obtain information required for pollution abatement policy, IDA has merit to evaluate the contribution of various socioeconomic factors to time-series changes in pollutant emissions, which is appropriate to achieve the purpose of this study.

Decomposition of air-pollutant emissions

To understand the factors that affect energy-related air pollutant emissions from the residential sector in Ghana and Nigeria, we first decomposed the emissions by four variables (final energy demand by energy source, total final energy demand, population, and the number of households) as shown in Eq. (1). These variables were selected based on Shigetomi et al. (2018) who evaluated the driving forces of CO_2 emissions in the residential sector in Japan. Higher energy demand generally contributes to higher pollutant emissions. Different energy types have different emission intensities, which affect pollutant emissions differently. Also, it is expected that increases in population and the number of households that use energy contribute to increases in pollutant emissions.

$$\begin{aligned} TPE &= \sum_i PE_i = \sum_i \frac{PE_i}{E_i} \times \frac{E_i}{TE} \times \frac{TE}{P} \times \frac{P}{H} \times H \\ &= \sum_i PEI_i \times ET_i \times EI \times HS \times H, \end{aligned} \tag{1}$$

where TPE is total pollutant emissions ($PM_{2.5}$, NO_X, or NMVOC) from the residential sector of each country (kt), PE_i is pollutant emissions by energy source i (biomass, fossil fuels, and electricity: kt), E_i is household final energy demand of energy source i (TJ), TE is total final energy demand of the residential sector (TJ), P is the number of population, H is the number of households, PEI_i ($= PE_i / E_i$) is the emission intensity, ET_i ($= E_i / TE$) is the share of energy source i in total energy demand, EI ($= TE / P$) is energy intensity, and HS ($= P / H$) is the household size (or the number of people in each household).

Based on Eq. (1), we decomposed changes in air pollutants from the residential sector into five different factors: emission intensity (emission intensity effect), the share of each energy source (energy type effect), energy intensity (energy intensity effect), household size (household size effect), and the number of households (household effect). We identified each effect by the following equations (Eqs. (2)–(7)), which are the multiplicative form of the LMDI approach (Ang, 2015; Shigetomi et al., 2018).

Total effect:

$$D^{Total}_{(t)} = \frac{TPE_{(t)}}{TPE_{(0)}} = D^{PEI}_{(t)} \times D^{ET}_{(t)} \times D^{EI}_{(t)} \times D^{HS}_{(t)} \times D^{H}_{(t)}, \tag{2}$$

Emission intensity effect:

$$D^{PEI}_{(t)} = exp\left(\sum_i \frac{\left(PE_{i,(t)} - PE_{i,(0)}\right)/\left(lnPE_{i,(t)} - lnPE_{i,(0)}\right)}{\left(TPE_{(t)} - TPE_{(0)}\right)/\left(lnTPE_{(t)} - lnTPE_{(0)}\right)} ln\left(\frac{PEI_{i,(t)}}{PEI_{i,(0)}}\right)\right), \tag{3}$$

Energy type effect:

$$D^{ET}_{(t)} = exp\left(\sum_i \frac{\left(PE_{i,(t)} - PE_{i,(0)}\right)/\left(lnPE_{i,(t)} - lnPE_{i,(0)}\right)}{\left(TPE_{(t)} - TPE_{(0)}\right)/\left(lnTPE_{(t)} - lnTPE_{(0)}\right)} ln\left(\frac{ET_{i,(t)}}{ET_{i,(0)}}\right)\right), \tag{4}$$

Energy intensity effect:

$$D^{EI}_{(t)} = exp\left(\sum_i \frac{\left(PE_{i,(t)} - PE_{i,(0)}\right)/\left(lnPE_{i,(t)} - lnPE_{i,(0)}\right)}{\left(TPE_{(t)} - TPE_{(0)}\right)/\left(lnTPE_{(t)} - lnTPE_{(0)}\right)} ln\left(\frac{EI_{(t)}}{EI_{(0)}}\right)\right), \tag{5}$$

Household size effect:

$$D^{HS}_{(t)} = exp\left(\sum_i \frac{\left(PE_{i,(t)} - PE_{i,(0)}\right)/\left(lnPE_{i,(t)} - lnPE_{i,(0)}\right)}{\left(TPE_{(t)} - TPE_{(0)}\right)/\left(lnTPE_{(t)} - lnTPE_{(0)}\right)} ln\left(\frac{HS_{(t)}}{HS_{(0)}}\right)\right), \tag{6}$$

Household effect:

$$D^{H}_{(t)} = exp\left(\sum_i \frac{\left(PE_{i,(t)} - PE_{i,(0)}\right)/\left(lnPE_{i,(t)} - lnPE_{i,(0)}\right)}{\left(TPE_{(t)} - TPE_{(0)}\right)/\left(lnTPE_{(t)} - lnTPE_{(0)}\right)} ln\left(\frac{H_{(t)}}{H_{(0)}}\right)\right), \tag{7}$$

where subscripts (t) and (0) indicate the target year and base year, respectively. In this study, the base year is 1990, and t takes years from 1990 to 2018.

These equations are applied to the emissions of each air pollutant in each country.

Data

We collected data for variables shown in Eq. (1) from global/international databases.

Air pollutant emissions were taken from the Emissions Database for Global Atmospheric Research (EDGAR) of the European Commission.[2] Using a consistent estimation way, the EDGAR provides emissions by sector and energy source (only biomass and fossil fuel) for all countries in the world,[3] and we gathered emissions from the residential and other sectors of both energy sources.[4] Although we primarily focus on the residential sector, the choice of sector classification is due to the data limitation.

Final energy demand by source and the total were taken from the World Energy Balances of the International Energy Agency (IEA) (International Energy Agency, 2020). Because the EDGAR only classifies the emission sources into biomass and fossil fuel, as mentioned above, we also aggregated the energy types of the IEA into biomass, fossil fuels, and electricity. It is worth noting that because air pollutants are not emitted from electricity use, $PE_{electricity}$ is considered zero for all years for both countries.[5] Although this database has an independent residential sector, we also added final energy demand of the commercial sector to be consistent with the data for the emissions. In Ghana and Nigeria, final energy demand of the residential sector is much larger than the commercial sector. As a result, the decomposition results are not affected even if we only use the final energy demand of the residential sector. It is also expected that pollutant emissions from the residential sector will be much larger than those from the commercial sector in the two countries.

Population data was taken from World Bank (2022), and the number of households was taken from the database provided by the Helgi Library.[6]

Table 1 presents the descriptive statistics of pollutant emissions and their factors.

Fig. 2 shows the trends of the variables used for our decomposition analysis by normalizing the 1990 level as one. The total $PM_{2.5}$ emissions showed a decreasing trend in Ghana and an increasing trend in Nigeria (see the Results section for details). In both Ghana and Nigeria, the population and the number of households increased, but the growth rate of the number of households is higher. Although electricity consumption largely increased in both countries, higher growth is observed in Ghana than in Nigeria. In Ghana, final energy demand from biomass decreased, while that from fossil fuels (and electricity) increased. By contrast, in Nigeria, final energy demand from biomass increased, while that from fossil fuels decreased. This suggests that Ghana successfully replaced high-polluting energy with low-polluting energy, while that did not happen in Nigeria.

Results

Figs. 3–5 show the results of decomposition analysis for $PM_{2.5}$, NO_X, and NMVOC in Ghana and Nigeria. In Ghana, pollutant emissions increased until 1999 compared to the 1990 level, but the emissions decreased since then. In 2018, the emissions had fallen to 44–72% of the 1990 levels. By contrast, in Nigeria, pollutant emissions continuously increased since 1990 and reached 180–199% of the 1990 levels in 2018.

Because the qualitative trends of time-series pollutant emissions are similar by pollutant in each country, we hereafter focus on $PM_{2.5}$ emissions to describe the results of the decomposition analysis. In both countries, the household effect is the main effect of increasing pollutant emissions: 236% in Ghana and 261% in Nigeria in 2018 compared to the 1990 levels. These results suggest that $PM_{2.5}$ emissions have increased with increases in the number of households.

The household size effect, which showed a constant reduction, is a factor in decreasing emissions: 85% in Ghana and 79% in Nigeria in 2018 from the 1990 levels.

The emission intensity, energy type, and energy intensity effects showed different trends in these two countries. In Ghana, these three factors, especially the emission intensity and energy intensity effects, are essential decreasing factors. In contrast, they are stable (a slight decrease or increase was observed) in Nigeria. In Ghana, the emission intensity and energy intensity factors were fairly constant until 1999 but started to decrease since then and reached 54% and 61% of the 1990 level in 2018, respectively. Similarly, the energy type factor was constant until around 2000 but decreased since then, reaching 74% in 2018. These results suggest that Ghana experienced a shift in energy sources from more air-polluting (i.e., biomass energy) to less air-polluting (i.e., fossil fuels and electricity) and successfully reduced the emission intensity, whereas such a shift did not happen in Nigeria.

In Ghana, although the household factor worked to increase $PM_{2.5}$ emissions, other factors contributed to emission reduction and successfully realized the reduction. By contrast, in Nigeria, compared to Ghana, the emission intensity, energy type, and energy intensity factors were not enough to realize a decrease in $PM_{2.5}$ emissions.

Discussion

This section discusses the findings from the decomposition analysis of energy-related pollutants for Ghana and Nigeria. In both countries, the household effect, which measures the number of households, was the primary source of increasing pollutant emissions in line with Shigetomi et al. (2018) and Yuan et al. (2019). The household population, and the general population in Ghana and Nigeria, has increased over the period. The population growth also implied an increased number of households which consequently led to increased emissions and agrees with the literature on the effect of population on emissions (Opoku & Boachie, 2020). Increased population implies increased levels of human activities that contribute to emissions. The growth in population also implies an increased demand for energy and, consequently, increased energy consumption which has also been found to increase emissions (Adams et al., 2020). By contrast, the household size effect was responsible for decreasing pollutant emissions and moved in the same direction for both countries, which is consistent with Olaniyan et al. (2018). For each household, the total level of pollution-related activities is expected to decline due to fewer persons in the household leading to lower emissions overall. This holds valid despite recent literature suggesting that increasing household sizes tend to reduce emissions 'per capita' due to the sharing of common resources (Ivanova & Büchs, 2022; Zhang et al., 2023).

The point of departure between Ghana and Nigeria with respect to the decomposition of pollutant emissions, however, is that pollutant emissions increased in Ghana from 1990 till 1999, whereafter emissions took on a downward trend till 2018, where it reached around 50% of the 1990 emission levels. In contrast, an increasing trend is observed in

---

[2] https://edgar.jrc.ec.europa.eu/emissions_data_and_maps

[3] Further descriptions of the estimation methodology can be found here (https://edgar.jrc.ec.europa.eu/methodology).

[4] The other sector includes the commercial sector.

[5] This study only considers direct emissions. Furthermore, according to the EDGAR, $PM_{2.5}$ emissions from electricity and heat production are much smaller than those from the residential sector (e.g., less than 0.02 % in 2018 in both countries), meaning that the emissions from electricity are negligible even if we consider indirect emissions.

[6] https://www.helgilibrary.com/

Table 1
Descriptive statistics of variables used for the decomposition analysis.

		Unit	Average	Standard Deviation	Maximum	Minimum	Data sources
Ghana	PM$_{2.5}$ emissions (total)	kt	27.38	10.98	46.16	16.60	EDGAR[a]
	PM$_{2.5}$ emissions (fossil fuels)	kt	0.05	0.01	0.07	0.02	EDGAR[a]
	PM$_{2.5}$ emissions (biomass)	kt	27.33	10.99	46.11	16.55	EDGAR[a]
	NO$_X$ emissions (total)	kt	4.80	1.36	7.47	3.33	EDGAR[a]
	NO$_X$ emissions (fossil fuels)	kt	0.85	0.28	1.31	0.39	EDGAR[a]
	NO$_X$ emissions (biomass)	kt	3.95	1.53	6.59	2.36	EDGAR[a]
	NMVOC emissions (total)	kt	56.39	23.95	93.41	33.31	EDGAR[a]
	NMVOC emissions (fossil fuels)	kt	0.18	0.06	0.28	0.09	EDGAR[a]
	NMVOC emissions (biomass)	kt	56.21	23.99	93.22	33.10	EDGAR[a]
	Energy (total)	TJ	126,551.90	20,485.65	164,745	98,006	International Energy Agency (2020)
	Energy (fossil fuels)	TJ	8,347.03	3,310.35	16,249	3,937	International Energy Agency (2020)
	Energy (biomass)	TJ	106,312.17	22,130.90	149,434	78,463	International Energy Agency (2020)
	Energy (electricity)	TJ	11,892.69	8,039.23	32,808	3,258	International Energy Agency (2020)
	Population	People	21,698,976.55	4,562,189.19	29,767,108	14,773,274	World Bank (2022)
	Household	Household	4,600,181.98	1,273,529.37	6,910,462	2,925,739	Helgi Library[b]
Nigeria	PM$_{2.5}$ emissions (total)	kt	1,071.85	233.16	1,478.14	743.27	EDGAR[a]
	PM$_{2.5}$ emissions (fossil fuels)	kt	0.16	0.06	0.27	0.07	EDGAR[a]
	PM$_{2.5}$ emissions (biomass)	kt	1,071.69	233.21	1,478.02	743.05	EDGAR[a]
	NO$_X$ emissions (total)	kt	157.08	32.89	215.26	110.67	EDGAR[a]
	NO$_X$ emissions (fossil fuels)	kt	3.01	1.22	5.16	1.31	EDGAR[a]
	NO$_X$ emissions (biomass)	kt	154.08	33.87	212.95	106.53	EDGAR[a]
	NMVOC emissions (total)	kt	2,175.13	428.04	2,954.06	1,645.54	EDGAR[a]
	NMVOC emissions (fossil fuels)	kt	0.64	0.26	1.11	0.28	EDGAR[a]
	NMVOC emissions (biomass)	kt	2,174.48	428.25	2,953.57	1,644.66	EDGAR[a]
	Energy (total)	TJ	3,216,427.76	719,089.24	4,563,784	2,213,159	International Energy Agency (2020)
	Energy (fossil fuels)	TJ	42,517.86	17,573.07	73,465	18,450	International Energy Agency (2020)
	Energy (biomass)	TJ	3,127,243.34	712,439.05	4,455,370	2,133,198	International Energy Agency (2020)
	Energy (electricity)	TJ	46,666.55	21,725.06	81,474	21,078	International Energy Agency (2020)
	Population	People	139,140,594.31	30,530,249.86	195,874,740	95,212,450	World Bank (2022)
	Household	Household	27,367,647.14	7,616,308.17	40,883,667	15,665,734	Helgi Library[b]

Note: a: https://edgar.jrc.ec.europa.eu/emissions_data_and_maps; b: https://www.helgilibrary.com/; c: We referred to Shigetomi et al. (2018) to determine the driving factors.

Nigeria from 1990 through 2018, reaching nearly double the 1990 levels. The three major factors contributing to this are the emission intensity effect, the energy type effect, and the energy intensity effect. In Ghana, the emission intensity and energy intensity effects began to decline after 1999, while the decline in the energy type effect was steeper after 1999 compared to the period prior to 1999 whereas in Nigeria, these three factors were fairly constant over the period. The implication is that a significant shift away from heavy polluting energy sources, such as biomass, in favor of less polluting energy sources was observed in Ghana, leading to lower emission intensity after 1999, whereas the same was not the case for Nigeria. The drop in emission intensity in Ghana around 1999–2000 could be linked to several factors. The government of Ghana embarked upon various policies to reduce reliance on biomass fuel and increase the liquified petroleum gas (LPG) penetration rate across the country. The Government of Ghana put an LPG promotion program in place in 1990 with numerous components implemented over time. One component of the LPG promotion program was the free distribution of LPG cylinders to households and food catering providers in urban areas in Ghana (Ahunu, 2015). Another component was the institution of the Unified Petroleum Price Fund program to incentivize transporters to make deliveries to rural and underserved areas while the Ministry of Energy took steps to improve the retail of LPG.[7] The government also introduced a subsidy on the price of gas to make it affordable in the early years of introducing LPG.[8] The government then established the Ghana Cylinder Manufacturing Company (GCMC) in 1998 to manufacture and supply LPG cylinders at affordable prices to consumers (Adjei-Mantey & Takeuchi, 2022). With the establishment of the GCMC in 1998, the supply of LPG cylinders on the local market increased soon afterwards. All of these actions possibly culminated in the significant shift in residential energy to less polluting sources after 1999. As a result of these interventions, annual LPG consumption in Ghana grew from 6 kt in 1990 to 42 kt in 2000, while annual LPG consumption in Nigeria, which stood at 44 kt in 1990, dropped to 17 kt in 2000 (International Energy Agency, 2020). This could be partly accountable for the non-decreasing energy type and emission intensity effects observed in Nigeria. It is worth noting that Nigeria's household cooking fuel subsidy has historically applied to kerosene (Adeoti et al., 2016; Zinecker et al., 2020), which is a relatively highly polluting fuel compared to LPG. Access to electricity is another potential cause for the observed energy type and emission intensity effects in the two countries. Access to electricity (% of population) stood at 37% for Nigeria and 30.6% for Ghana in 1993 (World Bank, 2022). By the year 2000, the access rates had increased to 43.1% for Nigeria and 43.7% for Ghana, and by the year 2018, the access rates were 56.5% for Nigeria and 80.4% for Ghana (World Bank, 2022). Two key implications are drawn from these statistics. First, the growth in access to electricity was steeper in Ghana between 2000 and 2018, while it was slower in Nigeria over the same period. Secondly, because Nigeria's population is more than Ghana's population (currently more than six times), any proportion of the population without access to electricity invariably translates into a larger number of people, in absolute terms, who are without access to electricity. These imply that in Nigeria, larger numbers of people are more likely to resort to high-polluting alternatives in the absence of electricity for residential use, whereas, in Ghana, a smaller number of people may have had to resort to such alternatives over the period for which reason the energy type and emission intensity effects were observed to be declining for Ghana without same being observed in Nigeria. Ghana's higher electricity access growth rate over the period could be linked to policies by the government to accelerate electrification across the country. The Government of Ghana, as part of its National Electrification Scheme, instituted the Self-Help Electrification Program (SHEP) in 1989, which over time, has accelerated rural electrification greatly. Under this program, rural communities are organized to provide for themselves with some logistics needed to connect their communities

---

[7] http://energycom.gov.gh/files/SE4ALL-GHANA%20ACTION%20PLAN.pdf

[8] The subsidy has since been removed for fiscal stability reasons.

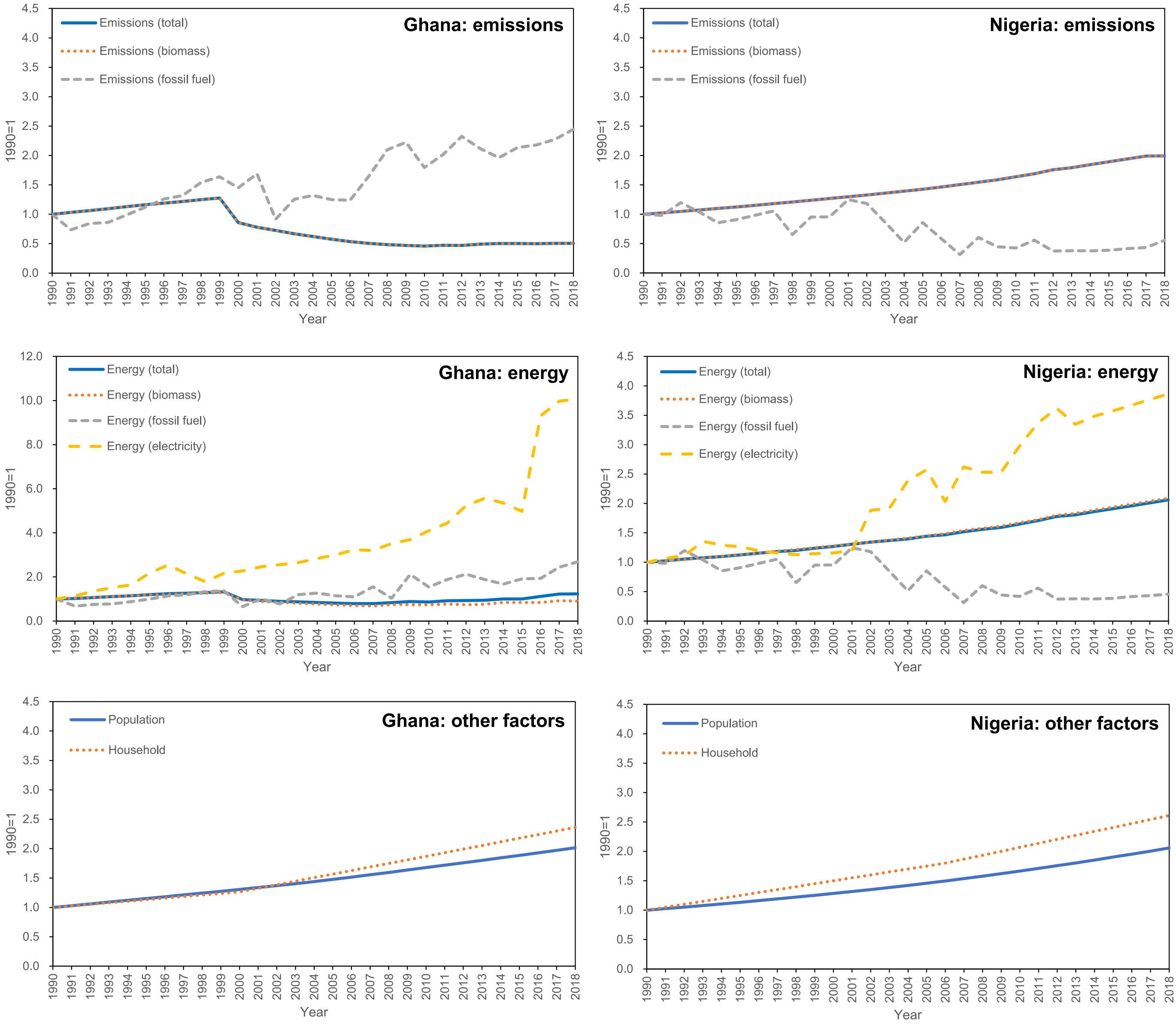

Fig. 2. Trends of variables used for the decomposition analysis (1990 = 1). Emissions here are for $PM_{2.5}$, but other pollutant emissions show similar trends.

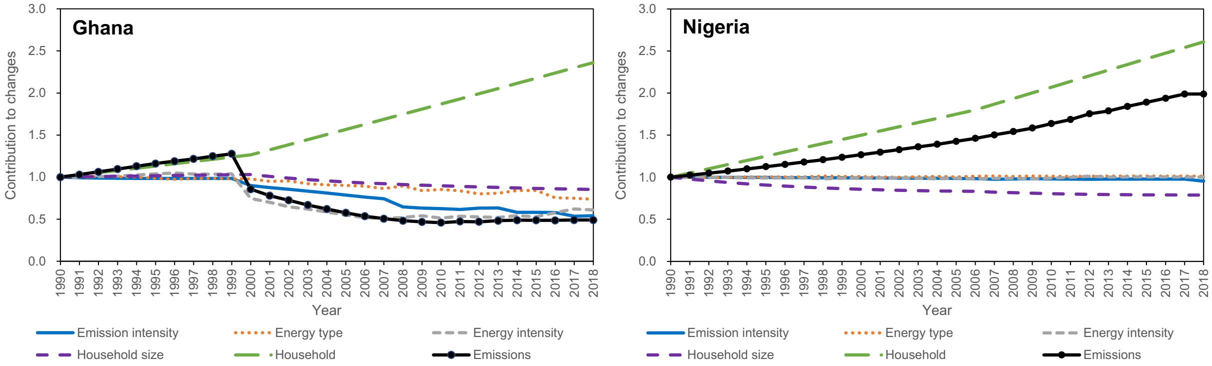

Fig. 3. $PM_{2.5}$ emissions and the driving factors of the emissions. The data for this figure is presented in the Supplementary Material.

to the national grid. Such communities were expected to provide low-voltage electricity poles as well as electricity meters and have at least a third of households in the communities wired (Kemausuor & Ackom, 2017). Through this 'self-help' initiative, many rural communities got electrified earlier than they ordinarily would, had they waited for the government to extend electricity to their communities based on the

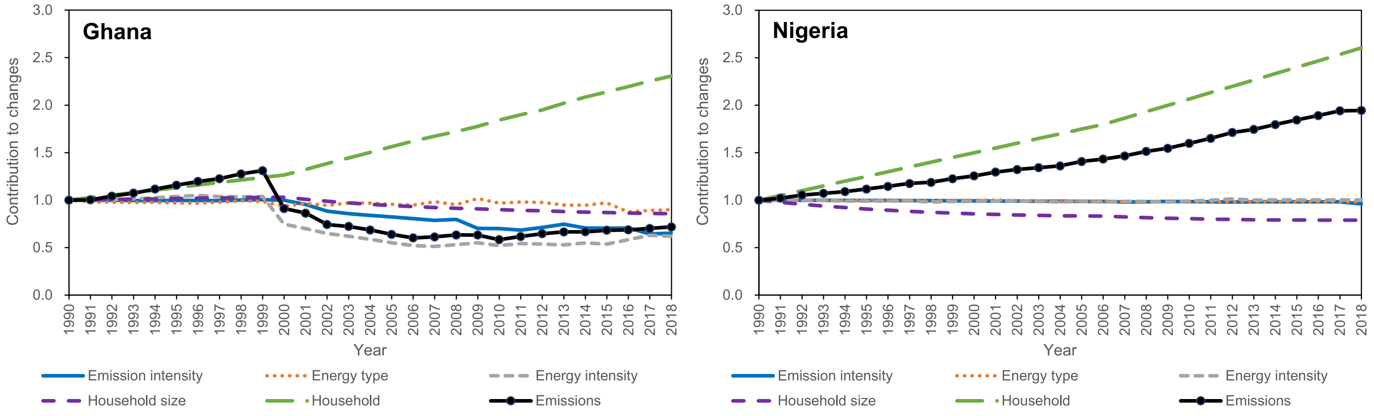

Fig. 4. NO_X emissions and the driving factors of the emissions. The data for this figure is presented in the Supplementary Material.

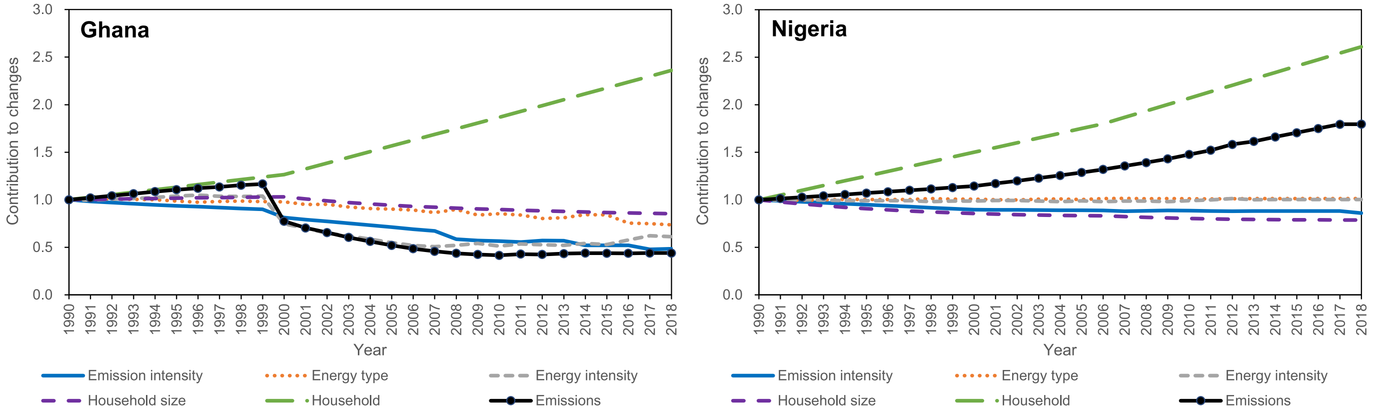

Fig. 5. NMVOC emissions and the driving factors of the emissions. The data for this figure is presented in the Supplementary Material.

government's own schedule. Consequently, rural electrification rates improved significantly, contributing to a high electrification rate in Ghana. The SHEP increased the electricity access rate for the entire population from less than 35% around the time of its inception to 76% by 2015 (Asumadu-Sarkodie & Owusu, 2016). Another program that accelerated the electricity access rate was the Ghana Energy Development and Access Project, which started in 2007 and aimed to improve electricity distribution efficiency and, subsequently, electricity penetration rate (Kumi, 2017). These programs have been crucial in accelerating the population's access to electricity in Ghana, contributing to decreasing pollutant emissions through the energy type and emission intensity effects in Ghana. In addition to the emission intensity and energy type effects, the energy intensity effect would also be affected by this energy transition: from low-efficient biomass to high-efficient electricity in Ghana. In Ghana, the share of biomass energy decreased from 92.5% in 1990 to 68.0% in 2018, while that of electricity increased from 2.6% to 21.4% in the same period in the residential sector (International Energy Agency, 2020). By contrast, such trends did not happen in Nigeria (96.4% to 97.6% for biomass and 1.0% to 1.8% for electricity; International Energy Agency, 2020). This indicates that increasing the share of electricity, which is more efficient energy than biomass, contributed to a reduction in pollutant emissions through the reducing energy intensity effect observed in Ghana, while the same was not observed in the case of Nigeria. Such a different trend in the results can be seen in the literature. Energy intensity leading to declining emissions confirms the findings of O'Mahony et al. (2012) and Danish and Khan (2020) but contrasts those of Shahbaz et al. (2015), who found energy intensity to increase emissions.

A plethora of empirical research has found that socioeconomic factors especially income and higher education are crucial determining influences for the adoption and uptake of LPG or other cleaner cooking fuel over biomass fuel (Adjei-Mantey et al., 2021; Choumert-Nkolo et al., 2019; Muller & Yan, 2018). Therefore, we compare the two countries on the basis of poverty and higher education to explain the likely higher preference for heavy-polluting fuel in Nigeria compared to Ghana. Gross domestic product (GDP) growth rates recorded over the last two decades (from 1999, when the divergence in trends started, to 2018, the last year of our dataset) were generally higher for Ghana than for Nigeria. While Ghana recorded a GDP growth of 4.4% at the start of the last two decades in 1999, reaching an all-time high of 14% in 2011 and ending the last decade at 6.2%, Nigeria began the last two decades with a growth rate of 0.6%, reaching an all-time high of 15.3% in 2002 and ended the last decade at 1.9% in 2018 having recorded a negative growth of 1.6% in 2016 (World Bank, 2022). In addition, the latest statistics show that poverty headcount ratios in Nigeria are higher than in Ghana. In other words, the proportion of the population who live below the respective national poverty lines is higher in Nigeria (30.9% in 2018) compared to Ghana (25.3% in 2016) (World Bank, 2022). Furthermore, gross tertiary enrollment rates in Nigeria are lower (12% in 2018) than in Ghana (19% in 2020) per the most recent data available (World Bank, 2022). Thus, going by these statistics and the literature on cleaner household fuel adoption, there is a higher chance that residents in Ghana are more likely to opt for cleaner fuel compared to those in Nigeria due to more favorable socioeconomic outcomes, and this could partly account for the observed divergent trends in the emission intensity, energy intensity, and energy type effects.

In summary, this study observed that while the household effect increased in both Ghana and Nigeria and the household size effect reduced for both countries, the emission intensity, energy type, and energy intensity effects did not move in the same direction for the two countries. Whereas Ghana has trended downwards, Nigeria has remained constant over time. This suggests Ghana's increasing shift to low-polluting energy sources and a consequent reduction in emission and energy intensity compared to Nigeria, which led to overall air pollutant emissions reducing over time in Ghana without the same being observed in Nigeria. Mostly, government-led policies in the area of cleaner cooking fuels and access to electricity have been noted as being the likely causes of the declining trends in Ghana.

Conclusion

Air pollution at the residential level is a key concern for many developing countries where there is considerable reliance on heavy polluting fuels by households. Exposure to air pollutants, such as $PM_{2.5}$, is receiving increased attention due to the adverse health effects suffered by households. Ghana and Nigeria, two of West Africa's largest economies, are both faced with high proportions of households that rely on these heavily polluting fuels as primary energy sources. This has prompted the need for further investigations to reveal new insights to guide policy. To this end, this study examined five socioeconomic drivers for three energy-related air pollutants (i.e., $PM_{2.5}$, NO_X, and NMVOC) from the residential sector in Ghana and Nigeria from 1990 to 2018 using IDA. In addition, we compared the similarities and differences in the driving factors of the two countries that showed different emission trends. First, we identified factors contributing to increasing/decreasing emissions in the two countries. In particular, the household effect was an increasing factor, and the household size effect was a decreasing factor for both countries. In contrast, the emission intensity, energy type, and energy intensity factors affected pollutant emissions differently for the two countries. In Ghana, these three effects showed declining trends, while they are stable in Nigeria, mainly due to the differences in the policies implemented in the two countries. These findings suggest that energy-related policy has a considerable impact on the trends of air pollutant emissions. To further reduce emissions or change the trends of emissions to decline, it is recommended that both countries, especially Nigeria, improve emission intensity, energy intensity, and the sources of energy used. These can be achieved mainly by substituting low-polluting fuels for high-polluting ones. The Nigerian government's recent attempt to scrap kerosene subsidies is a good policy to dissuade the patronage of kerosene. However, for the benefits to be better realized, it is recommended that the subsidies be re-directed at LPG consumption instead, which is a lower-polluting energy source, particularly for rural and deprived areas. Beyond direct price subsidies for LPG, other interventions for consideration are improving the LPG supply infrastructure in these underserved areas to promote high uptake by rural communities. Further, more action is needed to extend electrification to the large population in Nigeria without access to electricity to discourage the use of dirtier alternatives in the absence of electricity. This would reverse the upward trend of pollutant emissions in Nigeria. Meanwhile, it is recommended that Ghana sustained its current electrification policies to achieve a 100% electrification or universal access within the shortest possible time while exploring other means of increasing LPG penetration since it currently lags behind its target of 50% penetration rate by the end of year 2020. This would be crucial to maintaining the decreasing trends in pollutant emissions observed in the country. For both countries, it is recommended to increase investments in renewable electricity, make it affordable for households, and push through energy transition from biomass and fossil fuels, especially as renewable resources exist in abundance in Ghana and Nigeria. This will go a long way to reducing air pollutants from the residential sector.

This study contributed to the literature by finding the driving factors of changes in air pollutant emissions in African countries at the national level, yet there are a few limitations with respect to the data. First, the data only classified emission sources into two types (biomass and fossil fuel). However, the degree of emission intensity is obviously different by energy types within each category. Further disaggregation of emission sources is useful to precisely analyze the impact of transition of energy sources. Second, only national-level data exist for the two countries but not the sub-national-level data. Sub-national-level analysis might be useful in providing further insights for example, by allowing for evaluating the differences in energy transition and socioeconomic dynamics in urban and rural areas.

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.

Acknowledgments

This study was supported by JSPS KAKENHI (grant numbers JP21KK0187, JP21H03673, and JP22H03817) and Sumitomo Foundation (FY2020 Environmental Research Project). We thank Ms. Narumi Kira, Nagasaki University, for her help in gathering the literature.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2023.101288.

References

Adams, S., Adedoyin, F., Olaniran, E., & Bekun, F. V. (2020). Energy consumption, economic policy uncertainty and carbon emissions; causality evidence from resource rich economies. *Economic Analysis and Policy, 68*, 179–190.

Adeoti, J. O., Chete, L., Beaton, C., & Clarke, K. (2016). Compensation mechanisms for fuel subsidy removal in Nigeria. In *Global Subsidies Initiative Report 2016*.

Adeyemi, A., Molnar, P., Boman, J., & Wichmann, J. (2021). Source apportionment of fine atmospheric particles using positive matrix factorization in Pretoria. *South Africa. Environmental Monitoring and Assessment, 193*, 716.

Adjei-Mantey, K., & Takeuchi, K. (2021). The effect of in utero exposure to household air pollution on child health: evidence from Ghana. *Health Policy OPEN, 2*, Article 100029.

Adjei-Mantey, K., & Takeuchi, K. (2022). Estimating the spill-over impacts of a clean cooking fuel program: evidence from Ghana. *Energy Nexus, 8*, Article 100151.

Adjei-Mantey, K., Takeuchi, K., & Quartey, P. (2021). Impact of LPG promotion program in Ghana: the role of distance to refill. *Energ Policy, 158*, Article 112578.

Agbo, K. E., Walgraeve, C., Eze, J. I., Ugwoke, P. E., Ukoha, P. O., & Van Langenhove, H. (2021). A review on ambient and indoor air pollution status in Africa. *Atmospheric Pollution Research, 12*, 243–260.

Ahunu, L. (2015). LPG promotion program. In *Africa Center for Energy Policy Working Paper 2015*.

Ali, M. U., Yu, Y., Yousaf, B., Munir, M. A. M., Ullah, S., Zheng, C., … Wong, M. H. (2021). Health impacts of indoor air pollution from household solid fuel on children and women. *Journal of Hazardous Materials, 416*, Article 126127.

Ang, B. W. (2015). LMDI decomposition approach: a guide for implementation. *Energ Policy, 86*, 233–238.

Ang, B. W., & Goh, T. (2016). Carbon intensity of electricity in ASEAN: drivers, performance and outlook. *Energy Policy, 98*, 170–179.

Asumadu-Sarkodie, S., & Owusu, P. A. (2016). A review of Ghana's energy sector national energy statistics and policy framework. *Cogent Engineering, 3*, 1155274.

Beidari, M., Lin, S.-J., & Lewis, C. (2017). Decomposition analysis of CO_2 emissions from coal - sourced electricity production in South Africa. *Aerosol and Air Quality Research, 17*, 1043–1051.

Berrill, P., Gillingham, K. T., & Hertwich, E. G. (2021). Drivers of change in US residential energy consumption and greenhouse gas emissions, 1990–2015. *Environmental Research Letters, 16*, Article 034045.

Bokpin, G. A. (2017). Foreign direct investment and environmental sustainability in Africa: the role of institutions and governance. *Research in International Business and Finance, 39*, 239–247.

Chen, S., Jin, H., & Lu, Y. (2019). Impact of urbanization on CO_2 emissions and energy consumption structure: a panel data analysis for Chinese prefecture-level cities. *Structural Change and Economic Dynamics, 49*, 107–119.

Choumert-Nkolo, J., Combes Motel, P., & Le Roux, L. (2019). Stacking up the ladder: a panel data analysis of Tanzanian household energy choices. *World Development, 115*, 222–235.

Danish, Ulucak R., & Khan, S. U. D. (2020). Relationship between energy intensity and CO_2 emissions: does economic policy matter? *Sustainable Development, 28*, 1457–1464.

Danlami, A. H. (2019). Assesment of factors influencing firewood consumption in Bauchi state, Nigeria. *Journal of Sustainability Science and Management, 14*, 99–109.

Ebohon, O. J., & Ikeme, A. J. (2006). Decomposition analysis of CO_2 emission intensity between oil-producing and non-oil-producing sub-Saharan African countries. *Energy Policy, 34*, 3599–3611.

Eleri, A. I. (2021). Expanding demand for clean-cooking in Nigeria. In *International Centre for Energy, Environment and Development Report 2021*.

Fujii, H., Okamoto, S., Kagawa, S., & Managi, S. (2017). Decomposition of toxicity emission changes on the demand and supply sides: empirical study of the US industrial sector. *Environmental Research Letters, 12*, Article 124008.

Ghana Statistical Service. (2022). *Ghana 2021 Population and Housing Census: General Report Volume 3K*. Ghana Statistical Service: Accra.

Health Effects Institute. (2022). *The State of Air Quality and Health Impacts in Africa: A Report from the State of Global Air Initiative*. Boston, MA: Health Effects Institute.

Hu, P., Zhou, Y., Gao, Y., Zhou, J., Wang, G., & Zhu, G. (2022). Decomposition analysis of industrial pollutant emissions in cities of Jiangsu based on the LMDI method. *Environmental Science and Pollution Research, 29*, 2555–2565.

Inglesi-Lotz, R., & Blignaut, J. N. (2011). South Africa's electricity consumption: a sectoral decomposition analysis. *Applied Energy, 88*, 4779–4784.

International Energy Agency. (2020). *World Energy Balances* (2020 ed.). Paris: International Energy Agency.

Ivanova, D., & Büchs, M. (2022). Implications of shrinking household sizes for meeting the 1.5 °C climate targets. *Ecological Economics, 202*, Article 107590.

Kemausuor, F., & Ackom, E. (2017). Toward universal electrification in Ghana. *Wiley Interdisciplinary Reviews: Energy and Environment, 6*, Article e225.

Kumi, E. N. (2017). The electricity situation in Ghana: challenges and opportunities. *Center for Global Development Policy Paper*, 109.

Kurata, M., Takahashi, K., & Hibiki, A. (2020). Gender differences in associations of household and ambient air pollution with child health: evidence from household and satellite-based data in Bangladesh. *World Development, 128*, Article 104779.

Kwakwa, P. A., Adjei-Mantey, K., & Adusah-Poku, F. (2022). The effect of transport services and ICTs on carbon dioxide emissions in South Africa. *Environmental Science and Pollution Research*, 10457–10468.

Kwakwa, P. A., Adusah-Poku, F., & Adjei-Mantey, K. (2021). Towards sustainable Environment: does electricity crisis matter for the effect of industrialisation and urbanisation on carbon dioxide emissions? In E. K. Adae, J. P. B. Kosiba, R. E. Hinson, K. K. Twum, N. Newman, & F. F. Nutsugah (Eds.), *Responsible Management in Emerging Markets: a Multisectoral Focus* (pp. 297–323). Cham: Palgrave Macmillan.

Li, K., & Lin, B. (2015). Impacts of urbanization and industrialization on energy consumption/CO_2 emissions: does the level of development matter? *Renewable and Sustainable Energy Reviews, 52*, 1107–1122.

Matsumoto, K., Shigetomi, Y., Shiraki, H., Ochi, Y., Ogawa, Y., & Ehara, T. (2019). Addressing key drivers of regional CO_2 emissions of the manufacturing industry in Japan. *Energy Journal, 40*, 233–258.

Meng, J., Yang, H., Yi, K., Liu, J., Guan, D., Liu, Z., … Tao, S. (2019). The Slowdown in global air-pollutant emission growth and driving factors. *One Earth, 1*, 138–148.

Minh, N. N. (2020). Foreign direct investment and carbon dioxide emissions: evidence from capital of Vietnam. *International Journal of Energy Economics and Policy, 10*, 76–83.

Muller, C., & Yan, H. (2018). Household fuel use in developing countries: review of theory and evidence. *Energy Economics, 70*, 429–439.

National Bureau of Statistics. (2020). *2019 Poverty and Inequality in Nigeria: Executive Summary*. National Bureau of Statistics: Abuja.

Okorie, D. I., & Lin, B. (2022). Emissions in agricultural-based developing economies: a case of Nigeria. *Journal of Cleaner Production, 337*, Article 130570.

Olaniyan, O., Sulaimon, M. D., & Ademola, W. (2018). Determinants of household direct CO_2 emissions: empirical evidence from Nigeria. *MPRA Paper*, 87801.

O'Mahony, T., Zhou, P., & Sweeney, J. (2012). The driving forces of change in energy-related CO_2 emissions in Ireland: a multi-sectoral decomposition from 1990 to 2007. *Energy Policy, 44*, 256–267.

Opoku, E. E. O., Adams, S., & Aluko, O. A. (2021). The foreign direct investment-environment nexus: does emission disaggregation matter? *Energy Reports, 7*, 778–787.

Opoku, E. E. O., & Boachie, M. K. (2020). The environmental impact of industrialization and foreign direct investment. *Energy Policy, 137*, Article 111178.

Pata, U. K. (2018). The effect of urbanization and industrialization on carbon emissions in Turkey: evidence from ARDL bounds testing procedure. *Environmental Science and Pollution Research, 25*, 7740–7747.

Sarkodie, S. A., & Strezov, V. (2018). Empirical study of the Environmental Kuznets curve and Environmental Sustainability curve hypothesis for Australia, China, Ghana and USA. *Journal of Cleaner Production, 201*, 98–110.

Ščasný, M., Ang, B. W., & Rečka, L. (2021). Decomposition analysis of air pollutants during the transition and post-transition periods in the Czech Republic. *Renewable and Sustainable Energy Reviews, 145*, Article 111137.

Shahbaz, M., Solarin, S. A., Sbia, R., & Bibi, S. (2015). Does energy intensity contribute to CO_2 emissions? A trivariate analysis in selected African countries. *Ecological Indicators, 50*, 215–224.

Sharif, Hossain M. (2011). Panel estimation for CO_2 emissions, energy consumption, economic growth, trade openness and urbanization of newly industrialized countries. *Energy Policy, 39*, 6991–6999.

Sharma, S. S. (2011). Determinants of carbon dioxide emissions: empirical evidence from 69 countries. *Applied Energy, 88*, 376–382.

Shen, S., & Wang, C. (2017). Decomposition analysis on the air pollutant baseline emission factors in China's power sector. *Energy Procedia, 105*, 3355–3362.

Shigetomi, Y., Matsumoto, K., Ogawa, Y., Shiraki, H., Yamamoto, Y., Ochi, Y., & Ehara, T. (2018). Driving forces underlying sub-national carbon dioxide emissions within the household sector and implications for the Paris Agreement targets in Japan. *Applied Energy, 228*, 2321–2332.

Shimamoto, K. (2017). Decomposition analysis of the pollution intensities in the case of the United Kingdom. *Cogent Economics & Finance, 5*, 1316553.

Sun, Y., Hao, Q., Cui, C., Shan, Y., Zhao, W., Wang, D., … Guan, D. (2022). Emission accounting and drivers in East African countries. *Applied Energy, 312*, 118805.

Upadhyay, A. K., Singh, A., Kumar, K., & Singh, A. (2015). Impact of indoor air pollution from the use of solid fuels on the incidence of life threatening respiratory illnesses in children in India. *BMC Public Health, 15*, 300.

Ustyuzhanina, P. (2022). Decomposition of air pollution emissions from Swedish manufacturing. *Environmental Economics and Policy Studies, 24*, 195–223.

Wang, Y., Bechle, M. J., Kim, S.-Y., Adams, P. J., Pandis, S. N., Pope, C. A., … &Marshall, J. D. (2020). Spatial decomposition analysis of NO_2 and $PM_{2.5}$ air pollution in the United States. *Atmospheric Environment, 241*, 117470.

Wei, W., Mushtaq, Z., Sharif, M., Zeng, X., Wan-Li, Z., & Qaisrani, M. A. (2020). Evaluating the coal rebound effect in energy intensive industries of China. *Energy, 207*, Article 118247.

Weinzettel, J., & Kovanda, J. (2011). Structural decomposition analysis of raw material consumption. *Journal of Industrial Ecology, 15*, 893–907.

World Bank, 2022. World Development Indicators. https://databank.worldbank.org/source/world-development-indicators (accessed: December 22, 2022).

Xu, S., Zhang, W., Li, Q., Zhao, B., Wang, S., & Long, R. (2017). Decomposition analysis of the factors that influence energy related air pollutant emission changes in China using the SDA method. *Sustainability, 9*, 1742.

Xu, X. Y., & Ang, B. W. (2013). Index decomposition analysis applied to CO_2 emission studies. *Ecological Economics, 93*, 313–329.

Yang, J., Miao, Y., Li, Y., Li, Y., Ma, X., Xu, S., & Wang, S. (2019). Decomposition analysis of factors that drive the changes of major air pollutant emissions in China at a multi-regional level. *Sustainability, 11*, 7113.

Yuan, R., Rodrigues, J. F. D., & Behrens, P. (2019). Driving forces of household carbon emissions in China: a spatial decomposition analysis. *Journal of Cleaner Production, 233*, 932–945.

Zakaria, M., & Bibi, S. (2019). Financial development and environment in South Asia: the role of institutional quality. *Environmental Science and Pollution Research, 26*, 7926–7937.

Zhang, Y., Wang, F., & Zhang, B. (2023). The impacts of household structure transitions on household carbon emissions in China. *Ecological Economics, 206*.

Zhao, C., & Chen, B. (2014). Driving force analysis of the agricultural water footprint in China based on the LMDI method. *Environmental Science and Technology, 48*, 12723–12731.

Zinecker, A., Ibezim-Ohaeri, V., Adeyinka, T., Merrill, L., & Beaton, C. (2020). Gender and fossil fuel subsidy reform in Nigeria: findings and recommendations. *Global Subsidies Initiative Report, 2020*.