A framework for assessing air pollutant emissions and impacts in Sub-Saharan Africa and options for mitigation: Case studies for Cote d’Ivoire, Ghana and Nigeria

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Abstract

Air pollution is globally the largest environmental risk to human health. In Sub-Saharan Africa, there is a lack of quantitative data on current air pollution levels, the major sources which contributes to this and the most effective measures to mitigate the problem.

This thesis aim to develop and apply a framework for assessing air pollution impacts and mitigation strategies that is specifically designed to be applicable in Sub-Saharan African countries. The framework comprises first developing an integrated emission inventory of greenhouse gases, short-lived climate pollutants and air pollutants for a historical year using methodologies that are appropriate for the level of data available for countries in Sub-Saharan Africa and which account for specific sources that are particular to this context. The second part of this framework is the development of future projections for business as usual development and from the implementation of specific mitigation measures in key source sectors. Finally, the benefits of implementing these mitigation strategies are assessed in terms of the impacts on human health and global climate change to assess the overall effect of changes in emissions of GHGs, SCLPs and air pollutants on the impacts that provide the motivation for mitigation.

This framework was applied in Cote d'Ivoire, Ghana and Nigeria to assess emissions, emission reduction potential of mitigation measures and impacts between 2010 and 2050. The major sources of key pollutants in these countries vary but generally include residential, transport agriculture and waste sectors. For the first time in a comprehensive national inventory, emissions from illegal oil refining, backup generator use, 2-stroke motorcycles, simple kerosene wick lamps and unpaved road dust were included. While emission reductions from these sources would contribute to improving air quality in these countries, the largest emission reductions were from ambitious mitigation strategies implemented in the residential, transport and power generation.

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"Always remember people who have helped you along the way, and don't forget to lift someone up."

— Roy T. Bennett, The Light in the Heart

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Declaration

I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

Chapter 1

Introduction

There are increasing concerns about the deteriorating state of the atmospheric environment over the African continent (UNEP, 2014; USEPA, 2015; Assamoi and Liousse, 2010). Existing literature on air pollution indicate that pollution levels are substantially beyond current health-based air quality guideline limits that were set by the World Health Organisation (WHO, 2006), See Table 1.1. Given exceedance of these limits, there is the high likelihood that pollution across many parts of Africa will be affecting human health, vegetation and climate. (WHO, 2006; Knippertz et sal. 2015; Liousse et al. 2014; Zhou et al. 2014; Petkova et al. 2013; Lindén et al. 2012; Dionisio et al. 2010; Adeleke et al. 2011; Zhou et al. 2014; Pennise et al. 2009).

Table 1.1: WHO health-based air quality guideline limits for the protection of human health (WHO, 2006).

Pollutant	Limit value	Averaging time
$PM_{2.5}$	10 µg/m^3	Annual mean
	25 µg/m^3	24-hour mean
PM_{10}	20 µg/m^3	Annual mean
	50 µg/m^3	24-hour mean
Ozone (O_3)	100 µg/m^3	8-hour mean
Nitrogen oxide (NO_2)	40 µg/m^3	Annual mean
	200 µg/m^3	1-hour mean
Sulphur dioxide (SO_2)	20 µg/m^3	24-hour mean
	500 µg/m^3	10 min mean

N.B. $PM_{2.5}$ is the total mass concentration of all particles that pass through an inlet with 2.5 µm diameter with a 50% efficiency); PM_{10} is the total mass concentration that pass through an inlet with 10µm or less (Heal et al., 2012).

Currently, knowledge on air pollution in Africa is limited because data related to air quality (such as emissions and air quality monitoring data) are very few. For example, for Africa, there is a general lack of detailed anthropogenic emission inventories at both continental and regional scales (Liousse *et al.*, 2014) and very little surface air quality monitoring data compared with other global regions (Brauer et al. 2016). Where data do exist these were mostly collected as part of independent researcher projects and programmes and, in some cases, by air monitoring campaigns such as the African Monsoon Interdisciplinary Analyses (AMMA) and POLlution des Capitales Africaines (POLCA) (Mari et al. 2011; Liousse & Galy-Lacaux 2010; Petkova et al. 2013).

Of particular interest is West Africa which has been identified as one of the more polluted regions in Africa (Knippertz et al., 2015). A number of studies have been conducted in this region to explore the sources of air pollution, the resulting atmospheric concentrations of air pollutants and the impacts associated with air pollution. Most of these studies have been performed over relatively short time periods, usually for a few weeks and only in rare cases up to a year or more, for example, Efe & Efe (2008). In general, results of these studies indicate that pollution levels are high enough to cause significant impacts on human health. For example, the study by Efe & Efe (2008), which measured PM_{10} concentrations in a metropolitan area in Nigeria over six years found 24-hour mean PM_{10} levels of 126 µg/m^3 within metropolitan areas, well above the WHO standard of 50 µg/m^3.

Studies that have focussed on point source emissions support the view that PM concentrations in West Africa arise from a wide variety of emissions sources. Attempts at quantifying the emission sources of air pollutants have found agricultural practices and biomass burning to be important sources of methane (CH_4), nitrous oxide (N_2O) and carbon monoxide (CO) emissions in Nigeria, with nitrogen oxides (NO_X), non-methane volatile organic compounds (NMVOCs) and carbon dioxide (CO_2) emitted from fuel combustion sources (Laing & Obioh, 1994). Ana et al. (2012), (Olajire et al. 2011), Oguntoke et al (2012), and Efe & Efe (2008) measured PM_{10} concentrations from firewood cooking stoves, road traffic (road sides), cement factory and ambient concentrations at difference sites in a city respectively, for a period of a few days to a year depending on the study. PM_{10} concentrations obtained from these studies range from 28 - 729 µg/m^3. In addition, $PM_{2.5}$ concentrations were measured in Navrongo, a Ghanaian town, between February 2009 and February 2010 by Ofosu et al (2013) and at a cement factory in Nigeria by Oguntoke et al. (2012) for 2 months in 2008. On average, Ofosu et al. (2012) obtained a $PM_{2.5}$ concentration of 32 µg/m^3 and found high carbonaceous concentrations during the harmattan period (i.e. when dust from Sahara Desert is transported down to West Africa between November to March). When Ofusu et al analysed the $PM_{2.5}$ mass, six major $PM_{2.5}$ sources were identified, namely: two-stroke engines, soil dust, gasoline emissions, diesel emissions, biomass burning and re-suspended dust.

Importantly, some key studies indicate an underestimation of African air pollution emissions in global inventories since regional specificities (in emission source) are not included. Liousse et al. (2014) developed an emission inventory for Africa based on a bottom up approach which combined fuel consumption with emission factors which suggested an underestimate of emissions in global inventories. Fagbeja et al (2013) developed an inventory of residential emissions in the Niger Delta region of Nigeria and identified cooking using firewood and kerosene, and domestic lighting using gasoline-powered backup generators (BUGs) as the major residential sources of pollution in the Niger-Delta region of Nigeria. They also found highest emissions occurring in the urban areas of the region. Furthermore, Assamoi & Liousse (2010) highlight the importance of including black carbon (BC) and organic carbon (OC) emissions from the use of 2-stroke motorcycles, for both private and commercial use in West Africa, in inventories as they can influence regional climate through their radiative effects.

Future trends in air pollutant emissions have also not been well studied as current knowledge is mostly based on global studies. New, more regionally focussed studies are starting to emerge, such as those by Assamoi & Liousse (2010) and Liousse et al. (2014). These suggest very large increases in some key pollutants such as CO, NO_X, SO_2 and NMVOCs, in part driven by the rapid increases in population and economic growth that look set to continue to 2030. The estimated trends in these African emissions are consistent with emissions provided by global inventories, but they display a larger range of values (Liousse et al. 2014). Without the implementation of effective air quality management systems, air pollution will continue to increase in many parts of Africa with West Africa being a particular 'hot-spot' region for increasingly poor air quality.

Globally, air pollution and its various impacts which range from its effects on human health and vegetation (including crop yields) to impacts on buildings and materials have received varying levels of attention from policy makers (Murray 2013; Naiker et al. 2012; Longhurst et al. 2009). In the developed countries of Europe and North America, this attention has led to robust responses with sometimes decade-long efforts aimed at controlling and managing air quality (AQ) to protect human health (Cote et al. 2008; Fenger 1999; Longhurst et al. 2009). At the national level, the implementation of National Ambient Air Quality Standards (last reviewed in 2015) in the United States of America and the Air Quality Standards Regulations (2010) in the United Kingdom have driven substantial emission reductions from sources such as the transport sector. These have been realised through the implementation of increasingly strict vehicle emissions standards and the introduction of cleaner fuels (Bond et al. 2004). The United Nations Economic Commission for Europe's Convention on Long-range Transboundary Air pollution which began back in 1979 has shown how regional cooperation can be effective at reducing air pollution across the continent (UNECE 2016). In 2001, some countries in Asia also established air quality networks to improve air quality in the region (Clean Air Asia 2016). However, by contrast, in most countries in Africa, actions on air quality are few and weak. Those that do exist are primarily driven by intergovernmental organisations and international programmes that the countries are signatory to. Examples of such programmes are the Climate and Clean Air Coalition (CCAC; http://ccacoalition.org/en) which has a focus on reducing short-lived climate pollutants (namely ozone and black carbon) and the Renewable Energy Programme (REP, http://renewableenergy.gov.ng/) of the United Nations Framework Convention on Climate Change (UNFCCC). Government led air quality management systems at either the national or local level are non-existent in most countries except South Africa (Gulia et al. 2015), although, awareness for the need for such systems has been known for a long time (Fenger 1999). Even previous regional agreements that outlined necessary actions to reduce air pollution (such as the Abidjan Agreement, 2009 i.e. West and Central Africa Regional Framework Agreement on Air pollution) were not implemented due to lack of political will and finances (Johansson et al. 2012) . Establishment of appropriate national air quality management systems and regional programmes has to a certain extent been hampered by the limited knowledge available on the severity of air pollution and its impacts as described above. This results in an extremely limited understanding of the state of air quality in Africa and knowledge gaps in the areas of detailed emissions inventories, modelling studies and impact assessments (Johansson et al. 2012).

However, the need for action on air pollution is increasingly recognised as pollution levels in some parts of the world and associated likely impacts are becoming more apparent. The Global Burden of Disease study in 2013 (Brauer et al. 2016) ranked air pollution as the 4th highest risk factor for mortality globally with exposure to ambient air pollution accounting for estimated 2.9 million deaths (Brauer et al. 2016). Furthermore, existing air pollution studies in West Africa indicates that pollution levels are substantially above current WHO health based guidelines (WHO, 2006; Knippertz et al. 2015; Liousse et al. 2014; Zhou et al. 2014; Petkova et al. 2013; Lindén et al. 2012; Dionisio et al. 2010; Adeleke et al. 2011). Trends would therefore suggest that these adverse impacts will continue to grow in Africa as urban emissions are predicted to continue to increase (Monks et al. 2009; Mayer 1999; Liousse et al. 2014). This is particularly important as some key emission sources in West Africa were found to be high emitters and are currently omitted, or poorly accounted for, in existing global inventories (Liousse et al. 2014). Some key examples of emission sources that require more attention are the use of backup generators, 2-stroke motorcycles, and illegal refining of crude oil, among others (Lam et al. 2012a; Marais & Wiedinmyer 2016; Marais et al. 2014; Oseni 2016; Assamoi & Liousse 2010a).

African leaders have begun to show interest in managing these varied air pollution problems (UNEP 2014). However, undertaking effective actions on air pollution involves quantifying air pollutants in the atmosphere, planning and implementing emission reduction measures and assessing the effectiveness of the response (Longhurst et al. 1996; National Research Council, 2004). It is clear that in West Africa there are no reliable or comprehensive national data describing ambient air pollution concentrations. This is both an issue for researchers and policy makers in terms of assessing air pollution impacts and developing appropriate policy responses but is also a problem for the public who lack data on air quality and are therefore unable to take action or measures to try to reduce and avoid harmful levels. In view of these issues it is possible to identify a number of key questions that should be answered to improve our understanding of air quality and its impacts in West Africa:

1. Which key emission sources are currently omitted or poorly characterised in regional and global emission inventories? How important are these emission sources in determining ambient levels of air pollution? What influence will these emissions and consequent pollution levels have on human health and climate change? What are the uncertainties in emissions from these sources?
2. Given current and planned legislation, how will atmospheric emissions change in the near future (to 2030 and 2050)? Which emission source sectors will continue to play a large role in causing poor air quality? What impacts to human health and climate change are likely to accompany such changes in emissions?

3. What policy responses would most likely improve the air quality situation in West Africa?

Consequently, this research aims to quantify both current and future emissions of air pollutants in West Africa, evaluate the impacts associated to these pollutants and assess the mitigation actions required to achieve effective emission reduction that will ultimately allow the identification of policy options that can help improve air quality in the sub-region. Using three countries in West Africa as case studies, namely Nigeria, Ghana and Cote d'Ivoire, the aims of this research would be achieved with the following objectives:

1. Develop bespoke national emissions inventories of key air pollutants highlighting emissions from those sources that are currently omitted or poorly accounted for in existing regional or global emission inventories for (West) African countries.
2. Evaluate existing and planned national policies with direct or indirect influence on air quality against policies developed to achieve ambitious yet realistic emission reductions for each country.
3. Develop scenarios of likely future pollutant emissions for each country.
4. Quantify the impacts of emissions and resulting pollutant concentrations on human health and global change in temperature that arise from each country.

In this study, the impacts of air pollutant emissions that would be evaluated are the impacts on: (i) human health and (ii) change in global mean temperature. These impacts are affected by a number of air pollutants and greenhouse gases (GHGs). Table 1.2 summarises the different ways in which key pollutants prevalent in West Africa will be likely to cause impacts and also highlights which of these impact mechanisms will be explored within this study.

The most important air pollutant in terms of impact on human health is $PM_{2.5}$, defined as the total mass concentration of all particles that pass through an inlet with 2.5 µm diameter with a 50% efficiency. It may be produced through human activities such as fuel combustion or by natural processes e.g. particles from salt spray or deserts. 'Primary PM' is produced by physical and chemical processes within or shortly after being emitted from a source and includes black carbon (BC), organic carbon (OC) and 'Other PM' such as fly ash. 'Secondary PM' is formed in the atmosphere as a result of chemical and physical reactions that involve precursor gases (mainly SO_2, NO_X and NH_3). Particles larger than about 10 µm in diameter tend to settle on surfaces near the source of emission and so give rise to local nuisance. However, PM less than 10 µm in diameter (i.e. PM_{10}) can travel considerable distances because atmospheric residence times increase with a decrease in particle size. PM_{10} and especially $PM_{2.5}$ (particles less than 2.5 µm in diameter) also pose a greater threat to human health because they can penetrate more deeply into the respiratory tract. Dose-response relationships have been developed from epidemiological data and relate ambient pollutant concentrations to the risks of premature mortality (e.g. Anenberg *et al.*, 2012). The dose-response relationship used to assess human health impacts in this study are based on ambient $PM_{2.5}$ concentrations resulting from both natural and anthropogenic emissions of both primary PM and secondary PM precursors.

The impacts of air pollution on human health are mainly reduced through measures aimed at reducing emissions. However, apart from minimising the health impacts of air pollution through emission reduction, changes in human behaviours could also influence these impacts. These behaviours are approaches people use to reduce the susceptibility or risk of impacts associated with exposure to air pollution (Laumbach et al., 2015). Unfortunately, the effectiveness of these kind of personal actions is not well known due to the difficulties in assessing the effect of these actions on health impacts linked to air pollution (Laumbach et al., 2015). It is also compounded by the fact that such personal interventions or actions might even result in unintended health outcomes. Laumbach et al (2015) reviewed studies on these personal interventions, and some of them are:

- Staying indoors – Pollution occurs both indoors and outdoors. However, indoor concentrations are generally lower indoors, so, staying indoors might help reduce exposure to air pollution. If fact, some countries advise people to stay indoors on days with high air pollution (Plaia, A. and Ruggieri, M., 2011). On the other hand, indoor pollution might also pose a risk from indoor emission of air pollutants
- Cleaning of indoor air – This was found to be effective at reducing air pollutants from indoor space irrespective of the source(s) of the pollutants. However, the use of this approach might be limited owing to the cost involved, wear and tear of ventilation systems and noise generation.
- Reducing the amount of air pollutants that are inhaled reducing exertion. When we exercise, this causes us to inhale air at an increased rate. Exercising at a moderate rate was found to increase the deposition of ultrafine particles in the respiratory tract about 5 times compare to a rest position (Daiggle, CC., et 2003)
- Avoiding outdoor spaces when pollution levels are high. In some countries, there are extensive networks for monitoring air quality. These networks inform the public of

air pollution levels and people may use this information to plan or determine their movement from one place to another. Also, places that are known to have high pollution levels, for instance city centres due to traffic congestion, could be avoided especially at peak times e.g. rush hours when people are going or returning from work

- Using personal protective equipment (like respirators) – This is not a strange thing in some parts of the world. However, their effectiveness is also another consideration
- An individual's knowledge of his/her likelihood to be susceptible to air pollutants can help the individual optimise the risk and benefit of being exposed.

Further to the health impacts evaluated in this study, the impact of national emissions on global change in temperature is also considered from each of the three countries. BC has a positive climate forcing effect whereas OC, other primary PM and secondary PM all have a negative (cooling) effect on global temperature. The secondary air pollutant ozone (O_3) is a powerful positive climate forcer (as well has having potential impacts on health and crops that are not quantified in this study) and for this reason the main O_3 precursors (in addition to NO_X), CO, CH_4 and NMVOC, are also included in this study. Lastly, carbon dioxide (CO_2) does not have direct adverse impacts on human health and as a result, is not considered in this study as an air pollutant but it is required to be included in the assessment to understand the contribution of national emissions to the change in global mean temperature.

Therefore, in summary the pollutants included in this study are:

Sulphur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), ammonia (NH_3), particulate matter (PM) speciated into sizes < 2.5 µm in diameter ($PM_{2.5}$) and < 10 µm in diameter (PM_{10}) and methane (CH_4). PM comprises black carbon (BC) and organic carbon (OC) which are categorised separately as they have different radiative forcing properties (Shindell et al. 2012).

Geographically, this study focusses on three West African countries - Nigeria, Cote d'Ivoire and Ghana, these countries were selected for the following reasons:

- They are some of the most populous countries in West Africa, with population and economic growth (e.g. GDP) projected to increase substantially in coming decades.

- The sectors identified as important atmospheric emission sources in recent studies made for West Africa are important from socio-economic viewpoints in all three countries.
- They encompass the largest cities in the West African region namely Lagos, Abuja, Port Harcourt, Abidjan, Kano and Accra (ECOWAS, 2015).
- Together, they provide examples of countries at different levels of development transition to allow a comparison of the influence of policies targeting sustainable development.

Table 1.2: Summary of characteristics and impacts of key pollutants of West Africa. Indicated in ***bold italics*** are the impact mechanism pathways that are considered in the assessment of human health and change in global mean temperature explored in this study.

Pollutants	Characteristics and sources	Importance
SO_2	* It exists as a colourless gas having a sharp odour and is the most common of the oxides of sulphur * Predominant source is the combustion of fossil fuel such as heavy fuel oil and coal in energy and industrial sectors * Other sources include domestic heating, industrial processes such as crude oil refining, metal smelting, production of sulphuric acid and other chemicals * In Africa, biomass burning, and vehicle exhaust are important sources.	**Health effects** * Increases the risk of respiratory infections in human beings and can worsen existing respiratory conditions such as asthma and bronchitis * Can cause inflamed respiratory tract resulting in coughing and the secretion of mucus * Can cause eye irritation **** A precursor of secondary PM*** **Environmental effects** * Deforestation due to acid rain as SO_2 combines with water to form hydrochloric acid (H_2SO_4) **** On conversion to secondary PM will act as a negative climate forcer.***
NO_X	* Are highly reactive gases * NO and NO_2 are the two most important air pollutants with NO_2 largely used to represent oxides of nitrogen * Majorly emitted into the atmosphere through fuel combustion	**Health effects** * Inhalation of NO_2 in high concentrations over short periods can cause irritation of human respiratory system and worsening of respiratory illnesses, especially asthma

	* NO_2 are precursors to the formation of other compounds including photochemical oxidants (such as ozone), acids and aerosols * Can be transported over long distances	* Long exposures to high concentrations may contribute to asthma development and increase bronchitis symptoms in asthmatic children * Also linked to exposure to NO_2 is increased lung function **** A precursor of secondary PM*** **Environmental effects** * Atmospheric NO_X contributes to coastal waters nutrient pollution * Causes haze and reduced visibility when it forms aerosols * Acid rain caused because of chemical reaction NO_X undergoes in the atmospheric harm sensitive ecosystem **** It is a precursor to the formation of ground-level ozone thereby contributing to climate change*** **** On conversion to secondary PM will act as a negative climate forcer.***
CO	* It is a colourless, odourless gas produced because of incomplete combustion of any organic matter * Major source is the combustion of fossil fuel in vehicles. Other sources are industrial processes (in particular, steel and aluminium production) which produces it as a by-	**Health effects** * Can cause death when a high concentration is inhaled indoors as it causes a reduction of the amount of oxygen circulating with the blood in the body to vital organs by combining irreversibly with haemoglobin in the blood

	product, leaking furnaces, unvented kerosene and gas space heaters. * Common use of diesel and gasoline fuelled backup generators in Sub-Saharan African countries as well as biomass for cooking are important sources of CO * It is mainly a local air pollution problem; however, its transboundary influence can be significant as it is a precursor to ground-level ozone	* Can also cause less fatal health effects when inhaled indoors causing dizziness, unconsciousness * It is a precursor to the formation of ground-level ozone which also has human health impacts **Environmental effects** **** It is a precursor to the formation of ground-level ozone thereby contributing to both regional air quality and climate warming***
NMVOCs	* They are organic compounds which are composed of different chemical constituents but most act the same way in the atmosphere * They are emitted into the atmosphere from combustion sources (fossil fuels, biomass), vaporised from the use of solvents and other products * They are ozone precursors	**Health effects** * Exposure to some NMVOC species in high enough concentrations can cause cancer in human beings * Can indirectly worsen existing respiratory conditions such as asthma due to their involvement in ozone formation * It is a precursor to the formation of ground-level ozone which also has human health impacts **Environmental effects** **** Their role in ozone formation means they contribute to the damage of crops and other materials and climate warming***

NH_3	* NH_3 occurs naturally, can be manufactured for various uses and is also emitted as a pollutant * It is a colourless gas and unpleasant to smell * Major source is agricultural practices e.g. fertilizer application, livestock management * Can affect the rate of oxidation of acidic pollutant species such as SO_2 and NO_X enhancing the transport and deposition of these species	**Health effects** * Exposure to high concentrations can cause eye, skin and nose irritation * Reacts with SO_2 and NO_2 to form secondary PM **Environmental effects** * Atmospheric NH_3 can undergo wet or dry deposition on vegetation resulting in injury to plants at high concentration or over-fertilisation of soils * It can cause imbalance of soil nutrient, acidification of soil, reduced productivity and the decline of forests **** On conversion to secondary PM will act as a negative climate forcer.***
BC	* BC is a type of PM emitted as the major component of anthropogenic or natural soot. * It is a product of incomplete combustion of fossil fuel, biomass and biofuels * Emission sources include diesel engines (both on-road and off-road), residential (especially simple kerosene wick lamps) and commercial combustion, industrial processes, and agricultural waste burning.	**Health effects** **** BC is the major component of*** $PM_{2.5}$ ***responsible for environment induced ill health for humans and premature mortality*** **Environmental effects** **** It has a warming effect on the climate which occurs at a rate 460 - 1500 times more than*** CO_2 ***and also speeds up the melting of snow and ice by reducing their albedo***

	*Atmospheric lifetime is between a few days to a few weeks * Usually co-emitted with other pollutants including organic carbon and sulphates which cools the atmosphere. BC emission ratio to other co-emitted pollutants depends on the emission source. For instance, diesel engines have higher BC emission ratio compared with open-burning of biomass	* BC influences the formation of clouds affecting regional atmospheric circulation and rainfall patterns
OC	* Emitted into the atmosphere as a product of incomplete combustion and usually co-emitted with BC *A component of PM and consist of carbon -containing compounds	**Health effects** *Can cause inflammation of the air way, bronchial washing ****Has a cooling effect on the atmosphere*** ****Increases mortality linked to high*** $PM_{2.5}$ ***concentration***
Other PM	* $PM_{2.5}$ is the total mass concentration of all particles that pass through an inlet with 2.5 µm diameter with a 50% efficiency *PM exists both as solid particles and as liquid droplets in the atmosphere * Size and properties (physical and chemical) of a particle varies depending on the source	**Health effects** * $PM_{2.5}$ is the primary PM of concern because it can penetrate deep into the lungs where it can do more harm **** Increased mortality is found to be closely linked with exposure to high PM concentrations*** * Even at low concentrations, PM exposure still have health effects and current exposure globally means many people both in developed and

	* Source can be primary (i.e. when directly emitted from a source e.g. fires, unpaved roads) or secondary (when formed because of chemical and physical processes on gases in the atmosphere) * Particle sizes of major concern are those less than 2.5µm because they can penetrate deep into the respiratory system	developing nations, rural and urban experience some form of adverse effect * The risk of having heart and respiratory diseases as well as lung cancer among adults and acute lower respiratory diseases in children is particularly high in developing countries because of indoor exposure to PM from biomass burning for cooking in additional to exposure to ambient PM. **Environmental effects** * It causes reduced visibility and haze **** PM will act as a negative or positive climate forcer (depending on its absorptive or reflective characteristics)***
CH_4	* Main anthropogenic sources include biomass burning, animal husbandry, rice cultivation, oil and gas production, municipal waste and wastewater management * It is the second most important greenhouse gas after CO_2 based on the radiative effects * It is a precursor to ozone formation * Atmospheric lifetime is 12 years	**Health and crop effects** * No direct health/crop impacts * Has indirect impacts on ecosystems and human health resulting from it being a precursor to ground-level O_3 formation which is known to reduce the yield of crops and adversely affect human health **Environmental effects** **** It directly influences earth's climate through action as a radiative forcer***

	***It indirectly influences climate change through reactions that lead to changes in total column O_3 concertation**

Sources: USEPA (2016), World Health Organization (2016), Department for Environment Food and Rural Affairs (2016), National Atmospheric Emissions Inventory (2016), Scottish Environmental Protection Agency (2016), Vallack & Rypdal (2012), and Behera et al (2013).

In order to ensure that air pollution is properly framed as a major problem in all three countries and to allow the establishment of the right policies by policy makers, this study was conducted using the DPSIR framework (i.e. driving forces, pressure, state, impacts and response framework). The DPSIR framework is a causal framework adopted by the European Environment Agency (EEA) and it describes the interactions between society and the environment (EEA, 2019). It is an extension of the earlier PSR (pressure, state, response) model developed by the Organisation for Economic Cooperation and Development (OECD). It is an overall framework developed to assess and analyse environmental problems in an organised, well-structured manner so that information are properly handled and gaps in assessment and analysis are avoided (Stanners D. et al., 2007). It is a framework which assumes that the relationship or the interplay between social, economic and environmental systems is a cause-effect relationship and has been used in several environmental contexts such as in the management of agricultural systems, marine resources, land and soil resources, and water resources (EPA, 2015). The DPSIR chain is made up of five components, which starts from the driving forces stage to pressure, state, impact and finally, the response stage. At the response stage, any of the other stages could be revisited and revised based on the outcome of the response as seen in Figure 1.1 below.

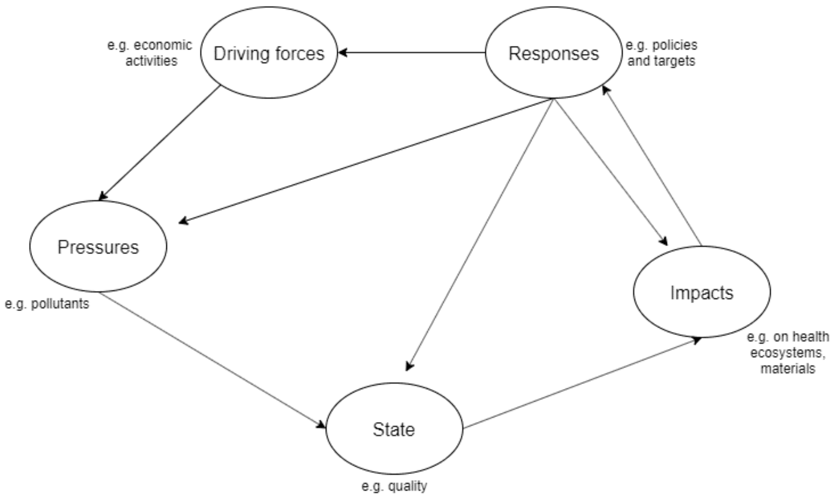


Figure 1.1: Schematic diagram of the DPSIR model for reporting on environmental issues (Stannners D. et al., 2007) .

Social, economic and demographic changes are necessary for human existence which means there are demands for energy, transportation, food and materials met by human activities which result in the release of substances or the use up of resources. These principal demands causes the release of substances into the environment and may be referred to as the **driving forces** for the production of those substances (Dore et al., 2003). While the substances released into the environment or the resources that are used up (e.g. land) put **pressure** on the environment. These substances may be physical, biological or chemical agents indicated by air pollutants emitted into the atmosphere, noise production, waste generation, land pollution, etc. (Stanners et al., 2007).

In order to ensure the sustainability of social and economic development, substances or pollutants released into the environment by human activities must be evaluated to know if the level of pollutants in the environment exceed the levels that can cause harm (Dore et al., 2003). An example of this evaluation is the atmospheric concentration of a pollutant in an area. Knowing the **state** of the environment (which could be presented as air quality) will help determine whether actions are required to manage the pollutants. If the pollutants are to be managed, then, a knowledge of their **impacts** on human health and/or the environment is required. It is necessary to know what pollutant affects which part of the environment or human being and to what extent (Dore et al., 2003). Most times, the effect of a pollutant is compared against a threshold or measured as exposure (Stanners et al., 2007). Finally, designing an appropriate management strategy for the pollutants released into the environment requires a focused **response** such that adverse social and economic effects are prevented or minimised.

Following this introductory chapter (Chapter One) which provides the context for this research, are four other chapters. These chapters are structured based on the DPSIR framework, although with a slightly different arrangement. Chapter Two addresses the second component of the framework describing and quantifying the pressure on the environment in terms of air pollutant emissions in this study. It contains the description of the method used to develop emission inventories for the three countries including specifically, the approach used to estimate the activity data for five key emission sources identified as being either omitted or poorly characterised in existing regional and global emission inventories. This chapter presents 2010 emissions results for all three countries as well as the results of the comparison of national emissions among the three countries and with existing inventories. The importance of emissions from the five key sources are also highlighted here along with various discussions on how emissions vary between the three countries, the key uncertainties, likely future trends in emissions and the impacts associated with the emissions.

Chapter Three of this work contains future projections of emissions for all three countries under different scenarios. It quantifies possible future emissions, so, this chapter also corresponds to the “pressure” on the environment component of the DPSIR framework. The driving forces of emissions are also discussed here It describes the development of four emission scenarios (i.e. a baseline or reference scenario and three mitigation scenarios that span the years 2010 to 2050). The results section of this Chapter describes the likely future pathways for emissions and the emission reduction potential of the three mitigation scenarios. The Chapter also contains a discussion of the uncertainties involved in estimating emission and compares the results obtained in this study with other regional and global studies. Pollutants and sectors which require control to improve future air quality are also highlighted.

Chapter four presents both current and future impacts of pollutant concentrations associated with these emissions for each country studied. It corresponds to the “state” and “impacts” component of the DPSIR framework. It describes the methodology used to estimate human health impacts due to exposure to ambient $PM_{2.5}$ and the impact on climate calculated as the contribution of each country’s emissions to global mean temperature change. Based on these results, the emissions pathways likely to reduce emissions were identified, along with a discussion of other key findings and uncertainties.

Chapter five is the conclusion chapter which corresponds to the response stage of DPSIR framework which presents a DPSIR-based framework for assessing and managing air pollution, presents the key findings of this research and subsequently the recommendations. This Chapter also discusses the likelihood of the policies identified being adopted. Recommendations for future work are also included in this Chapter.

Chapter 2

Air pollutant emissions inventories for Cote d'Ivoire, Ghana and Nigeria

2.1. Introduction

The first step in managing air quality in a defined geographical area (for instance, a country, a city or a community) is an understanding of the air pollutants emitted and the quantity of pollutants released into the atmosphere at that location. This is usually done by developing an emission inventory of air pollutants which clearly shows the sources of pollution or emitting activities, the rate at which emissions are released from those activities and the quantity of pollutants emitted (Shrestha et al. 2013; Trozzi 2005). The measure of the rate of an activity is called the activity rate / data (A) while the rate of emission per unit of activity is the emission factor (EF) (EMEP/EEA 2016). Using these two parameters (i.e. activity data and emissions factor), emission estimates are usually calculated following two main approaches known as the "top-down approach" and the "bottom-up approach." Either or both approaches can be used in estimating emissions (Shrestha et al. 2013; Hutchinson, 2003). (NB: Confusingly, atmospheric modellers may also use the term 'top-down' to refer to inverse modelling techniques, using atmospheric measurements in conjunction with dispersion modelling, to constrain/estimate the emission inventory. But in this thesis, the more traditional meaning is used as described below.)

The difference between the top-down and bottom-up approaches stems from the way the activity data is quantified. The top-down approach relies on the use of statistical data such as the activity data or used in calculating the activity data for an emission source or activity, which is then combined with average emission factors for that source. An example of such statistical data is total fuel consumption (e.g. natural gas) by thermal power plants in a country. Data required to compile emissions using this approach are usually at the national or regional level, thus, the inventories developed are usually national or regional inventories. However, emissions obtained can be further broken down to specific locations based on the availability of additional information which may influence emissions in the area covered by the inventory such as demographic, geographic, economic data and so on (Shrestha et al. 2013, Hutchinson, 2003). The top-down approach is the least costly one because statistical data are more readily available and can be used as an initial source of emission inventory for management decision making for an area. However, uncertainties of the estimates are larger using this approach (Shrestha et al. 2013, Economopoulos, 1993). By contrast, the "bottom-up" approach requires (local) data that are specific to individual emission sources or activities in the geographical area covered by the inventory (Shrestha et al. 2013; Hutchinson 2003). Emission estimates for individual sources or sectors are then aggregated to obtain total emissions for the area. Although, this approach may be expensive due to data collection, better estimates are usually produced.

Furthermore, the methodological complexity of emission inventories varies. International guidebooks (IPCC, 2006; EMEP/EEA, 2016) have used the tiered approach in developing an emission inventory to show this level of complexity (EMEP/EEA, 2016). It is used to rate the complexity of the activity data and the emission factors used. There are three tiers, namely: Tier 1, Tier 2 and Tier 3. Tier 1 is the basic or simple method which involves the use of readily available activity data and default emission factors. The activity data are usually statistical data on the intensity of processes while the default EFs assumes an average description of a process and indicates a direct link between the activity data and the resulting emissions (EMEP/EEA, 2016). Tier 2 method is an intermediate level of methodological complexity. Although, it is similar to Tier 1, it requires more specific locally derived emission factors which consider specific process conditions peculiar to a country. Emission estimates obtained using this approach have reduced uncertainties compared to Tier 1. Tier 3 is the most complex and accurate approach. It refers to any methodology which requires more details than a Tier 2 approach. This means it could be a methodology that requires more disaggregated activity data and EFs or one which involves the use of a complex dynamic model where the processes that results in emissions must be described in detail (EMEP/EEA, 2016).

In this study, emission inventories for the three countries were compiled using "The Global Atmospheric Pollution Forum" (GAPF) Air Pollutant Emissions Inventory Manual (Vallack & Rypdal 2012) and its associated Microsoft Excel Workbook tool. This tool was considered appropriate for this study as both the tool and user manual were designed for easy use in developing bespoke emission inventories using the top-down approach in various developing and rapidly industrialising countries. The tool is essentially at the Tier 1 level of methodological complexity but with the use of a more detailed approach for the activity data for certain sources to obtain more robust emission estimates for each of the three countries studied (i.e. Cote d'Ivoire, Ghana and Nigeria). These emission sources are the road transport sector and the 5 key sources or activities identified earlier in Chapter One – that is, use of backup generators (BUGs), illegal oil refining (ILL), use of kerosene wick lamps (SIM), use of 2-stroke motorcycles (TWO) and resuspension of dust from unpaved roads (UNP).

It is important to note that the term 'key source' has a specific meaning in emissions inventories. Also referred to as key category, it is the emission source or category that is treated as a priority when national emissions of air pollutants are compiled because of its significant contribution to the emission of a pollutant or a number of pollutants in a country. The significance could be in terms of the absolute value of emissions, trend or the uncertainty associated with the emission (Dore et al., 2019). However, in this study, the term key sources refers to the 5 emitting activities or sources listed above as being omitted or poorly characterised in global inventories (i.e. BUGs, ILL, SIM, TWO and UNP).

The GAPF tool was designed to be compatible with international initiatives for developing emission inventories such as the European Monitoring and Evaluation Programme (EMEP)/ European Environment Agency (EEA) air pollutant emission inventory guidebook (EMEP/EEA, 2016); and the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006). The GAPF manual covers emissions from both fuel combustion and non-fuel combustion sources. These two broad emission sources are composed of various sectors and sub-sectors as seen in Figure 2.1 below. Pollutants covered by the GAPF manual include: sulphur dioxide (SO_2), nitrogen oxides (NO_X), ammonia (NH_3), non-methane volatile organic compounds (NMVOCs), carbon monoxide (CO), particulate matter ($PM_{2.5}$ and PM_{10}), black carbon (BC), organic carbon (OC)), methane (CH_4), and carbon dioxide (CO_2).

To ensure that emission inventories developed in this study are reliable, of high quality and complies with international standards, the basic principles of good practice in inventory development were followed in the compilation process. These principles are accuracy, completeness, consistency, comparability and transparency (EMEP/EEA, 2019).

Accuracy – Emission estimates must be as accurate as possible. This means that uncertainties and bias must be minimised to avoid either overestimation or underestimation of emissions, double counting or omission (EMEP/EEA, 2019). In this study, data that best represents the required parameters for each country were used. For instance, activity data were sourced from reputable and well-known national sources and/or international databases such as The

International Energy Agency (IEA), National Statistical Department of each country, Food and Agricultural Organisation (FAO), among others. Also, the emission factors used are either those measured in the three countries or similar countries or those measured or suggested for Africa by international emissions inventory guidebooks such as EMEP/EEA 2019.

Completeness – This means that emissions should be estimated for all relevant pollutants and pollution sources, and the estimates cover the entire geographic scope of the inventory (refs). One of the key objectives of this work is to develop bespoke annual emission inventories for each of the three case study countries based on publicly available data. These inventories are to include key or important emission sources that are currently omitted or poorly characterised in existing inventories. As a result, key 5 emission sources were included in this study in addition to the established emission sources broadly categorised as fuel and non-fuel combustion sources. Also, the pollutants covered include all those commonly considered when assessing the quality of air in a country, namely: SO_2, $NO_{X,}$ CO, NMVOCs, NH_3, $PM_{2.5}$, PM_{10}, BC, OC and CH_4. For each of these pollutants, annual estimates that represent emissions from all parts of each country considered were presented.

Consistency – An emission inventory should show consistency in the methodology and datasets used to estimate emissions (EMEP/EEA, 2016). All elements across the source sectors and pollutants for all the reported years must be consistent. The use of the GAP Forum Workbook for this study ensured that national emissions for the base year, 2010, for all three countries were compiled consistently. While future emissions reported in this work were done using the use of LEAP-IBC for all three countries. The LEAP-IBC uses GAP Forum Workbook template.

Comparability – This means emission estimates must be comparable to other inventories. The inventories developed here can be easily compared with other inventories because the tools used to compile them were developed to be compatible with international guidelines for developing emissions inventories. For instance, the definition of the source sectors in GAP Forum Workbook is broadly the same as that of EMEP/EEA (2016).

Transparency – An emission inventory must be transparent such that it can be easily assessed and replicated by users of the inventory besides the compilers. As a result, it should clearly show how it was compiled, the sources of data used, and the assumptions made in the process. In this study, all data sources were accurately documented and presented alongside the assumptions made in developing the inventories. A general description of the methodology used to estimate emissions is first presented followed by further details for each source sector. Each source sector contains the source(s) of the activity data and emission factors used and the assumptions made in estimating emissions. In the case of the key 5 emission sources identified earlier, more detailed description of the source(s) and/or how the activity data and emission factors were obtained were required. These were clearly presented as in Section 2.2.3.

This Chapter describes the methods used to estimate emissions for all three countries and the emission estimates obtained for all the pollutants mentioned in the previous paragraph together with the uncertainties associated with the estimates. Section 2.2 outlines the method used to estimate emissions and contains the data sources and/or data used to estimate emissions from both fuel combustion and non-fuel combustion sources. The methods used to estimate emissions from the 5 key sources, as well as the method used to estimate the uncertainty bounds of all emissions, are also described here. Section 2.3 gives the emissions results for all three countries while Section 2.4 presents a discussion of the results.

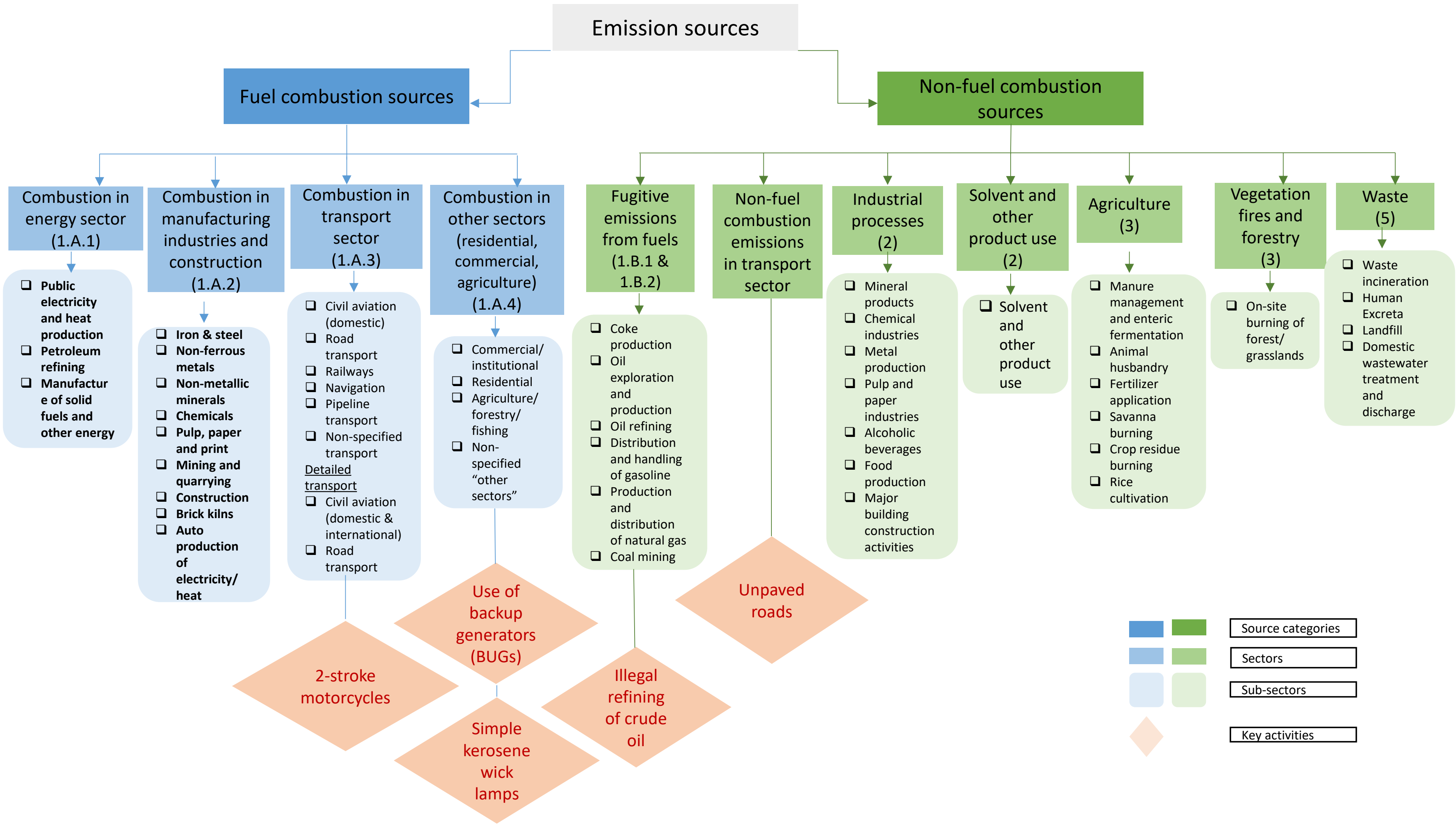

Emission sources
Fuel combustion sources
Non-fuel combustion sources
Combustion in energy sector (1.A.1)
Public electricity and heat production
Petroleum refining
Manufacture of solid fuels and other energy
Combustion in manufacturing industries and construction (1.A.2)
Iron & steel
Non-ferrous metals
Non-metallic minerals
Chemicals
Pulp, paper and print
Mining and quarrying
Construction
Brick kilns
Auto production of electricity/ heat
Combustion in transport sector (1.A.3)
Civil aviation (domestic)
Road transport
Railways
Navigation
Pipeline transport
Non-specified transport
Detailed transport
Civil aviation (domestic & international)
Road transport
Combustion in other sectors (residential, commercial, agriculture) (1.A.4)
Commercial/ institutional
Residential
Agriculture/ forestry/ fishing
Non-specified "other sectors"
Fugitive emissions from fuels (1.B.1 & 1.B.2)
Coke production
Oil exploration and production
Oil refining
Distribution and handling of gasoline
Production and distribution of natural gas
Coal mining
Non-fuel combustion emissions in transport sector
Industrial processes (2)
Mineral products
Chemical industries
Metal production
Pulp and paper industries
Alcoholic beverages
Food production
Major building construction activities
Solvent and other product use (2)
Solvent and other product use
Agriculture (3)
Manure management and enteric fermentation
Animal husbandry
Fertilizer application
Savanna burning
Crop residue burning
Rice cultivation
Vegetation fires and forestry (3)
On-site burning of forest/ grasslands
Waste (5)
Waste incineration
Human Excreta
Landfill
Domestic wastewater treatment and discharge
2-stroke motorcycles
Use of backup generators (BUGs)
Simple kerosene wick lamps
Illegal refining of crude oil
Unpaved roads
Source categories
Sectors
Sub-sectors
Key activities

Figure 2.1: Emission sources included in this study showing the two broad sources (fuel combustion and non-fuel combustion) divided into various source sectors and sub-sectors or emitting activities. Numbers under the names of the source sectors are the NFR numbering.

They are broadly categorised as fuel (blue) and non-fuel (green) combustion sources along with their associated sub-categories. Within each of these categories are a number of specific source sectors. Also shown (in orange) are five key activities that are particular to the 3 west African countries studies and which are thought to be sources of pollutant emissions not always captured in existing emission inventories.

2.2. Emission estimation methods

Emissions were estimated as the product of the rate of an activity (activity data) and the rate of pollutant release from that activity (i.e. emission factor) (EMEP/EEA, 2016; Vallack & Rypdal 2012) as seen in Equation [1]. In situations where there is a form of emission control or abatement which is not already accounted for in the emission factor, this is subtracted from the emissions as described in Equation [2].

$$E = A \times EF \qquad \text{Equation [1]}$$

$$E = A \times EF \times (1 - R/100) \qquad \text{Equation [2]}$$

Where,

E = Emission of a pollutant

A = Activity rate (i.e. the rate of occurrence of a pollutant emitting activity)

EF = Emission factor (i.e. the rate of emission of a pollutant from a particular activity or process)

R = Abatement/Recovery (expressed as %)

Using the GAPF emission inventory Workbook, emissions were estimated from all source sectors using Equation 1. However, some source sectors require a more complex method to estimate emissions where more than a single activity type or emissions factor is needed. Examples are agriculture, waste and road transport.

In order to meet the objectives of this research, emission estimates required are national level estimates. So, the data (i.e. activity data and the emissions factors) required to estimate national emissions should ideally come from national sources (EMEP/EEA, 2016). Unfortunately, this was not always possible due to a general lack of statistical data readily accessible to the public in all three countries. Where the required activity data were not available from national sources, data were obtained from international databases such as the International Energy Agency (IEA) and the Food and Agriculture Organisation of the United Nations (FAO). For fuel combustion sources, there are some annual fuel consumption data available for Ghana and Nigeria (e.g. National Petroleum Authority, NPA, 2016; Nigeria National Petroleum Authority, NNPC, 2012). However, these data could not be used because they do not provide the level of detail required by the GAPF workbook in terms of fuel disaggregation. Consequently, fuel consumption data for all three countries were sourced from IEA's Energy Statistics and Balances database (IEA, 2012) which uses the same fuel categories as those of the GAPF Workbook. For non-fuel combustion sources, the required activity data and sources vary depending on the sector or sub-sector e.g., quantity of waste incinerated was estimated following IPCC (2006) methodology, while annual (vegetation) area burnt, number of various livestock reared, or quantity of each fertilizer type used were sourced from FAO (2015).

The GAPF Workbook was developed using emissions factors (EFs) mainly sourced from international emissions inventory guidelines such as EMEP/EEA (2016); IPCC (2006) and US EPA's AP-42 (US EPA, 1995). These default EFs were mainly used in the this study however, for organic carbon (OC) and for certain activities (e.g. brick kilns) that were not well covered by these international guidelines, EFs were sourced from published literature (such as Bond et al. 2004; Bertschi et al. 2003; Battye et al. 1994; among others). It is important to note that the EF of one pollutant differs from another and the EF of a pollutant is also likely to differ between two different emitting activities. Sections 2.2.1 and 2.2.2 below describe the emission source sectors from both fuel combustion and non-fuel combustion sources and the sources of the EFs for all the sectors are presented in the accompanying tables with default EFs and those from other sources clearly outlined in different columns.

These data were used to compile emissions inventories for the year 2010 for each of the three countries. A large part of the inventories developed relied on the use of statistical data and irrespective of the source, statistical data often requires time to prepare and made available publicly. So, year 2010, which is four years before the start of this research, was selected as the base year to ensure that the data used are comprehensive and reliable. In addition, further analysis in this study (in Chapters 3 and 4) requires the use of the Long-range Energy Alternatives Planning – Integrated Benefits Calculator (LEAP-IBC) tool which by default requires a year 2010 emissions inventory as the base year.

It is important to note that in this study key sources refers to the relatively unique emission sources to these three countries (that is, the use of backup generators, two-stroke motorcycles, illegal oil refining, simple kerosene wick lamps and unpaved roads) that are specifically included in the work as opposed to the official usage where it means a key source or category that is prioritised in a national inventory because it is vital or important for one or more pollutants in the emissions inventory of a country (EMEP/EEA, 2019). Also, solvents are not included in this work because of unavailability of data to be able to make estimates of emissions from this source. Solvent emissions were also not included to fill the gap because one of the objectives of this research is to develop bespoke national emissions inventories using publicly available data.

2.2.1. Fuel combustion sources

Combustion of fuels, especially in uncontrolled situations, is common in all three countries studied. It is an important source of most atmospheric pollutants covered by the GAPF Workbook. There are four sectors under fuel combustion, namely: (i) Energy industries (ii) Manufacturing and construction industries (iii) Transport and (iv) Other combustion sector - residential, commercial and agriculture (see Figure 2.1). Activity data under this emission source category is the quantity of fuel consumed by each emitting activity of each sector in a year. Except for the transport sector, fuel consumption data used were sourced from the IEA database. Emissions from the transport sector (e.g. road) were estimated using a more detailed method where the activity data required were generated using a combination of variables such as the number of vehicle types by fuel in each country and the total distance covered by each type of vehicle. Further details on this are provided in Section 2.2.1.3 below and sources of EFs for all fuel combustion sectors described below (Sections 2.2.11 – 2.2.14).

Furthermore, SO_2 emissions from fuel combustion depends on the sulphur content of each fuel type, the proportion of sulphur retained in ash after combustion (for solid fuels) and emission reduction achieved as a result of any emissions control applied (expressed in percentage). Consequently, SO_2 emission factors for each fuel type under the fuel combustion source category were calculated using Equation [3] below. The factor of 2 in this Equation is for converting sulphur, S, to SO_2 because the molecular weight of SO_2 is approximately double that of S.

$$SO_2\ EF = 2 \times B/100 \times 10^6/E \times (100 - C)/100 \times (100 - D)/100 \qquad \text{Equation [3]}$$

Where,

EF = Emission factor (kg/TJ)

B =Fuel sulphur content (%)

C = Sulphur retention in ash (%)

D = Emission control efficiency of SO_2 *(%)*

E = Net calorific value (TJ/kt)

The sulphur contents of fuels (B) were obtained from IPCC (2006), Kato and Akimoto (1992), Reddy and Venkataraman (2002b) and USEPA (1996).

Of the 5 key emitting activities identified in Chapter One, emission of pollutants from three activities result from fuel combustion (i.e. use of backup generators for electricity, use of kerosene wick lamps, and use of 2-stroke motorcycles). The methods used to estimate the emissions from these particular activities are described in detail in Section 2.2.4. All other fuel combustion source sectors are described here as follows.

2.2.1.1. Fuel combustion in energy industries

Energy industries are important sources of SO_2, NO_X, CO, NMVOC, PM (including BC and OC), CO_2. They refer to industries or sub-sectors involved in the production of energy, that is: (i) public electricity and heat production (ii) petroleum refining, and (iii) manufacture of solid fuels and other energy industries. The required activity data here is the annual amount of fuel consumed by each source or emitting activity per year. While the required disaggregated fuel consumption data from national sources for each country was not available, it was assumed that the IEA (2012) database is the most appropriate source of this data for all three countries. Furthermore, because no form of emission control from sources under this sector is known in all three countries, default uncontrolled emission factors from international guidelines and the literature were assumed to be appropriate in estimating emissions for all three countries. Sources of emission factors used (apart from SO_2 calculated by the mass balance approach) are given in Table 2.1 below.

Table 2.1: Sources of emission factors for combustion in energy industries sector. In the third column are default emission factors and in the fourth are those from other literature sources.

Sector	Sub-sectors	Emission Factors (Defaults from international guidelines)	Emission Factors (from other literature sources)
Combustion in energy industries	Public electricity and heat production; Petroleum refining; Manufacture of solid fuels and other energy	• EMEP/EEA (2016) Tier 1 EFs for all pollutants apart from OC, NH_3, CH_4 and CO_2. • CH_4, CO_2 - IPPC (2006) - Tier 1 default EFs	• Bond et • al (2004) – BC for coke ovens and for all coal combustion in other sectors. • Bond et al (2004) – OC for coke ovens and for all coal combustion. For other fuels, the OC EF was calculated from EMEP/EEA (2016) Tier 1 BC EFs using OC/BC ratios given in Bond et al (2004). • Battye et al (1994) – NH_3 for all fuels apart from wood for charcoal production. • Bertschi et al (2003) – NO_X, CO, NMVOC and NH_3 for earthen charcoal-making kilns (in Zambia)

2.2.1.2. Fuel combustion in manufacturing industries and construction

This sector covers major fuel-consuming industrial and construction activities which are divided into ten sub-sectors as shown in Figure 2.1. Activity data are defined as the quantity of various fuel types used. Just like the energy industries presented above, these data were obtained from IEA's energy balance data (IEA, 2012) on the assumption that it is the most reliable source in the absence of national data. Emission factors were also assumed to be the uncontrolled defaults from international guidelines and from the literature in some cases as detailed in the in Table 2.2 below.

Table 2.2: Sources of emission factors for combustion in manufacturing industries and construction. In the third column are default emission factors and in the fourth are those from other literature.

Sector	Sub-sector	Emission Factors (Defaults from international guidelines)	Emission Factors (from other literature sources)
Combustion in manufacturing industries and construction	Iron and steel; Non-ferrous metals; Non-metallic minerals; Chemicals; Pulp, paper and print; Mining and quarrying; Construction; Brisk kilns; Auto-production of electricity/heat; Non-specified industry	• EMEP/EEA (2016) Tier 1 EFs for all pollutants apart from OC, NH_3, CH_4 and CO_2. • EMEP/Corinair (1996) – NH_3 for motor gasoline and diesel • IPPC 2006 Guidelines - Tier 1 default EFs – CH_4, CO_2	• Bond et al. (2004) – OC EFs derived from EMEP/EEA (2016) Tier 1 BC EFs using OC/BC ratios given in Bond et al. • Battye et al. (1994) – NH_3 for all fuels apart from motor gasoline and diesel

2.2.1.3. Fuel combustion in transport sector

Fuel combustion in the transport sector is a source of NO_X, SO_2, CO, NMVOC, PM (including BC and OC), and CO_2. These pollutants are emitted from civil aviation, rail, road, navigation (i.e. water transport), pipeline transport and non-specified transport (e.g. ground activities at airports). In this sector, the activity data is the total amount of fuel consumed by each of the different sources or modes of transport listed above except for road transport and civil aviation. These two sources are the largest sources of emissions within the transport sector in all three countries and a more detailed approach was used to calculate the activity data. This is to enable a more accurate estimation of emissions as it involved the use of an increased level of vehicle disaggregation and differing EFs. For road transport, the activity data required is the total distance travelled (TDT) by each type of vehicle per year in each country while the number of landing and take-off cycles by the different types of aircrafts is the required activity data for civil aviation. These data (i.e. for road transport and civil aviation) were derived from national sources or region-specific literature rather than international databases (see Table 2.3). On the other hand, fuel consumption data from IEA were assumed to be appropriate for other emission sources within the transport sector due to the absence of such data from national sources. The EFs used in estimating emissions from this sector were assumed to be the uncontrolled defaults because no form of emission control is known to exist in all three countries. In some cases, more relevant EFs from the literature were assumed to be appropriate for some emission sources. Sources of EFs for transport emissions, and the specific vehicle classes where relevant, are detailed in Table 2.4 below.

Road transport emissions are affected by the type and age of vehicles, speed, emission controls in place, existing maintenance culture, fuel type and fuel quality, and in general, how vehicles are being operated. Vehicle classes included in this study are gasoline fueled motorcycles, diesel and gasoline fueled passenger cars, light-commercial vehicles and heavy-duty vehicles. The total distance travelled, TDT for each vehicle class was calculated using:

$TDT_{vehicle\ class}$ *= number of vehicles in use (for each vehicle class) x Average distance travelled per vehicle*

Of the three countries, detailed vehicle statistics were only available for Ghana (through personal communication with Ghana's Environmental Protection Agency's Daniel Benefor). In the absence of, or lack of access to, similar statistical data for Cote d'Ivoire and Nigeria, the ratio of gasoline vehicles to diesel ones for each type of vehicle (i.e. passenger cars, etc.)

in Ghana were assumed to be applicable to the other two countries. As a result, estimates of the total number of various types of vehicles obtained from the International Organisation of Motor Vehicle Manufacturers (OICA) for the other two countries (OICA 2015) were divided using this ratio. Table 2.5 gives the details of the variables used to calculate the activity data (i.e. TDT) for all three countries. The table also contains total fuel (i.e. gasoline and diesel) consumed in road transport in each country. These fuel consumption estimates, based on vehicle statistics, were used to estimate SO_2 emissions since the sulphur content of a fuel determines the emission of SO_2 . In this case, fuel consumption data from the IEA were not used as they were less than those calculated in this study and thus, believed to be quite conservative. The illegal refining of crude oil as well as the possible under reporting of imported refined petroleum products is believed to greatly contribute to these discrepancies.

To assign the appropriate EFs, vehicles in each country were categorized into different emission control categories (e.g. Uncontrolled, conventional, moderate control, Euro I, Euro II etc.) based on EMEP/EEA (2016) guidebook. Most of the vehicles used in each of the three countries are imported second-hand (i.e. used) vehicles and are usually over 10 years old with the catalytic converters removed (Roy, 2016). As a result, it was assumed in this work that vehicles used in 2010 in each country were not controlled for emissions. Therefore, they are classed as uncontrolled or conventional, meaning the highest rate of exhaust emissions (i.e. EFs) were assigned to all vehicle classes.

As part of road transport source of air pollution, re-suspended dust due to vehicular use of unpaved roads are estimated under this source sector. In each of the three countries, a maximum of only 15% of all road networks are paved (Kumar & Barrett 2008; Federal Ministry of Works, FMW, 2013;, Central intelligence Agency, CIA, 2015), thereby, resulting in the resuspension of significant amounts of particulate matter due to vehicular use of unpaved roads. Methods used in estimating PM emissions from unpaved roads are given in Section 2.2.3

For civil aviation, the required activity data are the number of landing/take-off (LTO) cycles per aircraft type per year for both domestic and international flights. Official LTO data were available for both Ghana and Nigeria but not Cote d'Ivoire. The lack of these data for Cote d'Ivoire means that it is one of the areas where the emission inventory compiled in this study for this country can be improved in future. Due to lack of data on the specifications of the aircraft used in the countries, the aircraft were assumed to be “average fleet” for international flights and “old fleet” for domestic flights for the purposes of assigning emission factors.

Table 2.3: Sources of activity data for combustion in transport sector used to develop the 2010 emissions inventories for Cote d'Ivoire, Ghana and Nigeria.

Sector	Sub-sectors	Activity data	Cote d'Ivoire	Ghana	Nigeria
Transport	Civil aviation	Annual fuel consumption for landing/take off activities = Number of LTOs x Fuel consumption/LTO	• Not available	• General Statistics (Domestic/International, Aviation • Statistics, Ghana Civil Aviation Authority	• Nigeria Civil Aviation Authority
	Road transport	Vehicle-kilometer travelled per year	• Assamoi E. and Liousse C., 2010 (for motorcycle estimates) • OICA (International Organisation of Motor Vehicle Manufacturers) – for total number of vehicles by types • IRF (International Road Federation)	• Assamoi E. and Liousse C., 2010 (for motorcycle estimates) • Data from Daniel Benefor (Ghana EPA) – total number of vehicles by type • IRF (International Road Federation) • Fraction of TDT by vehicles on unpaved	• Assamoi E. and Liousse C., 2010 (for motorcycle estimates) • OICA – total number of vehicles by types • Vehicle Manufacturers) • IRF (International Road Federation)

			• Fraction of TDT by vehicles on unpaved roads (Assumption based on Nigeria's data)	roads (Assumption based on Nigeria's data)	• Fraction of TDT by vehicles on unpaved roads (FMW, 2013)
	Rail transport	Annual fuel consumption	←	IEA	→
	Navigation	Annual fuel consumption	←	IEA	→
	Pipeline	Annual fuel consumption	←	IEA	→
	Non-specified transport	Annual fuel consumption	←	IEA	→

Table 2.4: Sources of emission factors for combustion in transport sector. In the third column are the default sources while the fourth column are those from other literature.

Sector	Sub-sector	Emission Factors (Defaults from international guidelines)	Emission Factors (from other literature sources)
Combustion in transport	Road transport	• EMEP/EEA (2013) Tier 2 exhaust EFs, Tables 3.16 – 3.25 • EMEP/EEA (2013) uncontrolled EFs = Tier 1 maximum value for passenger gasoline vehicles and motorcycles for NO_X, CO, NMVOC, NH_3, PM_{10}, $PM_{2.5}$ • EMEP/EEA (2013) Tier 3 fraction BC (%) and Organic matter (OM) to BC ratio (Table 3-114) assuming OM = 1.3xOC	• Derived from Gillies et al. (2005) - PM_{10} for unpaved roads in dry weather (days when precipitation < 0.25 mm) assuming 30 kph average speed for all vehicles and average weights of 0.4 t for motorcycles, 1.4 t for passenger cars, 2.5 t for light commercial vehicles and 5 t for heavy duty vehicles • Guinot et al (2014)
	Civil aviation	• Assuming 0.05% S content of the jet kerosene • Tier 1 defaults given by EMEP/EEA (2013) for jet kerosene • Assume PM_{10} = $PM_{2.5}$	
	Railways, navigation, navigation	• EMEP/EEA (2013) Tier 1 emission factors • Derived from EMEP/EEA (2013) Tier 1 emission factors for combustion using net calorific value • uncontrolled EFs derived from AP-42 (EPA, 2005) – PM_{10}	• Bond et al. (2004) – for BC (navigation, pipeline)

	and pipeline transport	• Derived from EMEP/EEA (2013) Tier 1 emission factors - BC

Table 2.5: Estimated fuel consumption in the road transport sector for Cote d'Ivoire, Ghana and Nigeria for the year 2010. (G) means gasoline and (D) means diesel fuel, so, passenger cars (G) means passenger cars fueled by gasoline.

Country	Vehicle type	Vehicle numbers ('000)	Average distance travelled per vehicle ('000 km/yr)	Total distance travelled (TDT) (millions km/yr)	Typical fuel consumption (g/km)	Total fuel consumption (kt)	Total fuel consumption (kt)	Default NCV (toe/t)	Total fuel consumption (ktoe)	Total fuel consumption by fuel type (ktoe)
Cote d'Ivoire	Motorcycles (G)	446.6	7.98	3561	35	124.6	1214	1.070	133	
	Passenger cars (G) – 95%	323.0	13.13	4241	70	296.9	297	1.070	317	
	Passenger cars (D) – 5%	17.0	15.85	269	608	16167.4	16	1.035	17	Gasoline 783
	Light duty commercial vehicles (G) – 49%	149.6	13.58	2031	100	203122.5	203	1.070	217	Diesel 1740
	Light duty commercial vehicles (D) – 51%	155.7	15.60	2429	80	194346.9	193	1.035	201	

	Heavy duty vehicles (G) – 10%	11.9	50.93	6045	177	107013.0	107	1.070	115	
	Heavy duty vehicles (D) – 90%	106.8	57.36	6129	240	1471022.0	1471	1.035	1523	

Ghana	Motorcycles (G)	131.6	7.98	1050	35	36734.1	37	1.070	39	Gasoline 672 Diesel 1759
	Passenger cars (G) – 63%	346.2	13.13	4545	70	318164.9	318	1.070	340	
	Passenger cars (D) – 27%	204.1	15.85	3235	60	194100.7	194	1.035	201	
	Light duty commercial vehicles (G) – 49%	127.6	13.58	1732	100	173278.5	173	1.070	185	
	Light duty commercial vehicles (D) – 51%	134.7	15.60	2102	80	168192.5	168	1.035	174	
	Heavy duty vehicles (G) – 10%	110.9	50.93	565	177	99951.4	1000	1.070	107	

	Heavy duty vehicles (D) – 90%	971.3	57.36	5572	240	1337216.3	1337	1.035	1384	
Nigeria	Motorcycles (G)	5570.3	7.98	44423	35	1554788.7	1555	1.070	1664	Gasoline 4446 Diesel 2923
	Passenger cars (G)- 95%	2280.0	13.13	29936	70	2095542.5	2096	1.070	2242	
	Passenger cars (D) – 5%	120.0	15.85	1902	60	114122.6	114	1.035	118	
	Light duty commercial vehicles (G) – 49%	243.4	13.58	3306	100	330553.6	331	1.070	354	
	Light duty commercial vehicles (D) – 51%	253.4	15.60	3953	80	316271.6	316	1.035	327	
	Heavy duty vehicles (G) – 10%	19.3	50.94	984	177	174148.6	174	1.070	186	
	Heavy duty vehicles (D) – 90%	173.9	57.36	9975	240	2393880.1	2394	1.035	2478	

Sources: OICA (2015); Daniel Benefor (Ghana EPA), Assamoi & Liousse (2010) and EMEP/EEA, 2016

2.2.1.4. Fuel combustion in other sectors

Emission sources included in this sector are: (i) commercial/institutional (ii) residential (iii) agriculture/forestry/fishing and (iv) non-specified “other sectors.” Similar to other fuel combustion sources, activity data for each of these sources is the total quantity of fuel consumed per year. However, some of the required fuel consumption data from national sources were not publicly available, consequently, resulting in the use of data from IEA. This was assumed to be the most reliable source for this study and it was used together with uncontrolled EF defaults from EMEP/EEA (2013) and IPCC (2006). Where more appropriate EF from the literature on regions similar to West Africa were available such as Zhang et al (2000), these were assumed to be applicable in this study in calculating emissions from some sources. Further details on the EFs used are provided in Table 2.6 below. In the IEA database, ’primary solid biomass’ was not further disaggregated to the different types. So, on the assumption that this was predominantly wood, the emission factors for wood fuel (from EMEP/EEA, 2016) were adopted for this category. Also, the quantity of kerosene used in the residential sector was provided by IEA as a single figure for each country. However, kerosene is used for cooking, lighting using hurricane lamps or simple wick lamps. So, based on Lam et al. (2012), total kerosene consumed in the residential sector was divided into 3 portions, one for each use of kerosene in the residential sector.

Table 2.6: Sources of emission factors used to estimate emissions from combustion in other sectors. In the third column are default sources and in the fourth are other literature sources.

Sector	Sub-sector	Emission Factors (Defaults from international guidelines)	Emission Factors (from other literature sources)
Combustion in other sectors	Residential	• EMEP/EEA (2013) Tier 1 EFs for all pollutants apart from OC, NH_3, CH_4 and CO_2. • IPCC 2006 Guidelines- Tier 1 default EFs for CH_4 and CO_2.	• Zhang et al. (2000) - NO_X, CO average EFs for household stoves burning coal, kerosene and biomass fuels in China • NO_X, NMVOC, NH_3 - Bertschi et al (2003) EFs for charcoal cookstoves (in Zambia).

			• Bond et al. (2004) – PM, BC and OC EFs for traditional biomass cookstoves • Venkataraman et al (2010) - PM_{10} EF for Indian LPG cookstove
	Commercial/ institutional; Agriculture/ forestry/ fishing; Non-specified "other sectors"	• EMEP/EEA (2013) Tier 1 EFs for all pollutants apart from OC, NH_3, CH_4 and CO_2. • IPCC 2006 Guidelines- Tier 1 default EFs for CH_4 and CO_2.	• Bond et al for OC (assuming the BC/OC ratio as for industry) – Tables 9 & 10 • NH_3 from EMEP/EEA (2016)

2.2.2. Non-fuel combustion sources

This category of emission sources covers all non-fuel combustion sectors or activities whereby air pollutants are emitted by the processes involved in the activity. Sectors included are: (i) Fugitive emissions from fuels (ii) Industrial process emissions (iii) Solvent and other products use (iv) Agriculture (v) Vegetation fires and forestry, and (vi) Waste treatment and disposal. Although, emissions from non-fuel combustion sources are not a result of fuel combustion for energy purposes, some combustion activities used to manage waste or clear land for agricultural purposes (as seen in (iv), (v) and (vi) above) are accounted for here. The basic method used to estimate emissions under this source category is the same as that of fuel combustion emission source category, that is, the product of activity data and EFs. However, as mentioned in Section 2.2, some sources of emission here require the use of more than one activity-related variable or emission-related factor. Further details on each sector which describes the type of activity data required and their sources, as well as the sources of EFs used, are presented in the following sections.

2.2.2.1. Fugitive emissions from fuels

Fugitive emissions from fuels includes non-combustion emissions from the production of coke; exploration, production and transportation of oil and natural gas; crude oil refining; distribution and handling of gasoline; and finally, coal mining. As seen in Table 2.7 below, different types of activity data are required to estimate emissions from these processes, the sources of which are also detailed in the table for each country. The activity data in this case are mostly local data sourced from national sources and Africa focused statistical database but, in some cases, from the IEA. Therefore, the data used were assumed to be as accurate as possible. The corresponding EFs used are found in Table 2.8 as they represent the uncontrolled defaults from international guidebooks due to no known emission control. Pollutants of concern in this sector include NMVOC, CH_4, SO_2, NO_X, and CO depending on the activity or sub-sector concerned.

Of all three countries, fugitive emissions in Nigeria is particularly interesting due to illegal refining of crude oil in the Niger Delta region of the country. This is a problem in the region as the inefficiency of the process involved is a major source of air pollution in the local area, not to mention the damage to land and water resulting from oil spillage. Emissions from this activity have not previously been estimated, so, this was done using a methodology described in detail in further section (i.e. Section 2.2.3) along with other key 5 emission sources.

Table 2.7: Sources of activity data for fugitive emissions from fuels for Cote d'Ivoire, Ghana and Nigeria.

	Sub-sectors	**Required activity data**	**Cote d'Ivoire**	**Ghana**	**Nigeria**
Fugitive emissions from fuels	Production of coke	• Quantity of coke produced per year	• Not applicable	• Not applicable	• Not applicable
	Oil exploration, production and transport	• No of wells drilled per year • Quantity of crude oil produced per year • Vol. of gas flared per year	• Cote d'Ivoire: Open data for Africa • Cote d'Ivoire: Open data for Africa	• IEA, 2012	• 2010 Nigerian National Petroleum Corporation Report

	• Mass of oil transported per year			
Oil refining	• Quantity of crude oil refined	• IEA, 2010	• IEA, 2012	• 2010 Nigerian National Petroleum Corporation Report
Distribution and handling of gasoline	• Quantity of gasoline produced per year • Quantity of gasoline consumed in road transport sector	• Cote d'Ivoire: Open data for Africa	• IEA, 2012	• 2010 Nigerian National Petroleum Corporation Report
Production and distribution of natural gas	• Quantity of gas produced per year • Quantity of gas sold per year	• EcoBank Research • IEA, 2012	• Not applicable	• 2010 Nigerian National Petroleum Corporation Report
Coal mining	• Quantity of mined coal per year	• Not applicable	• Not applicable	• National Bureau of Statistics

Table 2.8: Sources of emission factors for fugitive emissions sector for Cote d'Ivoire, Ghana and Nigeria.

Sector	**Sub-sector**	**Emission Factors (Defaults from international guidelines)**
Fugitive emissions from fuels	Oil exploration, production and transport	• IPCC (2006) average of Tier 1 default range • McEwen and Johnson (2012)
	Oil refining	Derived from default values (simple methodology) suggested by IPCC (2006)
	Distribution and handling of gasoline	EMEP/EEA (2016) Uncontrolled default values

	Production and distribution of natural gas	EMEP/EEA (2016) Uncontrolled default values
	Coal mining	IPCC (2006) average global default - Tier 1 middle of range

2.2.2.2. Industrial process emissions

Industrial process emissions are pollutants emitted due to the production process of a commodity rather than any fuel combustion involved. So, the activity data here is the quantity of the commodity produced per year. This sector covers process emissions during the production of minerals (such as cement), chemicals (like ammonia, nitric acid, ammonium phosphate, etc.), metals, pulp and paper, alcoholic beverages, food production and fugitive emissions from major construction activities. Generally, these data were not publicly available from official or national sources in all three countries. As a result, data from international databases where available were assumed to be applicable. Data on the production of food, alcoholic beverages and cement were sourced from the United Nations Industrial Commodities Statistical Yearbook (UN, 2016) while the World Steel Association's, WSA, online statistics (WSA, 2018) and the United States Geological Survey (USGS) mineral Yearbook (USGS, 2018) were used for metal production in each of the three countries. The FAO was explored for chemical production as well as paper and pulp production. However, data obtained from these sources were also limited. EFs used are the uncontrolled defaults from international guidebooks and literature as seen in Table 2.9 below. Pollutants quantified from this source sector are SO_2 , NO_X, NMVOC, CO, $PM_{2.5}$ and PM_{10} depending on the activity or item produced.

Table 2.9: Sources of emission factors for industrial process emissions sector for Cote d'Ivoire, Ghana and Nigeria.

Sector	**Sub-sector**	**Emission Factors (Defaults from international guidelines)**
Industrial process emissions	Mineral	• EMEP/EEA (2013) assuming 95% of Portland cement in clinker – $PM_{2.5\ \&\ 10}$ • Derived from IPCC (2006) Tier 1 factors – CO_2
	Chemicals	• EMEP/EEA (2013) Tier 2 (uncontrolled) emission factors
	Metals	Kato & Akimoto (1992) uncontrolled default
	Pulp and paper	• Stockton and Stelling (1987) uncontrolled default • EMEP/EEA (2016) Tier 2 defaults. Assume alkaline soda pulping has same emission factor as Kraft pulping.
	Alcoholic beverages	EMEP/EEA (2013) Tier 2 defaults
	Food production	EMEP/EEA (2016) Tier 2 defaults

2.2.2.3. Solvent and other product use

NMVOC is the main pollutant of concern from activities under this sector. These activities are paint application (water and solvent-based paints), metal degreasing, fabrics dry-cleaning, manufacture of chemical products, and other use of solvents. Activity data required to estimate emissions from this sector is the annual quantity of a product sold, consumed or processed. In all three countries, this data is not available either from national sources or international databases. Due to a lack of data on the activity rates required in this sector, emissions of NMVOC from this sector are not included in this study.

2.2.2.4. Agriculture

This sector includes a range of emission sources. They are manure management (for NH_3 and CH_4) and enteric fermentation (for CH_4), animal housing ($PM_{2.5\ \&\ 10}$), application of fertilizer (NH_3 and NO_X), rice cultivation (CH_4), savannah burning and lastly, agricultural crop residue burning, both of which produce a wide range of combustion-related emissions (SO_2 , NO_X, CO, NMVOC, NH_3, BC, OC, $PM_{2.5}$, PM_{10} and CH_4).

The methods used to estimate emissions from agriculture in this study follow procedures given by 1996 and 2006 IPCC guidelines for national greenhouse gas inventories, and EMEP/EEA (2013, 2016) guidebooks. Here, the type of activity data needed to estimate emissions from each source differs as seen in the list below while the details of their sources are found in Table 2.10. In the absence of such data from national sources, FAO is the most reliable source of data and this was assumed to be applicable for this study. Also, in calculating emissions from animal housing, the time spent in animal housing was assumed to be the EMEP/EEA (2016) defaults. For agricultural residue burning, the residue to crop ratio, fraction of dry matter, fraction burned and fraction oxidised were assumed to be the default values from EMEP/EEA (2013). In conjunction with the activity data, uncontrolled EF defaults from international guidebooks together with some more appropriate factors from the literature were used in estimating emissions from this sector. Sources of the EFs used are detailed in Table 2.11.

Activity data for:

(i) *Manure management* and *Enteric fermentation* is the number of live animals by type in a country for the year 2010 (obtained from FAO Statistical database)

(ii) *Animal housing* is the number of live animals multiplied by the time spent in animal housing for each type of animal (data obtained from FAO and EMEP/EEA, 2016)

(iii) *Application of fertilizer* is the amount of each type of nitrogen containing fertilizers (tonnes N per year) used in 2010 for each country (data obtained from FAO)

(iv) *Rice cultivation* is the annual harvested area (split between ‘rain-fed and deep-water’ ecosystem (80%) and ‘intermittently aerated ecosystem’ (20%)) multiplied by rice cultivation period (133 days) - (obtained from FAO)

(v) *Savanna burning* is obtained as a product of annual area burnt, fuel load biomass before burning and the fraction of biomass actually burned (FAO; IPCC, 2006)

(vi) *Agricultural residue burning* is the total biomass burned in the open obtained as a product of annual crop production (kt), residue to crop ratio, fraction of dry matter, fraction burned in fields and fraction oxidised (EMEP/EEA, 2013).

Table 2.10: Sources of activity data for various emission sources within the agriculture sector for Cote d'Ivoire, Ghana and Nigeria.

Sector	Sub-sectors	Required activity data	Cote d'Ivoire	Ghana	Nigeria
Agriculture	Manure management	Number of livestock by type	FAO Stat	• Country Stat: Ghana • FAO Stat	FAO Stat
	Animal housing	Total time spent in animal housing by each livestock type per year	• Assumed EMEP/EEA (2016) Tier 2 defaults	• Assumed EMEP/EEA (2016) Tier 2 defaults	• Assumed EMEP/EEA (2016) Tier 2 defaults
	Enteric fermentation	Number of livestock by type	FAO Stat	FAO Stat	FAO Stat
	N-containing fertilizer application	Quantity of each fertilizer type applied	FAO Stat	FAO Stat	FAO Stat
	Savanna burning	Quantity of biomass burned	FAO Stat	Kugbe et al. 2012	FAO Stat
	Crop residue burning	Total biomass of each crop burned per year	FAO Stat	FAO Stat	FAO Stat
	Rice cultivation	Annual area harvested	World Rice Statistics Database		

Table 2.11: Sources of emission factors for the sub-sectors of agricultural sector. In the third column are the default sources from international databases and in the fourth column are other literatures.

Sector	Sub-sector	Emission Factors (Defaults from international guidelines)	Emission Factors (from other literature sources)
Agriculture	Manure management, Animal housing, Enteric fermentation, N-containing fertilizer application, Savanna burning, Crop residue burning, Rice cultivation	• IPCC (2006) Tier 1 defaults for developing countries (Africa and Middle East) - CH_4 default factors for enteric fermentation and manure management • EMEP/EEA (2016) Tier 2 defaults - for NH_3, CO, NO_X, SO_2 , • EMEP/EEA (2016) Tier 1 default - for NO, PM_{10} & $PM_{2.5}$ • EMEP/EEA (2016) defaults for residue to crop ratio, dry matter fraction, fraction burned in fields and fraction oxidised • IPCC (1996) for fuel load biomass and fraction biomass burned • IPCC (2006) aggregated scaling factor for all water regimes before (rice) cultivation period • IPCC (2006) for (i) baseline emission factor for	• Bouwman et al (1997) for developing countries - NH_3 default factors • Andreae and Merlet (2001) - CH_4, NH_3, $PM_{2.5}$, BC & OC • Reddy and Venkataraman (2002b) - SO_2 • Reddy and Venkataraman (2002b) - Average PM emission factor for crop wastes for $PM_{2.5}$ and PM_{10} • Tyagi (1989) - Residue to crop ratio • TIFAC (1991) • Sinha P. et al (2003) - Emissions of trace gases and particles from

	continuously flooded field without organic amendments (ii) scaling factor to account for differences in water regime during the cultivation period	savannah fires in Southern Africa • Andreae and Merlet (2001) values given for agricultural residues - CO, CH_4

2.2.2.5. Vegetation fires and forestry

Data required for this sector is the total amount of biomass consumed per year for each vegetation type burnt for each of the countries. This was done by calculating the product of annual area burnt for each vegetation type and the weight of biomass consumed during a typical fire per hectare of a vegetation type. In the absence of national data describing these activities for the three countries, the source of data describing the annual area burnt was the FAO which provides data for the forest, grassland (excluding savanna) and shrub-land vegetation types. Although, this is not categorised as a fuel combustion source (as no useful energy is extracted), estimated pollutants cover the whole range of combustion emissions included in this study - SO_2 , NO_X, CO, CO_2, NMVOC, CH_4, NH_3, PM_{10}, $PM_{2.5}$, BC and OC.

2.2.2.6. Waste

Based on the treatment methods for wastes, this sector is further separated into four sub-sectors: (i) incineration (ii) human excreta in latrines / outside in the fields or bush (iii) landfill and (iv) domestic wastewater treatment. Apart from waste incineration, other waste sub-sectors are mainly relevant for the emission of only a few pollutants. NH_3 is the main pollutant from the use of latrines, and CH_4 is the main pollutant of concern from landfills and wastewater management.

Described below are the procedures followed in obtaining the activity data for waste incineration and latrine use, and a description of the methodology used in estimating CH_4 emissions from landfill and domestic wastewater management:

(1) *Waste incineration* – this activity was assumed to be undertaken as open burning and emissions estimated following IPCC 2006 guidelines (IPCC, 2006) using Equation [4]

$$MSB_B = P \times P_{frac} \times MSW_P \times B_{frac} \times 365 \times 10^{-6} \qquad \text{Equation [4]}$$

Where,

MSW_B = Total quantity of municipal solid waste open-burned

P = Population

P_{frac} = fraction of population burning waste

B_{frac} = fraction of waste burned relative to total quantity of waste treated

365 = number of days in a year

10^{-6} = conversion factor from kilogramme to gigagramme

(ii) *Human excreta in latrines / outside in the fields or bush* – emissions were estimated based on the EMEP/EEA (2013) guidelines. The percentages of households using various toilet facilities were obtained from the respective national statistical office websites, if available, as is the case for Ghana (GSS, 2012) and Nigeria (NBS, 2012). For Cote d'Ivoire, such data were not available and so data obtained for Ghana were assumed to be applicable as both countries are of similar population size and both have a similar rural/urban ratio. The proportion of households using pit latrines was 29% in Ghana and 55% in Nigeria. The percentage using "outside in the field" were assumed to be those without toilet facilities plus others unspecified. This is 19.7% (Ghana) and 24.8% (Nigeria).

(iii) *Landfill emission of* CH_4 was based on the IPCC (2006) Tier 1 methodology. As the three countries are developing countries, waste collected was assumed to be limited to the urban population. CH_4 emissions here were obtained using Equation [5]:

$$Landfill_{methane} = MSW_U \times MSWDS_F \times MCF \times DOC \times DOC_F \times F \qquad \text{Equation [5]}$$

Where MSW_U = Total urban municipal waste generated;

$MSWDS_F$ = Fraction of MSW_U sent to disposal sites;

MCF = Methane correction factor;

DOC = Degradable organic carbon;

DOC_F = Fraction of DOC dissimilated;

F = Fraction of CH_4 *in landfill gas*

(iv) *Domestic wastewater* – the estimation of CH_4 emissions was also based on Tier 1 IPCC (2006) guidelines. This depends on (i) the degradable organic component of the wastewater (BOD) (ii) the degree to which various types of wastewater treatment systems (UTS) were used by each of three income groups (IG) in a country (iii) the maximum capacity for producing methane (Max.C) and (iv) methane correction factor (MCF). IG and UTS were only available for Nigeria, and these were assumed to be the same for Cote d'Ivoire and Ghana. Methane recovery from wastewater is not known to take place in West Africa, therefore, MCF was assumed to equal zero in Equation [6]:

$$Wastewater_{methane} = Total\ population \times BOD \times IG \times UTS \times Max.C \times MCF \qquad \text{Equation [6]}$$

2.2.3. Key five emission source sub-sectors

The following key five sub-sectors were identified in Chapter 1 as potentially important emission sources that should be included in emission inventories for countries in West Africa. The methods used in estimating emissions from these activities are presented separately since methods unique to this study have been developed and applied. The methods described below focus on the estimation of the activity rates which were then used with the appropriate emission factors.

2.2.3.1. Backup generators

Electricity supply in many African countries is inadequate leading to long and regular power outages (Andersen & Dalgaard 2013) which eventually result in the need to meet the demand for electricity using backup generators (BUGs). This need varies from one country to another, meaning the importance of BUGs as a combustion emission source in a country depends on the extent to which it is used or not. According to the World Bank, power outage occurs on average 2 times a month in Cote d'Ivoire, each lasting for about 4½ hours (World Bank Group, WBG, 2016). In Ghana, the frequency of power outage is higher at about 8 times a month lasting for approximately 8 hours each time. Nigeria has the highest estimated number of power outages at 33 times a month lasting for an average of 12 hours each time. So, based on this, emissions from the use of BUGs were quantified only for Ghana and Nigeria as BUGs use in Cote d'Ivoire was not considered significant. This is also supported by the fact that Cote d'Ivoire is a net exporter of electricity to neighbouring countries and only 6.5% of firms/businesses own or share generators (WBG 2016). In contrast, 52.1% of Ghanaian and 70.7% of Nigerian firms were shown to own or share generators (WBG, 2016). In addition, while BUGs emissions in Nigeria were quantified from both residential and commercial sectors, in Ghana, only the residential sector was considered as the required data to estimate emissions from the commercial sector was not available. Furthermore, double counting was avoided while estimating emissions from backup generator use because IEA database did not provide the use of gasoline or diesel in residential and commercial sources for Nigeria and from residential source for Ghana.

Emissions from the use of BUGs were quantified in this study based on the total amount of fuel used combined with EFs. Fuel used by BUGs was calculated as a product of four variables, namely: (i) the number of households or businesses using BUGs (A), (ii) average duration of daily use (B), (iii) hourly rate of fuel consumption by each type of BUGs (C) and (iv) the number of days a week for the use of BUGs (D). That is, $Total_{fuel/week} = A \times B \times C \times D$. However, when estimating the variables used in this calculation, a few key assumptions were made. Unless otherwise stated or referenced, these assumptions were based on the author's lived experiences having lived a greater part of his life in one of the case study countries, Nigeria. But then, care was taken to minimize or eliminate bias and ensure that these key assumptions best represent the situation on ground. The assumptions are:

i) *Average duration (hours) of daily BUGs use* – This was assumed to depend on the sector, either residential or commercial. In the residential sector, households were assumed to predominantly use generators in the evening, after sunset, between the end of a normal working day and bedtime hours (a range of 4 - 6 hours). In the commercial sector, these hours vary. In Nigeria, a survey by the National Bureau of Statistics and the Small and Medium Enterprises Development Agency of Nigeria in 2010 (NCS, 2010) reported the number of hours when alternative sources of power were used. These alternative sources were assumed to be BUGs and the hours estimated in the survey were adopted in this study for the micro-, small- and medium-sized businesses. For other big institutions or service providers not categorized as a small or medium size business but within the commercial sector (i.e. hospitals and telecommunication (base stations)), daily use of BUGs was assumed to be the duration of average power outage of approximately 12 hours from WBG (2016) with a lower and upper boundary limits of ± 6 hours. Commercial banks are also classed as a big institution but average daily duration for BUGs use was assumed to be the average daily working hours of 8½ hours.

ii) *Hourly rate of fuel consumption by BUGs* – Different households and businesses require different types and sizes of BUGs depending on power requirement. For the residential sector as well as businesses (i.e. micro, small and medium businesses), a mixture of both gasoline and diesel fueled generators were assumed to be used. Households living in single rooms or flats, and micro and small businesses, were all assumed to use petrol generators with sizes ranging from 0.9 kilovolt-amperes (kVA) to 2.5 kVA. Households living in duplex and whole building and medium scale businesses were assumed to use diesel generators rated at 5.9 kVA. The rate of fuel consumption by the different sizes of generators were assumed to be those estimated by the manufacturers of the common brands of BUGs used in Nigeria, although, these fuel consumption rates in real-time might be slightly different.

iii) *Weekly use of BUGs* – In the residential sector, BUGs were assumed to be used every day of the week. Under the commercial sector, BUGs were also assumed to be used every week day by hospitals and telecommunication masts but for just five days a week for micro to medium scale businesses and commercial banks.

Fuel consumption estimates were first obtained as weekly estimates (as seen in Table 2.12) from which the total for year 2010 were calculated. So, using the appropriate EFs as seen in Table 2.11, emissions were estimated for SO_2 , NO_X, CO, NMVOC, NH_3, PM_{10}, $PM_{2.5}$, BC, OC and CH_4.

Figure 2.2: The use of backup generators in Nigeria.

Table 2.12: Sources of emission factors for diesel and gasoline used in BUGs.

Pollutant species	Gasoline	Diesel	Sources
SO_2			Mass balance approach used assuming S content of 0.1% for gasoline and 0.3% for diesel (Ref).
NO_X	513 kg/TJ	942 kg/TJ	EMEP/EEA (2016) Tier 1 EFs for gasoline and Tier 2 (Table 3-37) for diesel
CO	66 kg/TJ	130 kg/TJ	EMEP/EEA (2016) Tier 1 EFs
NMVOC	25 kg/TJ	50 kg/TJ	EMEP/EEA (2016) Tier 1 EFs
NH_3	0.101 kg/t	0.101 kg/t	Battttye et al (1994)
PM_{10}	20 kg/TJ	96 kg/TJ	EMEP/EEA (2016) Tier 1 EFs
$PM_{2.5}$	20 kg/TJ	96 kg/TJ	EMEP/EEA (2016) Tier 1 EFs
BC	11.2 kg/TJ	40 kg/TJ**	Bond et al (2004) Tables 9 and 10 **Klimont et al (2017)
OC	3.2 kg/TJ	28 kg/TJ**	Assume OC EFs is 4x higher than BC as indicated by Bond et al (2004) **Klimont et al (2017)
CH_4	10 kg/TJ	10 kg/TJ	IPCC (2006) Tier 1 EFs

Table 2.13 (a-d): Estimates of fuel consumption through the use of backup generators (BUGs) in the commercial/institutions sector (i.e. businesses, telecommunication, hospitals, commercial banks) in Nigeria for 2010

(a)

Micro, small and medium size businesses BUGs fuel consumption in 2010 for Nigeria

[1]Business size	[1]Number	[1]Number of businesses based on the daily use of backup generators in hours (% share of businesses)	Number of businesses based on daily use of BUGs	[1]Daily use of BUGs (hours/day)			[2,3,4,5,6]Assumed power rating and fuel type of generator used	[2,3,4,5]Rate of fuel consumption (litres/hour)	Weekly use of generators (days/week)	Fuel used (litres/week)		
				Lower	Average	Upper				Lower A × B(lower) × C × D	Average A × B(Average) × C × D	Upper A × B(Upper) × C × D
			A	B				C	D			
Micro (1-10 employees)	17,261,753	1-5 (74.5%)	12860006	1	3	5	0.9 kVA petrol generator	0.69	5	44367020.7	133101062.1	221835103.5
		6-10, 8 (15.7%)	2,710,095	6	8	10	0.9 kVA petrol generator	0.69		56098966.5	74798622	93498277.5
		11-15, 13 (5%)	863,088	11	13	15	1.2 kVA petrol generator	0.73		34652983.2	40953525.6	47254068
		16-20, 18 (4.2%)	724,994	16	18	20	1.2 kVA petrol generator	0.73		42339649.6	47632105.8	52924562
Small (11-50 employees)	18319	1-5 (39.8%)	7291	1	3	5	2.5 kVA petrol generator	0.94		34267.7	102803.1	171338.5
		6-10, 8 (34.9%)	6393	6	8	10	2.5 kVA petrol generator	0.94		180282.6	240376.8	300471
Medium (50 - 100 employees)		11-15, 13 (13.3%)	2436	11	13	15	5.9 kVA diesel generator	1.86		249202.8	294512.4	339822
		16-20, 18 (12%)	2198	16	18	20	5.9 kVA diesel generator	1.86		327062.4	367945.2	408828
Total fuel consumed by BUGs - Businesses (litres/week)									Diesel	576265	662458	748650
									Petrol	177673170	296828495	415983821

(b)

Telecommunication (Base stations) BUGs fuel consumption in 2010 for Nigeria

[8,9,10]Estimated number of Base Transceivers Stations	[11]Daily use of BUGs (hours/day)			Assumed power ratings and types of generator used	Rate of fuel consumption (litres/hour)	Weekly use of BUGs (days/week)	Fuel used (litres/week)		
	Lower	Average	Upper				Lower A × B(lower)× C × D	Average A × B(Average) × C × D	Upper A × B(Upper) × C × D
A	B				C	D			
16500	6	12	18	15 kVA diesel generator	2.6	7	1801800	3603600	5405400

(c)

Hospital BUGs fuel consumption in 2010 for Nigeria

[12]Hospitals	Number of units	[11]Daily use of BUGs (hours/day)			Assumed power ratings and types of generator used	Rate of fuel consumption (litres/hour)	Weekly use of BUGs (days/week)	Fuel used (litres/week)		
		Lower	Average	Upper				Lower A × B(lower) × C × D	Average A × B(Average) × C × D	Upper A × B(Upper) × C × D
	A	B				C	D			
Federal Teaching Hospitals	20	6	12	18	1650 kVA diesel generator	196	7	164640	329280	493920
Federal Medical Centres	21				1650 kVA diesel generator	196		172872	345744	518616
Specialty hospitals	13				500 kVA diesel generator	76		41496	82992	124488
Total fuel consumption - Hospitals (litres/week)								379008	758016	1137024

(d)

Commercial Banks BUGs fuel consumption in 2010 for Nigeria

[13]Total Number of Banks including their branches	[14]Daily use of BUGs (hours/day)			Assumed power ratings and types of generator used	Rate of fuel consumption (litres/hour)	Weekly use of BUGs (days/week)	Fuel used (litres/week)		
	Lower	Average	Upper				Lower A × B(lower) × C × D	Average A × B(Average) × C × D	Upper A × B(Upper) × C × D
A	B				C	D			
4599	5	8.5	11	135 kVA diesel generator	15	5	1724625	2931863	3794175

Table 2.14 (a & b): Estimates of fuel consumption through the use of backup generators (BUGs) in the residential sectors in Nigeria and Ghana for 2010

(a)

Residential BUGs fuel consumption in 2010 for Nigeria

[7]Population for 2010	[7]Total number of households (at 4.5 people/ houshold)	Further breakdown of the number of households using BUGs based on house types and fuel type		[1]Daily use of BUGs (hours/day)			Assumed power rating and type of generator used	Rate of fuel consumption (litres/hour)	Weekly use of generators (days/week)	Fuel used (litres/week)		
				Lower	Average	Upper				Lower A × B(lower) × C × D	Average A × B(Average) × C × D	Upper A × B(Upper) × C × D
		A		B				C	D			
159 619 228	35 470 940	[7]Diesel generators (assumed to be used by % of households living in duplex (0.3%) and whole building (32.4%) in 2009; total = 32.7%)		4	5	6	5.9 kW diesel generators *For households living in duplex and whole buildings	1.86	7	74301338.16	92876672.7	111452007.2
Households using BUGs (12.3%)		1426677										
		[7]Petrol generators [assumed to be used by % of households living in single room (59.2%) and flat (7.2%) in 2009; total = 66.4%]										
4 362 926		Single room	2582852				0.9 kVA petrol generators *For households living in single room	0.69		49900700.64	62375875.8	74851050.96
		Flat	341131				2.5 kVA petrol generators *For households living in Flat	0.94		8978567.92	11223209.9	13467851.88
Total fuel consumption - Residential (litres/week)									Diesel	74301338	92876673	111452007
									Petrol	58879269	73599086	88318903

(b)

Residential BUGs fuel consumption in 2010 for Ghana

[15]Population for 2010	[15]Total number of households (at 4.4 people/ household)	Estimated daily use of BUGs (hours)			Assumed number of days per week for BUGs use[3]	[15]Diesel BUGs (assumed to be used by % of households living in separate house (28.7%) and semi-detached house (7.1%) in 2010; total = 35.8%)		[2,4,5]Assumed power rating and type of BUGs used	Rate of fuel consumption (litres per hour)	Fuel consumption (litres/week)		
		Lower	Average	Upper						Lower A × B (lower) × C × D	Avergae A × B (average) × C × D	Upper A × B (upper) × C × D
		A			B	C			D			
24 658 823	5 604 278	4	5	6	4	13731		5.9 kVA diesel BUGs	1.86	**408635**	**510793**	**612952**
[15]Households using backup generators (0.7%)						[15]Petrol BUGs [assumed to be used by % of households living in flat (4.7%) and in room(s) in a compound house + others (59.5%) in 2010; total = 64.2%]						
39230						Flat	1844	2.5 kVA petrol BUGs	0.94	27734	34667	41601
						Room	23342	0.9 kVA petrol BUGs	0.69	257696	322120	386544
Total fuel consumption - Residential BUGs (litres/week)									Diesel	408635	510793	612952
									Petrol	285429	356787	428144

[1] National Micro, Small and Medium Enterprises (MSMEs) Collaborative Survey. Preliminary Report. Available online from: http://www.smedan.gov.ng/images/collaborative%20survey%20report.smedan-nbs.pdf

[2] https://www.jumia.com.ng/0.9kva-tg950-generator-tiger-mpg42135.html

2.2.3.2. Simple kerosene wick lamps

The use of kerosene lamps (as seen Figure 2.3) for lighting in developing countries is common and has recently been identified as an important residential source of black carbon (BC). According to Lam et al (2012), with reference to revised emission factors, BC emission from kerosene lamps could be as high as 20 times previous estimates. Commonly used kerosene lamps are hurricane lamps and simple wick lamps (SIM).

In this study, emissions from the use of SIM were estimated based on Lam et al (2012) which involves estimating the fraction of residential kerosene used in SIM for lighting. However, to do that, the total amount of kerosene used for lighting in the residential sector was first calculated. This fraction was given for West Africa as 24.5% (supplementary material to Lam et al. 2012). This was applied to the residential kerosene consumption values obtained from the IEA for all three countries. So, in Cote d'Ivoire, this amounts to approximately 16 ktoe (of total residential kerosene, 66 ktoe), 12 ktoe (of 49 ktoe) in Ghana and 139 ktoe (of 568 ktoe) in Nigeria in 2010. Following the calculation of kerosene used for lighting in the residential sector, the fraction used in SIM was then calculated based on the SIM hurricane lamp ratio provided by Lam et al (2012). Thus, 60% of residential kerosene for lighting was estimated to be used by SIM in West Africa while 40% was estimated for hurricane lamps. Based on this, approximately 10 ktoe of kerosene was used by SIM for lighting in Cote d'Ivoire, 7 ktoe in Ghana and 83 ktoe in Nigeria.

For the emission factors, those revised by Lam et al. (2012) were used for CO (11 kg/t) and particulates (i.e. BC (90 kg/t), OC (0.4 kg/t), $PM_{2.5}$ (93 kg/t) and PM_{10} (93 kg/t)) while EFs for CH_4 (10 kg/TJ) and NMVOC (5 kg/TJ) were sourced from IPCC (2006) Tier 1 factors for stationary combustion in the residential sector, and NO_X (25 kg/TJ) from Zhang et al (2000) for kerosene used in household stoves in China.

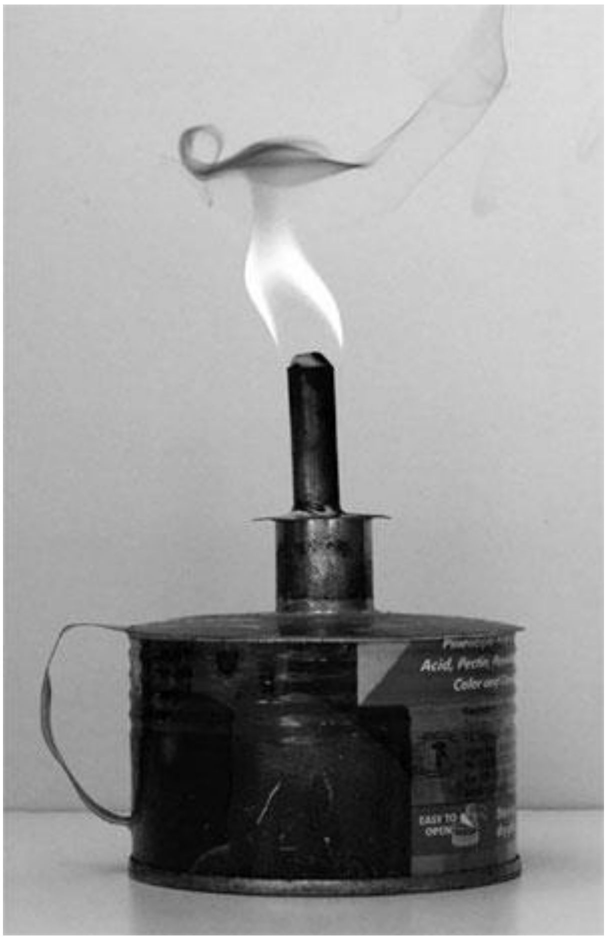


Figure 2.3: An example of a typical simple kerosene wick lamp commonly used in Cote d'Ivoire, Ghana and Nigeria.

2.2.3.3. Illegal oil refining

Exploration and production of crude oil is an activity that is now common to all three countries. However, the three countries vary widely in their capacity to undertake this activity. Nigeria has the largest capacity in the region, and indeed the whole of Africa, producing a daily average of 2.5 million barrels of crude oil (Nigerian National Petroleum Cooperation (NNPC), 2010), while Ghana only began commercial exploration in 2010 and Cote d'Ivoire's production rate is low (at 44 thousand barrels per day in 2010). Unfortunately, illegal refining of (stolen) crude oil, usually conducted in the bush, is a big problem in the oil industry of Nigeria causing serious damage to the environment, largely within the Niger-Delta region of the country. The processes involved are thought to constitute a major source of air pollutants that were not considered in existing inventories. Refining crude oil illegally is a complicated and dangerous process whereby taps are installed on oil pipelines and the stolen oil is transported to a different place, often in the bush, where it is “cooked” at night using a simplified fractional distillation technique before condensing into various petroleum products (mainly diesel ~ 41%, gasoline and kerosene ~ 2% each, with a wastage of ~55%). As a result, emissions are released into the atmosphere as both fugitive emissions and emissions from the fires used for heating the oil. The inefficiency of the process leads to a lot of wastage resulting in the pollution of both soil and water bodies of the surrounding areas.

Estimating emissions from this activity requires data which describes the exact or approximate amount of crude oil refined illegally and the appropriate emissions factors of pollutants released by this activity. Various sources, both official and unofficial, report a wide range in volume of crude oil stolen. The 2010 NNPC annual report confirmed a product loss of 194 kt in 2010, equivalent to 3,880 barrels of crude oil per day (bpd) due to pipeline vandalism (1,937 incidences) and rupture (37 incidences). A variety of other sources also estimated the quantity of crude oil stolen. Stakeholder Democracy Network, SDN (2013) estimated about 100,000 – 150,000 bpd; Chatham House (2013), 100,000 bpd; and Human Rights Watch (2003), 150,000 – 650,000 bpd. Following a special report on an extensive research performed by the United States Institute of Peace (USIP) in 2009, the range of the volume of stolen crude oil was 30,000 – 300,000 bpd (USIP, 2009) and the average of this range (I.e. 165,000 bpd) was assumed for this study. Based on data from SDN, it is assumed that 75% of stolen oil is exported illegally as crude oil while the remaining 25% is illegally refined locally (2013). Therefore, the quantity of crude oil refined illegally daily was estimated to be approximately 41,250 barrels per day amounting to approximately 2054 kt in 2010.

There are no known emissions factors for fugitive emissions from illegal oil refining. Therefore, the IPCC (2006) Tier 1 emissions factors for fugitive emissions from oil refining were used. Where available, the upper bound of the emission factor range was used bearing in mind that even with the use of the highest emission factors, emissions are likely to be substantially underestimated due to the inefficiency of the process. Emission factors for pollutants estimated from this source are SO_2 (0.92 kg/tonne crude oil), NO_X (0.06 kg/tonne crude oil), CO (0.09 kg/tonne crude oil), CH_4 (0.047 kg/tonne crude oil) and NMVOC (1.49 kg/tonne crude oil).

It is important to note that there are other emission sources associated with illegal oil refining besides fugitive emissions. In fact, they may make up the bulk of emissions from this activity. There are emissions from: i) the combustion of biomass and other types of fuel used as a source of energy to "cook" the crude oil ii) evaporation from spillage of oil iii) actual combustion of the products (e.g. diesel) by end users which were not estimated in this inventory iv) accidents that lead to unintentional oil explosions and fires due to destruction of illegal refining camps by for example, the Nigerian Navy. Consequently, emissions estimated here would still be underestimates considering these other factors.

Figure 2.4: Men conducting illegal oil refining in the Niger-Delta area (Southern region) of Nigeria. 2-stroke motorcycles

Motorcycles are common road transport vehicles used in West Africa (Figure 2.4). In the three countries, they are used as a means of private transport or commercially to generate income for many households, especially in Cote d'Ivoire and Nigeria. 2-stroke motorcycles which operates on the mixture of gasoline and oil (Assamoi & Liousse 2010) are very popular in this region as they are cheaper to buy compared with the 4-stroke ones. However, exhaust emissions of BC and OC from 2-stroke motorcycles were found to be high (i.e. 2.31 g/kg and 30.56 g/kg respectively) when measured in Cotonou (Benin Republic, another West African country) during the AMMA campaign (African Monsoon Multidisciplinary Analysis) in 2005. The study also agrees with the study by Volckens et al (2008). As a result, BC and OC as well as other combustion emissions were estimated in this work to determine how important emissions from this source are to the road transport sector and national emissions in each of the three countries.

The activity data here is total distance travelled by motorcycles. It is calculated as the product of total number of motorcycles per year (2-stroke or 4-stroke) and the average annual distance covered. Data describing the number of motorcycles in use in each of the three countries was based on the fraction of households (expressed in percentages) with motorcycles in 2010 (see Table 2.13). These fractions for 2002 were presented by Assamoi & Liousse (2010) for Cote d'Ivoire, Ghana and Nigeria. These were then scaled up to 2010 on the assumption that change in possession and use of motorcycles is driven by the change in the gross domestic product (GDP) between the two years for each country. So, the fraction of households with motorcycles in 2010 were obtained as a product of the difference in GDP and the 2002 fraction of households with motorcycles. This figure was then added to the 2002 fraction of households with motorcycles to give the 2010 fraction of households with motorcycles as seen in Table 2.13. The estimated number of motorcycles in use show that for every 1,000 people, there are approximately 22 motorcycles in Cote d'Ivoire, 5 motorcycles in Ghana and 35 motorcycles in Nigeria. Due to their popularity, 2-stroke motorcycles were assumed to account for 90% of the entire motorcycle fleet in each country, with the remainder being, 4-stroke. Furthemore, the average annual distance travelled by motorcycles in Ghana in 2010 was estimated at 7,975 km/yr (Daniel Benefor, Ghana EPA in 2015). In the absence of data for Nigeria and Cote d'Ivoire, the same value was also assumed to be the annual distance travelled by motorcycles in these countries.

The EFs reported by Guinot et al (2014) for BC and OC (i.e. 2.31 g/kg and 30.56 g/kg respectively) and also used by Assamoi & Liousse (2010) were used in this study but converted to g/km assuming the Tier 2 average fuel consumption value from Table 3.27, EMEP/EEA (2016) for 2-stroke motorcycles with engine size greater than 50 cm^3. EFs for other pollutants were assumed to be the uncontrolled EFs Tier 1 maximum values from EMEP/EEA (2016) converted to g/km assuming fuel economy from Table 3.14, EMEP/EEA (2016).

Figure 2.5: The use of 2-stroke motorcycles in Nigeria is widespread.

Table 2.15: Total number of motorcycles in Cote d'Ivoire, Ghana and Nigeria in 2010.

Country	Population (in 2010)	House -hold size	Number of households	Households with motorcycles (%)		Total number of motorcycles (2010)
				2002[c]	2010	
Cote d'Ivoire	20,131,707[a]	5.5	3,660,310	11.8	12.2	446,558
Ghana	24,658,823[b]	4.4	5,604,278	2.1	2.2	123,294[d]
Nigeria	159,616,228[b]	4.5	35,470,940	15.1	15.7	5,570,356

[a] Data from World Bank (2016)
[b] National data from: Ghana Statistical Service, 2013 for Ghana and National Bureau of Statistics, 2012 for Nigeria
[c] Data from Assamoi & Liousse (2010)
[d] This figure was replaced with the official number of motorcycles in Ghana in 2010 – 131,608 motorcycles

2.2.3.4. Unpaved roads emission

A high percentage of roads in West Africa are unpaved causing dust (i.e. PM) emissions when vehicles travel on them (Figure 2.5). In most cases, only an average of about a third or less of the entire road network in a country in Africa is paved while the rest are unpaved (Kumar & Barrett 2008; Federal Ministry of Works (FMW), 2013; Central Intelligence Agency World Factbook, CIAWF, 2017). However, most of the distance travelled by vehicles are on paved roads. Distance travelled on unpaved roads, DTU, (expressed as percentage of total distance travelled) was estimated to be 16.2% based on the data available for Nigeria (FMW, 2013). This parameter, along with the total distance travelled (TDT), percentage of dry days in a year and the EF were used to estimate dust resuspension for each type of vehicles in each country using Equation [7] below:

$E_{XUY} = TDT_Y \times DD (\%) \times DTU (\%) \times EF_D$ Equation [7]

Where,

E_{XUY} *= Emission of "X =* $PM_{2.5}$ or PM_{10}*" from "U = unpaved roads" by vehicle type "Y"*

TDT_Y *= Total distance travelled by vehicle type Y. It is a product of the total number of vehicle type "Y" and the average distance covered per year (see Table 2.5 for actual values)*

EF_D *= Dry weather EF for* PM_{10} *which requires DD (%)*(Gillies et al. 2005). $PM_{2.5}$ *was then assumed to be 10% of* PM_{10} *factor (USEPA, 2006b)*

DD (%) = This is the number of days when rainfall or precipitation is less than 0.25 mm in a year. Expressed as a percentage, it was assumed in this study to be the number of days of a typical dry season in West Africa, which is approximately 40%.

DTU (%) = Fraction of TDT on unpaved road, estimated as 16.2% for Nigeria. This was also assumed to be the case for Cote d'Ivoire and Ghana which lack such data. This was considered appropriate as the 3 countries have comparable percentages of unpaved roads (92% for Cote d'Ivoire, 87% for Ghana and 85% for Nigeria) (CIAWF, 2017).

Figure 2.6: Unpaved roads

2.2.4. Uncertainty analysis methods

Uncertainties in inventories can be combined using standard error propagation techniques. This technique was used in this study to estimate the level of uncertainties associated with the estimated emissions. Where the uncertain quantities are to be combined by multiplication, for example emission factor x activity rate, then the combined uncertainty is equal to the square root of the sum of the squares of the individual % uncertainties. For example, if the uncertainty for both was ±10%, the combined uncertainty would be SQRT (10^2 + 10^2) = ±14.1%. (This is called the 'Root-sum-squares' or the 'Rule B' method as described in Chapter 3 of the IPCC (2006) Guidelines.)

The 'Rule A' method (IPCC, 2006) can then be used where the uncertain quantities are to be combined by addition e.g., if the uncertainties in BC emissions (calculated using Rule B above) from different fuels used within a sector are to be combined. In this case, to give the overall uncertainty in BC emission for the whole sector, the individual % uncertainties must first be weighted according to that fuel's contribution to the total BC emission for that sector, and then the 'root-sum-squares' of these weighted %s will give the combined uncertainty of BC emissions from that sector.

The inventory is essentially the sum of products of emission factors and activity data and so Rules A and B was used repeatedly to estimate the combined uncertainty in the total emissions of a particular pollutant such as BC. Table 2.16 below shows a worked example of how the lower uncertainty bounds were calculated for $PM_{2.5}$ in Nigeria for combustion in energy sector 2010 emissions. This is intended to demonstrate how the lower uncertainty bound was calculated for each sub-sector before arriving at the lower uncertainty bounds for the energy sector. Following this, the overall lower uncertainty bound for $PM_{2.5}$ was then calculated in Table 2.17 for the whole country.

Table 2.16: Worked example of the calculation of the lower uncertainty bound for $PM_{2.5}$ for combustion in energy sector Nigeria for 2010 emissions

Sectors (in bold)/sub-sectors (italics)	**Fuel type, F**	**Activity data (ktoe) A**	**Net calorific value (toe/t), NCF**	**Emission factor (kg/t) EF**	**Emissions (t), E**	**Activity data uncertainty (%), Au**	**Lower EF 95% confident interval (kg/t), LEF**	**LEF as % of EF**	**Combined Lower uncertainty (%), C**	**Combined lower uncertainty weighted by contribution to emissions (%), CW**	**Sub-sector combined lower uncertainty (%)**
					E = A/NCF x EF				C = Sqrt (A^2 + LEF^2)	CW = C x E/sub-sector total emission	
Combustion in energy industries											
1. Public electricity and heat											
	Natural gas, F1	3609	1.2137	0.045	133.81	10	0.0225	50.0	51.0	16.7	
	Gas/diesel oil, F2	361	1.035	0.035	12.21	10	0.013	62.86	63.65	1.9	
	Heavy fuel oil, F3	323	0.9599	0.78	262.46	10	0.036	95.38	95.91	61.7	
	Sub-sector total emission (t), ESS₁				***408***						
	Sub-sector combined lower uncertainty (%), CSS₁ = Sqrt ((CW$_{F1}$)^2 + (CW$_{F2}$)^2 + (CW$_{F3}$)^3)										***63.9***

Sectors (in bold)/sub-sectors (italics)	Fuel type, F	Activity data (ktoe) A	Net calorific value (toe/t), NCF	Emission factor (kg/t) EF	Emissions (t), E	Activity data uncertainty (%), Au	Lower EF 95% confident interval (kg/t), LEF	LEF as % of EF	Combined Lower uncertainty (%), C	Combined lower uncertainty weighted by contribution to emissions (%), CW	Sub-sector combined lower uncertainty (%)
					E = A/NCF x EF				C = Sqrt (A^2 + LEF^2)	CW = C x E/sub-sector total emission	
2. Petroleum refining											
	Natural gas, F4	14	1.2137	0.045	0.52	10	0.0225	66.66	67.40	0.3	
	Refinery gas, F5	57	1.150	0.043	2.13	10	0.022	48.84	49.85	1.0	
	LPG, F6	14	1.130	0.042	0.52	10	0.021	50.00	50.99	0.2	
	Gas/diesel oil, F7	28	1.035	0.035	0.95	10	0.013	62.86	63.65	0.6	
	Heavy fuel oil, F8	277	0.9599	0.362	104.46	10	0.217	40.06	41.29	39.4	
	Petroleum coke, F9	2	0.7404	0.362	0.98	10	0.217	100.00	100.50	0.9	
	Sub-sector total emission (t), ESS_2				***109.56***						
	Sub-sector combined lower uncertainty (%), CSS_2 = Sqrt $((CW_{F4})^2 + (CW_{F5})^2 + (CW_{F6})^2 + (CW_{F7})^2 + (CW_{F8})^2 + (CW_{F8})^2)$										***39.39***

3. Manufacture of solid fuels and other energy										
• **Other own use**	Natural gas, F10	1978	1.2137	0.045	73.34	10	0.068	51.11	52.08	
• **Charcoal production**	Wood, F11	3349	0.3702	2.6	23520.8	10	0.87	66.54	67.29	
	Sub-sector total emission (t), ESS_3				***23594.14***					
	Sub-sector combined lower uncertainty (%), CSS_3 = Sqrt $((CW_{F1})^2 + (CW_{F2})^2 + (CW_{F3})^3)$									***85.09***
Total emissions for the Energy sector (t), ESS_T = $ESS_1 + ESS_2 + ESS_3$ = 24111.70										
Sector combined lower uncertainty (%), CS_1 = Sqrt $((CSS_1 \times ESS_1/ESS_T)^2 + (CSS_2 \times ESS_2/ESS_T)^2 + (CSS_3 \times ESS_3/ESS_T)^2)$										83

Table 2.17: Worked example of the calculation of lower uncertainty bounds for $PM_{2.5}$ from all emission source sectors in Nigeria for 2010 $PM_{2.5}$ emissions.

Sector	Emissions (t) E	Sector combined lower uncertainty (%) CS
Combustion in energy sector - (1)	24.13	83
Combustion in manufacturing industries – (2)	53.94	0
Combustion in transport sector – (3)	100.71	30
Combustion in other sectors –(4)	1863.11	48
Fugitive emissions from fuels – (5)	0.00	0
Industrial processes – (6)	0.73	51
Solvent and other product use – (7)	0.00	0
Agriculture – (8)	117.36	27
Vegetation fires and forestry – (9)	471.55	33
Waste – (10)	226.1	74
Total $PM_{2.5}$, ET =	**2857.63**	
Overall lower uncertainty bound for $PM_{2.5}$ emissions in Nigeria in 2010 = $(E1/ET \times CS1)^2 + (E2/ET \times CS2)^2 + (E3/ET \times CS3)^2 + (E4/ET \times CS4)^2 + (E5/ET \times CS5)^2 + (E6/ET \times CS6)^2 + (E7/ET \times CS7)^2 + (E8/ET \times CS8)^2 + (E9/ET \times CS9)^2 + (E10/ET \times CS10)^2$ = 32.3%		

2.3. Results

Previous sections of this chapter described how national emissions were estimated for Cote d'Ivoire, Ghana and Nigeria. This section presents the relative importance of emissions from the 5 key sources within the context of national emissions (Section 2.3.1) followed by the sectoral contribution of emissions from each of the 5 key sources (Section 2.3.2). Then, the share of national emissions from various emission source sectors (described in Sections 2.2.1 and 2.2.2) is presented in Section 2.3.3 including an analysis of how these vary among the three countries. Lastly, the national emissions obtained in this study are compared with other available inventories (Section 2.3.4).

2.3.1. Overview of emissions from the 5 key sources

Assessing the overall and individual contribution of emissions from the 5 key sources to national emissions in 2010 will allow an evaluation of the contribution of emissions or impacts from these sources in each country. Figure 2.7 below is a graph which shows the share of national emissions from the 5 key sources. It is clear from this figure that each of the 5 key sources (i.e. BUGs, ILL, TWO, UNP or SIM) is important for the emission of certain pollutant(s), that is, not all pollutants included in this study are emitted from these 5 key sources. SIM is important for BC emissions and UNP for PM emissions. In a case where a pollutant is emitted by more than one of the 5 key sources, emissions (of that pollutant) were added together before calculating its share of national emission from the 5 key sources. An example is NMVOC emissions from the use of BUGs, TWO and ILL in Nigeria.

Pollutants considered to be of significance from the 5 key sources are only those which accounts for 5% of national emissions or more. As a result:

(1) $PM_{2.5}$, BC, NMVOC, SO_2 and NO_X are the pollutants with substantial emissions from the 5 key sources. However, not all these pollutants are emitted from the 5 key sources in all three countries. For instance, in Ghana, $PM_{2.5}$ is the only pollutant of national significance from the 5 key sources whereas, in Cote d'Ivoire, pollutants significantly emitted from the 5 key sources are $PM_{2.5}$, NMVOC and BC.

(2) In Nigeria, emissions from the 5 key sources are generally more important than in Cote d'Ivoire and Ghana. Emissions of BC, NMVOC, SO_2 and NO_X from the 5 key sources in Nigeria all account for higher shares of national emissions than in Cote d'Ivoire and Ghana.

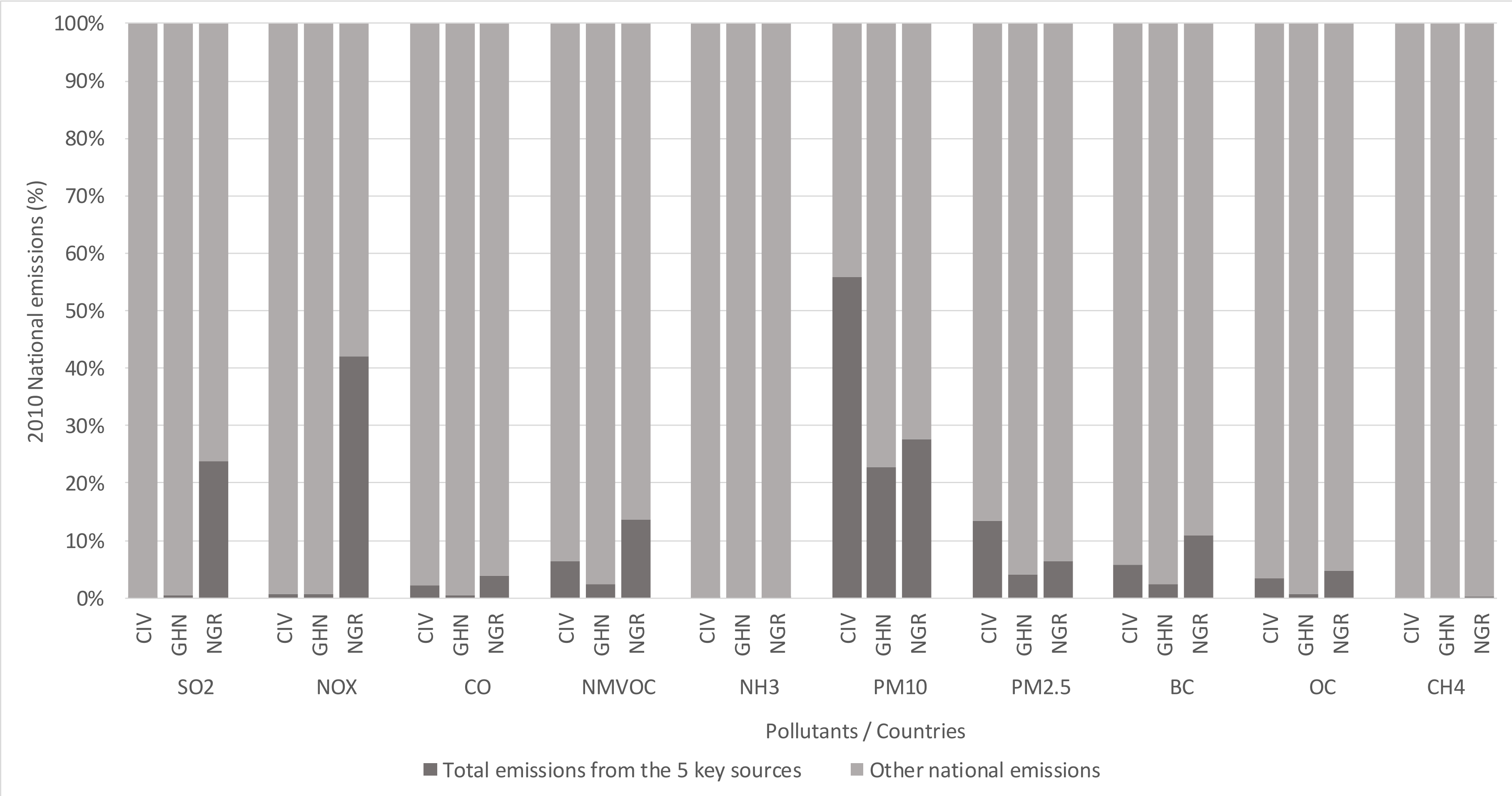


Figure 2.7: Share of national emissions from total emissions from the 5 key sources in Cote d'Ivoire, Ghana and Nigeria in 2010

(3) $PM_{2.5}$ emissions from all 5 key sources account for 13% of national estimates in Cote d'Ivoire and 9% in Ghana. This is essentially from unpaved road as there was no significant emission from the other key sources. NMVOC and BC emissions comprise 9% and 6% of national emissions in Cote d'Ivoire, and 13% and 8% in Nigeria respectively.

(4) NMVOC emissions from the 5 key sources were almost entirely from 2-stroke motorcycles although in Nigeria, BUGs also made a small contribution.

(5) For BC, the key source emissions were mainly from SIM and BUGs. In Cote d'Ivoire, SIM was the main source as emissions were not estimated from BUGs (see Section 2.2.3). However, in Nigeria, BC is only significant when emissions from the two sources are considered together and not singly. That is, BC emissions from SIM alone or BUGs alone did not meet the 5% significance criteria.

(6) NO_X and SO_2 emissions from the 5 key sources, mainly BUGs, were only significant in Nigeria accounting for 40% and 17% of national emissions respectively.

(7) The only pollutant from the 5 key sources that was significant in all three countries was PM_{10} accounting for approximately 52%, 42% and 18% of national emissions in Cote d'Ivoire, Ghana and Nigeria respectively.

2.3.2. Sectoral significance of emissions from the 5 key sources

The above analysis of the contribution of emissions from the 5 key sources to national estimates shows the pollutants of concern from these sources in each country. However, analysing emissions from the 5 key sources from a national perspective alone might obscure the relevance of emissions from each of the 5 key sources within the relevant source sectors. So, exploring the significance of emissions from each of the 5 key sources at the sectoral level will help determine if undertaking emission reduction measure(s) of each of the 5 key sources is beneficial at reducing emissions from the relevant sector.

2.3.2.1. Residential and Commercial sectors: Backup generators (BUGs) and Simple kerosene wick lamps (SIM)

The use of BUGs and SIM are classed under 'Fuel combustion in Other Sectors' which consists of the residential, commercial, agriculture/forestry/fisheries sectors. As explained earlier, emissions from the residential use of backup generators (rBUGs) were only estimated for

Ghana and Nigeria while emissions from SIM were estimated for all three countries (see Section 2.2.3.1).

Analysis of emissions from rBUGs show NO_X and SO_2 are the largest pollutants from this source going by the absolute values of emissions. In Nigeria, total residential NO_X and SO_2 emissions in 2010 were 503 kt and 212 kt respectively. Of these estimates, rBUGs account for almost half (i.e. 49%) of residential NO_X emissions and 15% of residential SO_2 emissions (Figure 2.3). However, in Ghana, emissions from rBUGs are of less significance where they account for 9% of residential NO_X emissions and 2% of residential SO_2 emissions. The difference between the share of emissions from rBUGs in the residential sector in Nigeria and Ghana is due to the difference in the demand for electricity met using rBUGs. In Nigeria, less than 20% of electricity required in the residential sector was met by the national grid (according to the LEAP-IBC modelling) in Chapter 3. As a result, a greater share (i.e. 77%) of electricity required in the residential sector in Nigeria was met by rBUGs as opposed to the situation in Ghana where over 80% of electricity required in the residential sector was met by national grid and only 8% of electricity came from rBUGs. Furthermore, the use of BUGs is not only restricted to the residential sector in Nigeria where they are also commonly used in commercial and institutional buildings. Together, the use of BUGs in Nigeria accounts for 39% of national NO_X emissions and 16% of national SO_2 emissions, clearly showing that it is a major source of these pollutants in this country.

On the other hand, BC is the main pollutant emitted from the use of SIM. In 2010, residential BC emissions in Cote d'Ivoire, Ghana and Nigeria were approximately 11 kt, 10 kt and 267 kt respectively. Of these values, SIM accounts for 10% in Cote d'Ivoire, 6% in Ghana and 3% in Nigeria. This suggests that, in all three countries, SIM is not a particularly big source of BC compared with other emission sources within the residential sector due to the level of activity involved. For instance, cooking using wood fuel is another residential source of emissions. Combustion of wood fuel here dominates all other combustion activities within the residential sector. In Ghana, 2848 ktoe of wood was used in traditional wood stoves for cooking in 2010 compared with 7 ktoe of kerosene used in simple wick lamps for lighting. So, although, the rate of BC emission (i.e. emission factor) from the use of SIM is high at 90 kg/tonne (Lam et al. 2012) compared with 1.12 kg/tonne (Klimont et al. 2016) for wood fuel combustion using traditional cook stoves, BC emissions from traditional cook stoves dominants residential emissions due to the amount of wood involved.

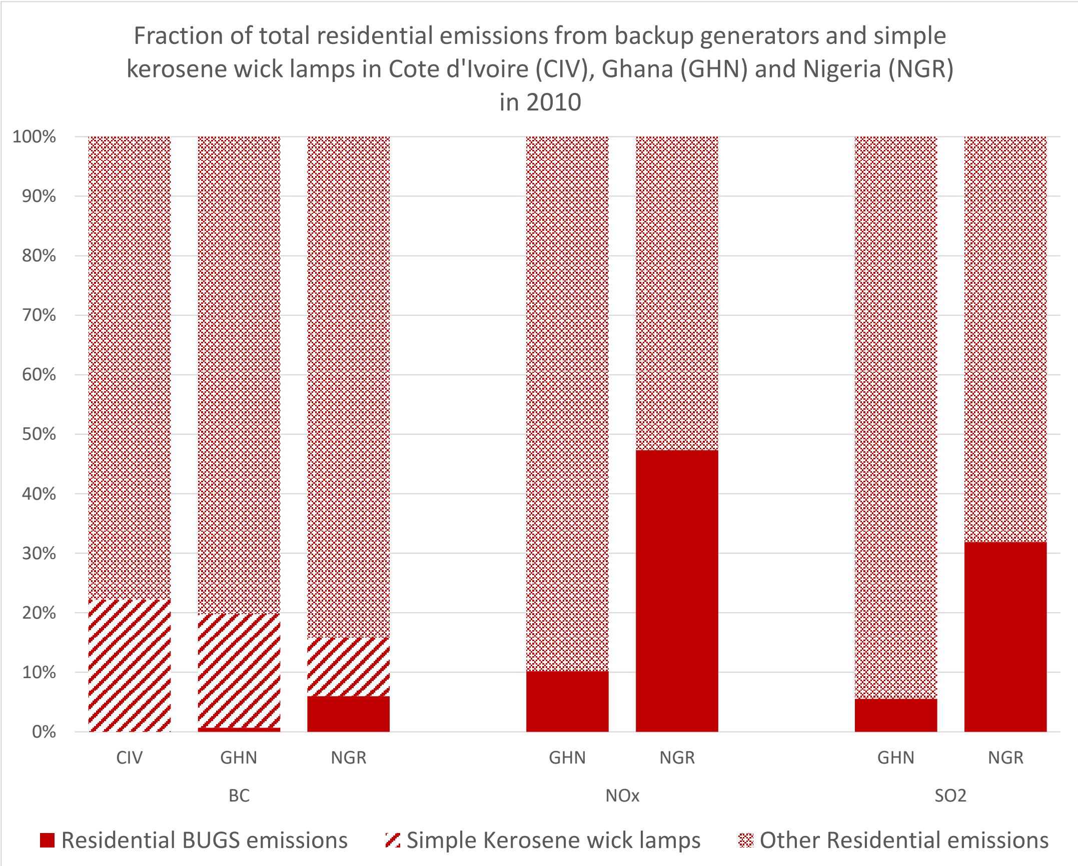


Figure 2.8: Residential emission of BC, NO_X and SO_2 showing the share of emission from the residential use of BUGS (rBUGs) and simple kerosene wick lamps in 2010 for all three countries (Note: emissions from rBUGs were not estimated for Cote d'Ivoire)

2.3.2.2. Fugitive emissions sector: Illegal oil refining

Common pollutants which escape or are released during the production and distribution of fuels are SO_2, NO_X, CO, NMVOC, CH_4, and PM (i.e. BC and OC from coke production). Among the three countries, illegal refining of crude oil only occurs in Nigeria and fugitive emissions from this source contributes 30% of total fugitive emissions for SO_2, NO_X and CO while only 2% of total fugitive NMVOC are emitted from this source and emissions of CH_4 are negligible.

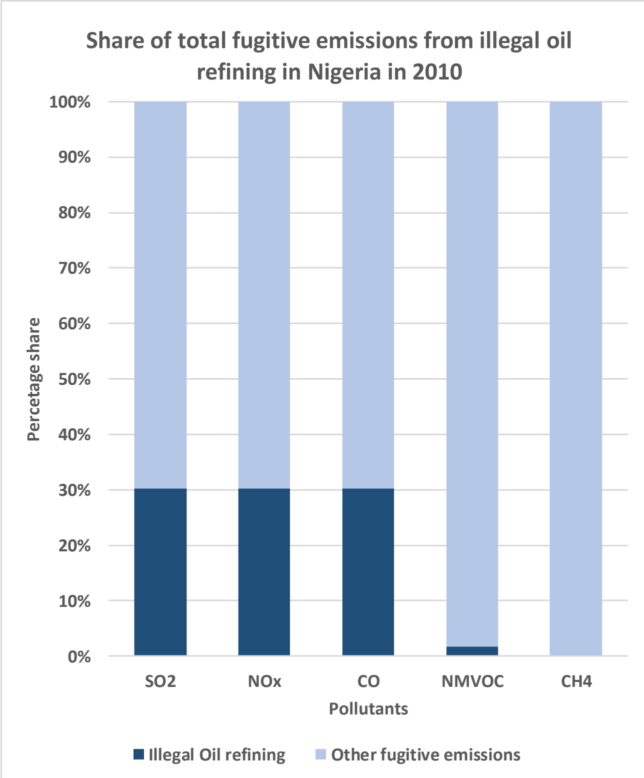


Figure 2.9: Chart showing the share of emissions from illegal refining of crude oil within the fugitive emissions sector in Nigeria in 2010.

2.3.2.3. Road transport: 2-Stroke motorcycles (TWO) and Unpaved roads (UNP)

Analysis of road transport emissions shows that the use of TWO is important for the emissions of several pollutants in the sector. In all three countries, NMVOC, CO and PM (especially OC) emissions from TWO each make up a significant fraction of road transport emissions (Figure 2.5). Apart from these three pollutants, BC emissions from TWO are also important in Nigeria.

Of all the pollutants identified here, NMVOC and OC are the largest ones based on the share of road transport emissions from TWO. In Cote d'Ivoire and Ghana, NMVOC is the largest pollutant from TWO. In 2010, it accounts for more than half of road transport emissions in Cote d'Ivoire, approximately 67%, while in Ghana, it accounts for 31%. Following NMVOC emissions from TWO in both countries is OC and CO. OC from TWO make up 48% and 18% of road transport OC emissions in Cote d'Ivoire and Ghana respectively while CO accounts for 28 and 11% respectively. In Nigeria, this order of importance based on the share of road transport emissions from TWO is different. While more than half of road transport NMVOC emission come from TWO (just like in Cote d'Ivoire) at approximately 77%, OC emissions from TWO is much more important in Nigeria at 80% of total road transport OC emissions in 2010. This is because 2-stroke motorcycles are prolific emitters of OC compared to other types of road vehicles (i.e. passenger cars, light duty vehicles or heavy-duty vehicles). For instance, the emission factor for 2-stroke motorcycles is 1.069 g/km. This is approximately 66 times more than the corresponding figure for gasoline fuelled (uncontrolled) passenger cars at 0.0022 g/km. So, the high number of 2-stroke motorcycles estimated for Nigeria (5,013,320) highlights 2-stroke motorcycles as a large OC source within the road transport sector.

Therefore, implementing emission reduction measures for TWO as a means of reducing road transport emissions would benefit Nigeria the most, being the country with the highest fractions of road transport emissions from TWO, followed by Cote d'Ivoire and then Ghana. This also corresponds to the number of 2-stroke motorcycles in each of the three countries suggesting that future increases in the number 2-stroke motorcycles might result in increase in its share of road transport emissions (see Section 2.2.3.4).

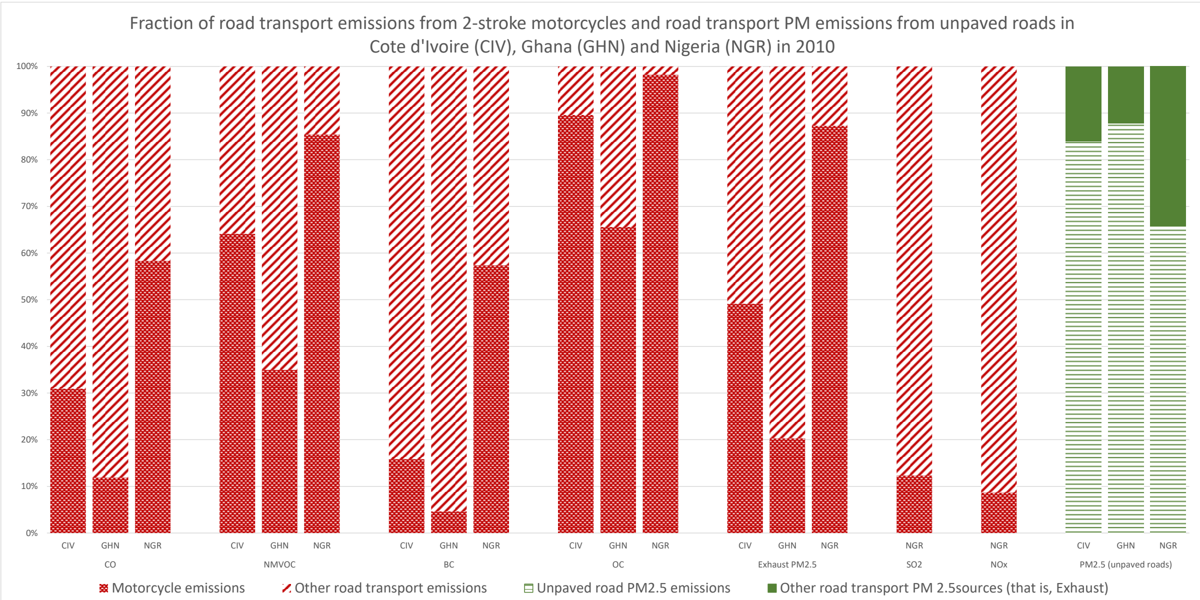


Figure 2.10: Share of road transport emissions from 2-stroke motorcycles and unpaved roads in all three countries in 2010

2.3.3. National emission estimates, uncertainty limits and sectoral breakdown of emissions by country

Presented in Table 2.14 are total emissions of pollutants for Cote d'Ivoire, Ghana and Nigeria in 2010. As expected, Nigeria is the biggest source of all pollutants among the three countries. It has the largest population size, consequently, having a high demand for energy, manufactured goods, transportation, food, and other requirements to meet its needs. In fact, total emission of any pollutant in Nigeria is at least approximately 7 times the equivalent in Cote d'Ivoire or Ghana and could be as high as 15 times, as the case of BC emission in Cote d'Ivoire.

Furthermore, Nigeria differs from Cote d'Ivoire and Ghana in the share of national emissions from various source sectors for most pollutants. The biggest source of almost all pollutants in Nigeria is the residential sector as seen in Figure 2.12, except for NH_3 and CH_4, where agriculture sector is the largest source. This is a result of the huge amount of energy required by people to cook in their homes and the demand was met using predominantly wood fuel. In addition to the use of wood fuel for cooking, residential use of BUGs to generate electricity is also equally important for NO_X emission from the residential sector in Nigeria. The use of wood fuel and BUGs are huge combustion emission sources due to the large amount of fuel required and the inefficient combustion processes of the two activities. For instance, cooking using wood fuel and the residential use of BUGs each account for approximately 16% of national NO_X emissions in 2010. So, on a national scale, both activities together account for approximately 33% of NO_X emissions. For other pollutants, the residential sector accounts for approximately 54% of SO_2, 51% of NMVOC, 58% of CO, 74% of BC and 62% of OC emissions in Nigeria.

On the other hand, Cote d'Ivoire and Ghana are similar to each other regarding the largest sources of most pollutants except for SO_2 and NMVOC. Vegetation fires and forestry is the biggest source sector for OC, $PM_{2.5}$ and CO in both countries. In Cote d'Ivoire, this sector accounts for 37%, 28% and 28% of national emissions of these three pollutants respectively while in Ghana, it accounts for 46%, 37% and 39% respectively due to the burning of large amount of biomass. For NO_X and PM_{10}, the transport sector is the biggest source accounting for 49% and 52% of national estimates respectively in Cote d'Ivoire while in Ghana, they account for 36% and 42% respectively. Most PM_{10} emission in the transport sector is from unpaved roads and not exhaust emission. In addition, the biggest source of NH_3 and CH_4 in both countries is the agriculture sector. In Cote d'Ivoire, the residential sector accounts for the biggest share of SO_2 emissions at 24%, while the transport sector is the largest source of NMVOC emissions at 36%. Conversely, the energy industry in Ghana accounts for the biggest share of SO_2 and NMVOC emissions because crude oil (with high sulphur content) is part of the fuel mix used by the power plants to generate grid electricity in the country.

Despite this wide gap in absolute values of emissions, all three countries are similar in their largest source of BC, NH_3 and CH_4. The residential sector is the largest source of BC in all three countries (46% (CIV), 33% (GHN), 74% (NGR)) because of the extensive use of wood fuel for cooking while the agriculture sector is the largest source of NH_3 (57% (CIV), 56% (GHN), 47% (NGR)) and CH_4 (29% (CIV & GHN), 33% (NGR)). This is mostly due to ammonia emissions from manure management and methane from the rearing of ruminant animals in large numbers. In addition, emissions from industrial processes, solvent and product use sector were insignificant reflecting the general low level of industrialisation across the sub-region compared to developed countries.

Table 2.18: Summary of national emissions in 2010 and the uncertainty estimates for all pollutants for Cote d'Ivoire, Ghana and Nigeria. In parenthesis under each pollutant and next to the lower and upper bounds are the uncertainty limits expressed in percentage.

Country/ Pollutants Uncertainty limits (%)	**SO_2**	**NO_X**	**CO**	**NMVOC**	**NH_3**	**PM_{10}**	**$PM_{2.5}$**	**BC**	**OC**	**CH_4**
Cote d'Ivoire (kt)	29	172	2859	470	98	591	250	24	110	412
Lower bound	26(-9)	155(-10)	2431(-15)	366(-22)	84(-14)	514(-13)	225(-10)	20(-15)	98(-11)	354(-14)
Upper bound	32(12)	186(8)	3317(16)	597(27)	108(11)	680(15)	275(10)	25(5)	123(12)	453(10)
Ghana (kt)	56	229	3710	468	114	720	346	31	159	470
Lower bound	45(-19)	188(-18)	3042(-18)	337(-28)	90(-21)	598(-17)	248(-18)	24(-22)	129(-19)	395(-16)
Upper bound	71(27)	261(14)	4452(20)	627(34)	137(20)	842(17)	388(12)	36(14)	188(18)	545(16)
Nigeria (kt)	392	1555	25743	4088	1144	4239	2858	364	1358	4091
Lower bound	333 (-15)	1228(-21)	15960(-38)	1962(-52)	915(-20)	3476(-18)	1934(-32)	174(-52)	1018(-25)	3231(-21)
Upper bound	800(104)	1866(20)	32436(26)	5069(24)	1362(19)	5086(20)	3658(28)	393(8)	1792(32)	5195(27)

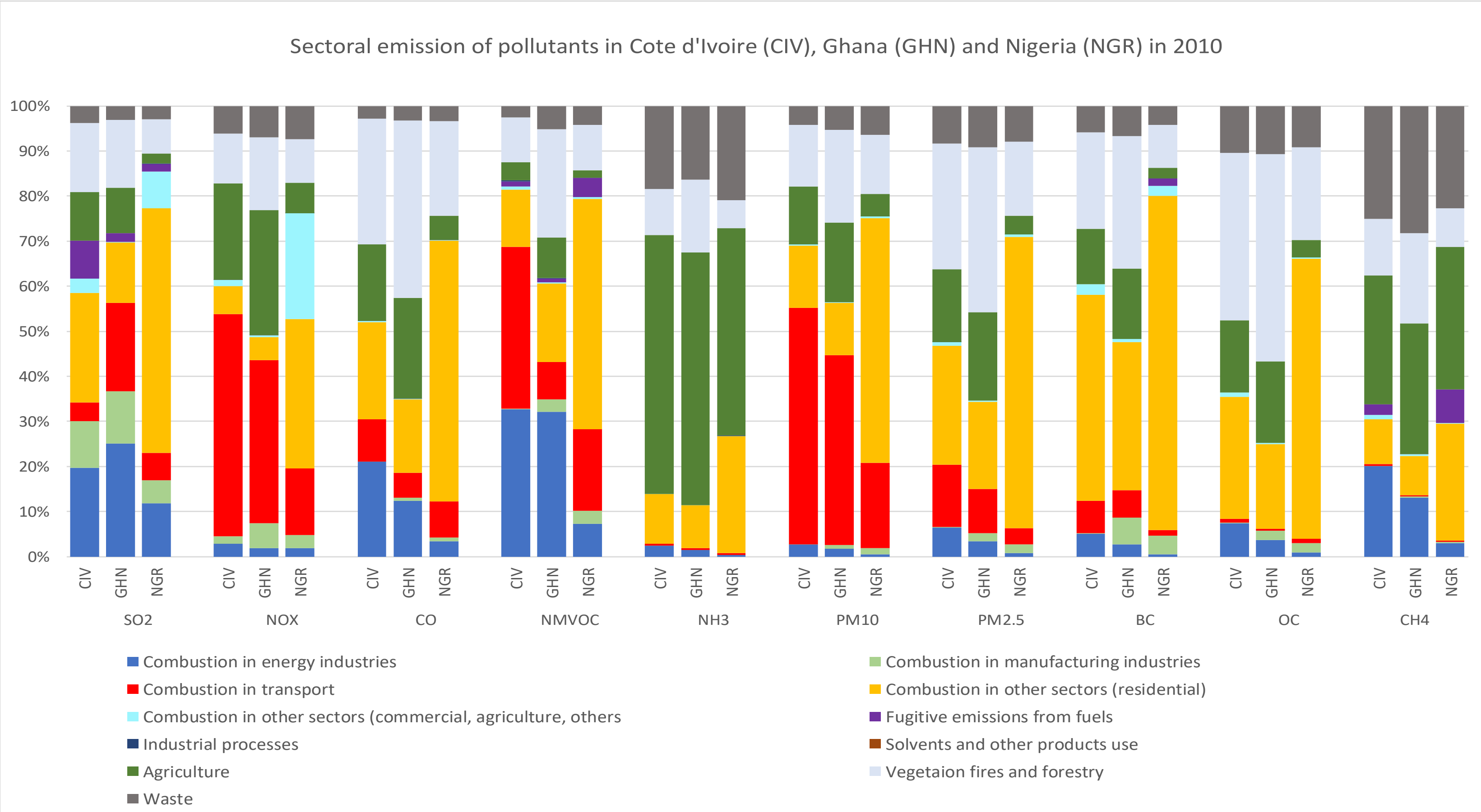


Figure 2.11: Share of national emissions from various source sectors for Cote d'Ivoire, Ghana and Nigeria in 2010. N.B.: For PM_{10} and $PM_{2.5}$, combustion in transport sector contains both road dust and exhaust emissions.

2.3.4. Comparison of estimates with global inventories

Emissions estimated in this study for Cote d'Ivoire, Ghana and Nigeria were compared with other available inventories. For this comparison, national estimates from global inventories, EDGAR (Emissions Database for Global Atmospheric Research) and GAINS (Greenhouse Gas and Air Pollution Interaction and Synergies), are the only inventories included. Specifically, they are EDGAR v4.3.1 and GAINS Eclipse V5a emissions for 2010. Although, there are greenhouse gas (GHG) inventories developed by each of the three countries to fulfil their commitments to the climate agreement of the United Nations Framework Convention on Climate Change, UNFCCC, these were not included due to their specificity and limitations on pollutants covered. Both EDGAR and GAINS inventories have corresponding estimates of all pollutants included in this study as well as broadly the same emission source sectors or categories. They both estimate emissions for traditional air pollutants and greenhouse gases.

On comparison of the three inventories (i.e. from this study, EDGAR v4.3.1 and GAINS Eclipse V5a), results show considerable differences in emissions. While EDGAR estimates for most pollutants are generally higher than GAINS estimates for Nigeria, the reverse is the case for Cote d'Ivoire and Ghana. However, estimated emissions in this study for all three countries are significantly higher than estimates from both EDGAR and GAINS for most pollutants. Exceptions to this are the emissions of SO_2 and BC in Cote d'Ivoire and Ghana, and CH_4 emissions for all three countries where emissions are higher in one of the two global inventories. For Cote d'Ivoire, SO_2 and BC emissions in this study are higher than the corresponding EDGAR estimates but lower than estimates from GAINS as seen in Table 2.16. For Ghana, SO_2 emission in this study is lower than EDGAR estimate but higher than GAINS estimate. For SO_2, this is probably due to differences in the assumption for the sulphur content of fuel while differences in BC emission factors might be responsible for the difference in BC emissions.

The high estimates obtained in this study are up to several-fold higher than those from EDGAR or GAINS for some pollutants with the largest difference in emissions being for NMVOC for all three countries. In this study, NMVOC estimates of 622 kt, 468 kt and 4088 kt for Cote d'Ivoire, Ghana and Nigeria respectively, are approximately 16 times higher than EDGAR estimate for Cote d'Ivoire, almost 6 times higher for Ghana and three times higher for Nigeria. When compared with GAINS estimates for NMVOC, the difference is much lower at 110% for Cote d'Ivoire, 39% for Ghana and 82% for Nigeria. Conversely, for those pollutants whose emissions are lower in this study than either EDGAR or GAINS estimates (mentioned above), estimated emissions in this study are less than EDGAR or GAINS estimates by a much smaller fraction. For instance, CH_4 estimated in this work is less than EDGAR estimate by 46%, 52% and 3% for Cote d'Ivoire, Ghana and Nigeria.

Furthermore, pollutants with significant national contribution from the 5 key sources show clear reduction in the differences between emissions estimated in this study and the global inventories when emission from the key sources are removed. For instance, total NO_X and SO_2 emissions from the 5 key sources in Nigeria accounts for 40% and 17% of national emissions while PM_{10} emissions from these key sources account for 52%, 42% and 19% in Cote d'Ivoire, Ghana and Nigeria respectively. Without emissions from the 5 key sources, national estimate of NO_X would have been 933 kt meaning a 50% increase of EDGAR emissions as opposed to the 149% (i.e. 3-fold) increase when NO_X emission from the key sources is included in the national estimate. PM_{10} emissions for Cote d'Ivoire without the contribution from the 5 key sources would have just been the same as EDGAR estimate, and PM_{10} estimate for Ghana which is higher than EDGAR or GAINS estimates by approximately 236% would have just been 95% higher. For Nigeria, PM_{10} would have just been higher than EDGAR estimate by 23% instead of 55% and the SO_2 emissions which is 95% higher than EDGAR estimate would have reduced to 62%.

Notably, road transport emissions calculated in this study are higher than the corresponding estimates by EDGAR for Cote d'Ivoire. This is also the case for Ghana and Nigeria except for CO and NMVOC in Ghana, and NO_X and CO for Nigeria. This is most likely due to the use of a more detailed approach used to estimate road transport emissions in this study which involves the disaggregation of vehicles into the different categories rather than just estimating based on total fuel consumption in road transport. While road transport emissions in this study for Cote d'Ivoire are also higher than GAINS transport estimates for most pollutants other than SO_2 , $PM_{2.5}$ and CH_4, GAINS transport estimates are higher for most pollutants in Ghana and Nigeria. Most likely, this is because GAINS transport emissions contains emissions from other transport sources besides road transport.

Sectoral analysis of emissions shows that the residential sector is the biggest source of most pollutants in all three countries in EDGAR and GAINS inventories. This is also true in this study for Nigeria emissions which includes large emissions from the residential use of BUGs but national estimates for Cote d'Ivoire and Ghana in this study show more diverse largest emission sources. This show the importance of including all relevant emissions sources when compiling national inventories. This is clearly not the case for EDGAR inventory which for most pollutants, does not contain emission estimates from savannah burning or vegetation fires and forestry which is common to all three countries.

Table 2.19: Comparison of emissions results with global inventories

Country / Pollutants		SO_2	NO_X	CO	NMVOC	NH_3	PM_{10}	$PM_{2.5}$	BC	OC	CH_4
Cote d'Ivoire (kt)	This study	29	172	2859	622	98	591	250	24	110	412
	EDGAR v4.3.1[a]	18	44	1619	38	66	281	94	18	387	768
	GAINS Eclipse[b]	33	58	1829	296	69	185	168	29	69	319
Ghana (kt)	This study	56	229	3710	468	114	720	346	31	159	470
	EDGAR v4.3.1[a]	60	99	1637	82	62	214	97	16	36	984
	GAINS Eclipse[b]	48	86	2243	337	65	212	195	33	78	285
Nigeria (kt)	This study	392	1555	25743	4088	1144	4239	2858	364	1358	4091
	EDGAR v4.3.1[a]	201	624	20765	1345	708	2732	1415	194	600	4229
	GAINS Eclipse[b]	120	598	10300	2250	657	996	883	149	346	4369

[a] 2010 EDGAR v4.3.1 emissions estimates and EDGAR CH_4 emissions for 2010 (unit: kt/yr). Available from: http://edgar.jrc.ec.europa.eu/overview.php?v=431 and http://edgar.jrc.ec.europa.eu/overview.php?v=42

[b] GAINS global Eclipse emissions for 2010 extracted for the three countries. Available from: http://www.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5a.html

2.4. Discussions

2.4.1. How important are the 5 key sources to national anthropogenic emissions for each country?

This inventory has assessed the role of 5 key emitting activities to total anthropogenic emissions for key pollutants in three West African countries. The importance of these activities varied depending on country, emission sector and the pollutant(s) considered. Total emissions from these 5 key sources were found to make up a substantial fraction of total NO_X, SO_2 , NMVOC, BC, $PM_{2.5}$ and PM_{10} emissions in Nigeria; they account for 40%, 23%, 13%, 8%, 5% and 19% of national emissions respectively, with the most influential of the key sources being the use of BUGs, the use of 2-stroke motorcycles and vehicular use of unpaved roads (see Section 2.3.2). In Cote d'Ivoire and Ghana, total emissions from these key activities have a far less significant contribution to the respective national estimates for most pollutants. The exception to this for both countries is $PM_{2.5}$ and PM_{10} which is largely from unpaved roads. $PM_{2.5}$ make up 13% and 9% of national emissions in Cote d'Ivoire and Ghana, and PM_{10} contributes 52% and 42% respectively. In addition, NMVOC and BC emissions from the 5 key sources are also significant in Cote d'Ivoire accounting for 7% and 6% of national emissions respectively. largely from the use of 2-stroke motorcycles and simple kerosene wick lamps.

Results obtained also show that within the (road) transport sector, the use of 2-stroke motorcycles is a large source of CO, NMVOC and OC in all three countries. Furthermore, in Nigeria, where the estimated number of 2-stroke motorcycles is more than other vehicle types, they can be a significant source of BC and CH_4 as well. Vehicles travelling on unpaved roads is the main source of PM emissions from road transport in all three countries.

In the residential sector the use of BUGs is a large source of NO_X and SO_2 while fugitive emissions from illegal oil refining is a major source of SO_2 , NO_X and CO. Although, BC is the largest pollutant from the use of simple kerosene wick lamps, other BC emissions within the residential sector from biomass fuel combustion obscures its significance.

Other studies also highlight the importance of some of these activities. Assamoi & Liousse (2010) developed an inventory of BC and OC from the use of 2-stroke motorcycles for West African countries in 2002. When their results were compared with those obtained in this study, for instance in Nigeria, analysis show that despite the use of the same EFs (see Sub-

Section 2.2.3.4) and a 21% increase in the number of 2-stroke motorcycles estimated in this study for Nigeria in 2010, BC emissions in the maximum scenario from Assamaoi & Liousse (2010), at 6.3 kt, is almost double that obtained in this study (i.e. approx. 3.2 kt). In fact, their BC estimate for 2-stroke motorcycles equals total road transport BC emissions estimated in this study. Further analysis shows that this is due to differences in the rate of fuel consumption. While Assamoi & Liousse (2010) estimated a total of 2,742 kt of gasoline was used by 3,966,348 2-stroke motorcycles, in this study, 1664 kt of gasoline were estimated for 5,013,320 2-stroke motorcycles. Also, the amount of daily fuel (4 litres/day) used by motorcycle taxis assumed in Assamoi & Liousse (2010) to account for half of total motorcycles in the country could also contribute to this difference as well as the mixing ratio of oil and gasoline used to operate the 2-stroke motorcycles which can vary between 2 and 8%. Furthermore, apart from BC and OC emissions from 2-stroke motorcycles, NMVOC was found to be a large road transport pollutant in this study especially in Nigeria where its use is particularly high.

Dionisio et al. (2010) undertook some monitoring activities of pollutants in both residential areas and road sides for over 22 months and found that household activities like lighting using kerosene lamps and cooking using biomass influence evening residential particulate matter peak obtained in their study. They also found traffic PM emissions to be generally higher than residential sources in the studied neighbourhoods in Accra, Ghana. Although, PM_{10} from unpaved roads may not be considered a serious health risk due to its big size, it may cause physical discomfort such as watery eyes (refs). Gillies et al. (2005) also found that PM_{10} from unpaved roads can potentially affect regional PM_{10} emissions.

Existing studies on the use of BUGs are mainly based on Nigeria, identifying them as an expensive alternative to power supply from the national grid (Ugwu et al., 2013; Foster and Steinbuks, 2008; Ikeme and Ebohon, 2005; Adurodija et al., 1998). On the other hand, residential use of kerosene in the region, has been mainly studied as cooking fuel (Anozie et al., 2007; Afrane and Ntiamoah, 2012). Studies on emissions from BUGs use are very few. Marais et al (2014) included BUGs emissions for NO_X and CO in the estimates obtained for combustion of fossil fuel in Nigeria in 2006. However, actual emissions estimates for the two pollutants were not given. Emissions obtained by Fagbeja et al (2013) from the residential use of BUGs in the Niger-Delta region of Nigeria for CO (25 kt) and SO_2 (21 kt) suggests high estimates when compared with results obtained in this study for the same pollutants, CO (34 kt) and SO_2 (33 kt) from the same source and for the whole country. A much lower estimate was obtained for NO_X (42 kt) in Fagbeja et al (2013) compared with this study, NO_X (250 kt). This variation in estimates is probably due to uncertainties associated with the methods used in both cases as well as the actual activity data and EFs. Furthermore, apart from pollutants emitted, the use of BUGs is also a source of noise pollution in Nigeria (Sonibare et al. 2014). There are no indications the continued use of BUGs will reduce anytime soon as Oseni (2016) found that regular and steady supply of electricity is required to persuade users otherwise.

As well as exploring the national level importance of emissions from the 5 key sources, it is also important to consider the local impact of emissions from these activities. This is because a specific source may not always contribute meaningfully to national emissions but may to some extent influence pollutant concentrations in more localised parts of the country. For instance, emissions from illegal refining of crude oil in the Niger-Delta region of Nigeria is not significant on a national scale, however, it contributes 30% of the country's fugitive emissions from fuels for each of SO_2 , NO_X and CO emissions. This is a problem in the Niger-Delta region of the country (Marais et al., 2014), which was home to 15% of total population in Nigeria in 2006 (Fagbeja et al., 2013). Although, this is the first attempt at quantifying emissions from illegal oil refining, other assessment studies confirmed all-round environmental damage affecting land, water and air, particularly exposing those involved in the practices and communities in the area to high levels of hydrocarbons such as benzene (United Nations Environment Programme, UNEP, 2011; SDN, 2013; Fawole et al. 2016; Aroh et al., 2010; Fawole et al., 2016).

A second example is the use of simple kerosene wick lamps for lighting. It is an activity that is mostly residential and indoor in nature putting users at health risk of being exposed to BC emissions. Populations exposed includes those without access to electricity and those that cannot afford better lighting options. This can be seen to affect a greater portion of the population in the three countries due to high levels of poverty. Lam et al. (2012b) considers that reducing emissions from this source, e.g. through the adoption of cheap LED lamps, would both improve human welfare and contribute substantially to global warming reduction.

2.4.2. How do the total anthropogenic emissions estimated here compare with other inventories and what is the role of the 5 key sectors in these comparisons?

As presented in Section 2.3.4, national estimates obtained in this work for the year 2010 are higher that the reported estimates by global inventories, EDGAR v4.3.1 and GAINS Eclipse V5a, suggesting that emissions might have been underestimated in the global inventories. Although, the two global inventories share similar sources of some activity data, specifically IEA energy balance data for fuel combustion sources and the FAO for agriculture sector, the use of more representative emissions factors is assumed to be responsible for some of the differences in emissions between this study and the global inventories. In most countries, fuel combustion is usually the most important source of emissions, however, the widely used source of fuel consumption data in the absence of reliable national or official sources, that is the IEA, may not always be accurate. This was discovered when a different but more detailed method was used to estimate emissions from certain sources like road transport. Total fuel consumed in the road transport sector for each of the three countries were found to be higher than the estimates provided by the IEA (see Table 2.5). IEA estimate for road transport gasoline and diesel in Cote d'Ivoire is 112 ktoe and 236 ktoe respectively, but in this study, 783 ktoe was estimated for gasoline and 1744 ktoe for diesel based on data on vehicle statistics. Likewise for Ghana, IEA road transport gasoline and diesel estimates are 727 ktoe and 792 ktoe but here, the estimates calculated are 672 ktoe and 1759 ktoe. The story is the same for Nigeria as well.

In addition to the differences in some activity data used, emissions estimated for 5 key sources described earlier (in Section 2.2.3) were not accounted for in EDGAR estimates. GAINS estimated emissions from some source like kerosene lamps, gas flaring and diesel generators. These were however not considered comprehensive enough. For example, in Nigeria, both diesel and gasoline fuelled backup generators are extensively used in Nigeria. In fact, in the commercial sector which includes businesses (of all sizes), institutions, and so on, gasoline use in backup generators was estimated to be more (at 12176 ktoe) than diesel (381 ktoe) in this study because of the millions of micro and small businesses which rely on the use of such small generators; although, the reverse is the case in the residential sector where the estimate is 3019 ktoe for gasoline and 4709 for diesel in 2010.

In examining the roles of emissions from the 5 key sources to national estimates obtained in this work, results show that national estimates without emissions from the 5 key sources are still higher than corresponding estimates from EDGAR and GAINS. Nonetheless, the nationally significant pollutants from the key sources widens these differences further validating the theory that emissions are underestimated in the global inventories. In fact, the sectoral impact of each of the key activities might be more important than considering it solely from a national perspective. For example, NO_X emission from the residential use of BUGs matches the fraction of NO_X emissions from cooking in the residential sector at 16% of national NO_X estimate in Nigeria. Emissions from the 5 key sources are more important in Nigeria because all five activities occur in Nigeria as opposed to Cote d'Ivoire and Ghana. However, there is still potential for increased estimates from these key sources if, for instance, more extended research is done to get more accurate emissions factors for some of the activities or generate activity data like fuel consumption in the commercial sector for Ghana.

2.4.3. What are the key uncertainties in the emission inventory estimates?

As the emissions inventories developed in this study relies on the use of statistical data from international databases, accuracy of emissions estimated will depend on how accurate the statistical data are as well as how well they represent emission sources in each country given that much of the data on emission factors derived other regions. The uncertainty in national total emissions accounting for uncertainty in the input data is shown in Table 2.16.

Emission factors used in this study were mostly obtained from the IPCC 2006 Guidelines for Greenhouse Gas Inventories and the EMEP/EEA 2016 air pollutant emission guidebook. These emission factors were mainly obtained from tests carried out in controlled environments in the developed countries of North America and Europe. Lack of country specific emission factors for various emission sources is potentially a major source of uncertainty as some emission sources in Africa are different from those in developed countries. For example, cooking using biomass (wood) is one of the biggest pollution sources in Africa. It occurs under various conditions but knowledge on the rate of emissions is very limited, if any. In using emission factors from international databases, the upper limits of the emission factors were used because emissions from most of the polluting sources such as cooking, road transport, illegal refining of crude oil, remain largely uncontrolled.

2.4.4. What are the likely future trends in emissions?

Emissions were estimated in this study for the year 2010. Although, future projection of emissions are not included in this part of the study, current figures and future projections of rapid population growth (UN, 2015) and continued urbanisation (UN, 2014) together with future growth in economy , will lead to future increase in demand for energy, food, and housing as well as transportation services (Ibitayo, 2012; Petkova et al., 2013). Meeting these future demands with the best technology available and affordable by the three countries mean a considerable amount of emissions would be released. These emissions are also set to continue to increase due to lack of adequate infrastructures (Kumar and Barrett, 2008). Without comprehensive air quality management strategies and effective implementation by each country, starting with the required legislative backing, all indicators only signify an upward projection of emissions for these three West African countries (references). From a wider view of the projections of main emissions drivers, that is population and GDP, it can be inferred that growth in emissions will not be limited to just the three countries included in this study but throughout the whole of West Africa and the entire African continent. Scenarios of future emissions from the three countries are explored in Chapter 3.

2.4.5. What are the impacts of these emissions?

Air pollutants have harmful effects on human health, crops and the ecosystems. Some also directly contribute or are precursors to pollutants that contribute to climate change. So, developing an inventory of these pollutants is foundational to the implementation of a management system. In a country or any other geographical area, sources of pollutants are diverse and ideally, the biggest effort at managing the problem would be directed at the biggest source. As a result, accurate estimation of emissions from the different sources is important for an effective management system. For instance, in this study, high emissions were estimated from the residential sector in all three countries. So, setting up an effective management plan must include measures to reduce emissions coming from the residential sector. The health and climate impacts of emissions estimated in this study are discussed in detail in Chapter 4.

Chapter 3

Scenarios of air pollutant emissions for Cote d'Ivoire, Ghana and Nigeria

3.1. Introduction

Air pollution is a growing problem in Africa that needs to be addressed (Lacey et al. 2017; Olowoporoku et al. 2012). As national governments of most countries on the continent seek to achieve goals that promote national development, the high projections of important world development indicators (specifically population and economic growth) suggest emissions will increase in coming decades unless concrete actions are taken to manage the problem. This need for actions to manage air pollutant emissions cannot be overemphasised as increasingly, the associated adverse impacts on human health, crops and climate are becoming more evident (Lelieveld et al. 2015; Fang et al. 2013). Unfortunately, Africa will be significantly affected by these negative impacts but ill-equipped to deal with them at the continental, regional or national levels. Knowing what the current emissions are (see Chapter Two) and how they might be expected to change in future (the focus of this Chapter) are the first steps in tackling the problem. This can most effectively be achieved by developing a set of emission scenarios that can describe the likely changes in air pollutant emissions for situations at a national scale.

Emission scenarios are projections of possible future emissions of atmospheric pollutants based on underlying factors known to drive the emission of these pollutants and how such factors might change over time (IPCC 2000; Cofala et al. 2007). These factors include changes in population, economic development, technology development and uptake, motorisation and urbanisation (IPCC, 2000; Chen and Kan, 2008). It is also important to consider existing national policies and actions planned for future implementation in order to assess how emissions will change in the future so that appropriate scenarios can be developed.

In general, the steps involved in making emissions projection are:

- Start with the latest emission inventory identifying the key categories or sources

- Project the activity data and emission factors based on the derived or calculated key parameters or factors (such as population and GDP)
- Use projected activity data and emission factors to calculate projected emissions
- Extract the values used to calculate the projections and document them
- Document and report the projection.

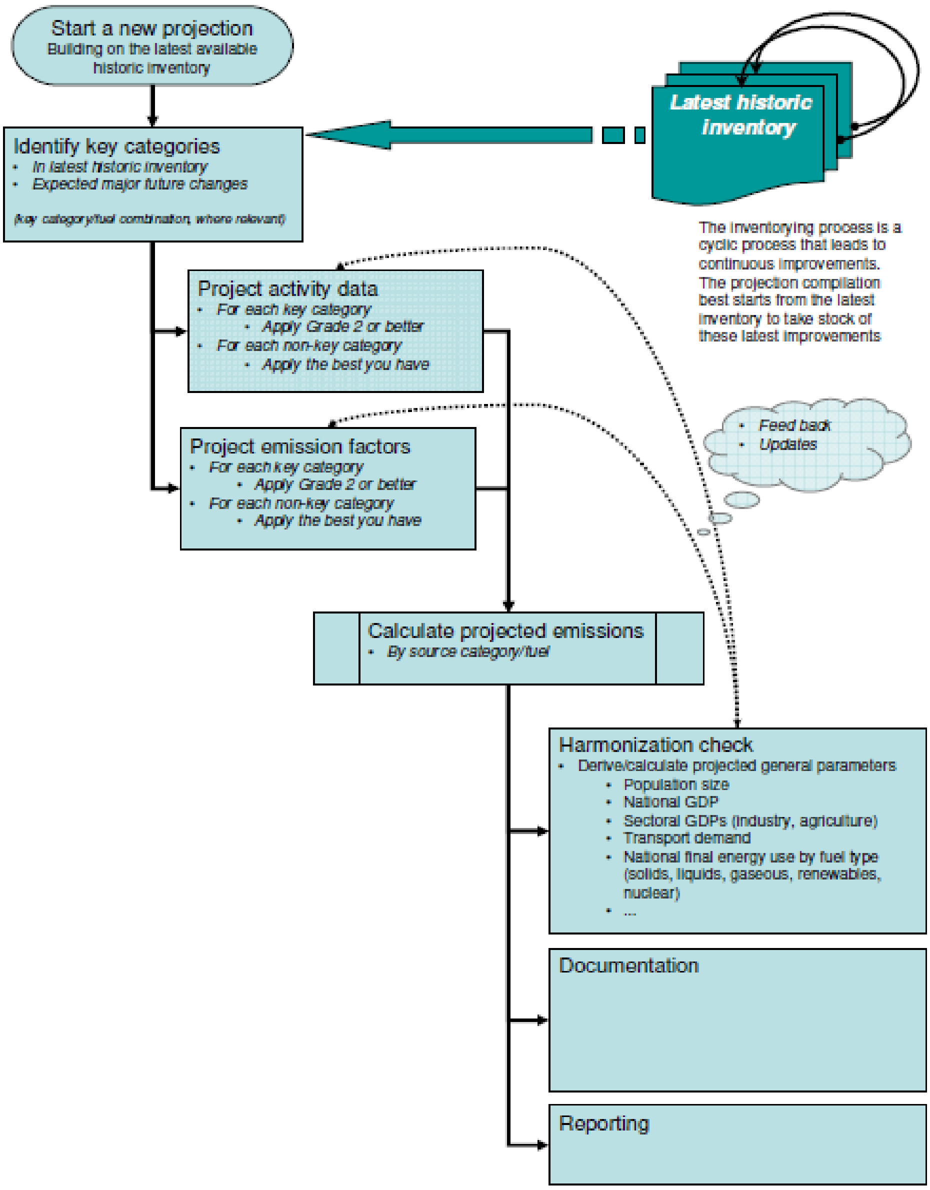


Figure 3.1: Flowchart showing the process for developing projections. Adopted from the Final Report of the General Greenhouse Gas Projection Guidelines for EU.

In developing an emission scenario, a review of the general literature on scenario development shows that the types and methods applied in creating scenarios depend on their intended use. A scenario could focus on one or more specific source sector(s) if the purpose is to evaluate changes in emission from these particular sectors (Ponche & Vinuesa 2005). In this case the scenarios could, for instance, simply be made by changing the emission factors due to the adoption of cleaner fuels (Ponche and Vinuesa, 2005) or reducing the occurrence of a particularly polluting activity or just based on the implementation of existing legislation (Cofala et al., 2007). A more complex scenario may be required if, for instance, the purpose is to achieve a regulatory goal for air pollutant concentrations or reduction in impacts. Here, different approaches would be required that take into consideration the chemical composition, atmospheric transport of the pollutants and the sensitivity of the receptors that might be impacted. Figure 3.2 below shows an example of the influence of different scenarios over time .

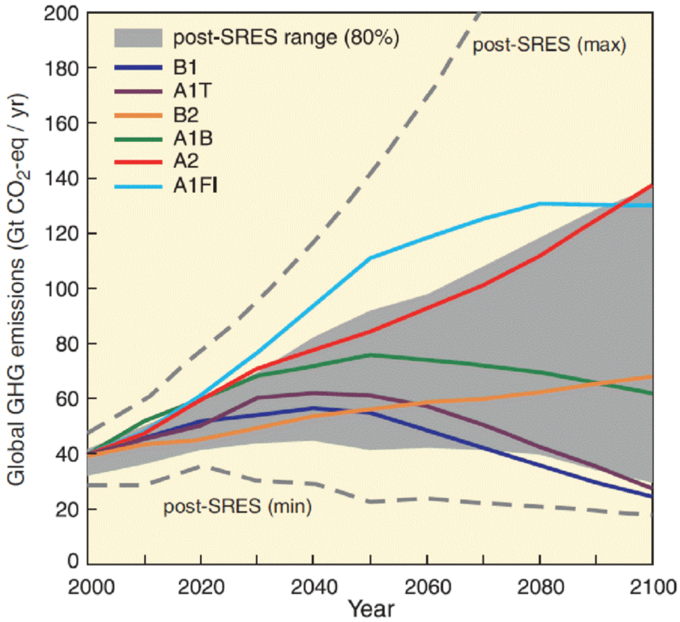


Figure 3.2: GHG emissions scenarios: global GHG emissions (in $GtCO_2eq$ per year) in the absence of additional climate policies: six illustrative SRES marker scenarios (coloured lines) and 80th percentile range of scenarios published since SRES (post-SRES) (gray shaded area). Dashed lines show the full range of post-SRES scenarios. The emissions include CO_2, CH_4, N2O and F-gases. Source: IPCC (2007)

However, there are common features present in all methods used to develop atmospheric emission scenarios. First, there is always a clearly defined time period and geographical area covered. The timeframe could be monthly, yearly or every ten years and the area covered could range from global to local (Ponche and Vinuesa, 2005; Cofala et al., 2007). Second, there is usually an underlying detailed emission inventory, so that, the implications of changes to the variables which affect emissions can be easily understood. Third, there is the development of a reference scenario (Ponche and Vinuesa, 2005). The reference scenario, often referred to as a baseline scenario, is used as a starting point against which alternative scenarios are evaluated or compared to analyse the implications of the emission reduction measures proposed. Reference scenarios are generally developed on the assumption that there is no further implementation of policies for mitigation actions beyond those already operating at the time of the base year selected for the scenario development ((U.S. Climate Change Science Program 2007; Ponche and Vinuesa, 2005). In scenario development, the underlying emission inventories are either sourced from emission databases or created using activity data which describes the emitting sources and appropriate emission factors for those sources recognising that both the activity data and emission factors can change with time.

There is a large body of literature on the development of emission scenarios. In general, they are developed with the following aims: (i) to understand trends in pollutant emissions at various geographical scales (mainly global and regional), (ii) to understand the effects of these emissions on air quality, human health, vegetation and climate, and (iii) to analyse mitigation or adaptation actions to avoid negative impacts. Furthermore, these scenarios have been predominantly developed taking a global perspective with emissions estimated for major world regions based on region-specific emission inventories (Klimont et al. *In* preparation; Cofala et al. 2007; Streets et al. 2004; Kram et al. 2000). However, detailed emission inventories required to make the best possible estimates of future emissions and associated impacts are quite limited for Africa (Liousse et al., 2014). The few inventories specifically designed to explore future emissions of countries in Africa are also limited in scope in terms of emission sources and the geographic area covered. For example, Liousse et al. (2014) estimated future emissions of air pollutants focussing only on the combustion of fuels (fossil and biofuel) in Africa. Their findings show large increases in future emission of the main air pollutants (BC, OC, CO, NO_X, SO_2 and non-methane hydrocarbons) by 2030, relative to 2005 emissions. In fact, the estimated OC emissions for 2030 could be large enough to account for half of global emissions. This highlights the substantial increase that is projected for future African emissions even without the inclusion of other important emission sources such as open waste burning, vegetation fires, savanna burning, and emissions from various agricultural activities. Lacey et al. (2017) estimated the human health impacts of air pollution for Africa based on updated emissions solely from fuel combustion sources for 2006 and 2030. Higher number of premature deaths were obtained due to improved emission estimates, however, the share of emissions and the corresponding impacts for each country in Africa are unknown.

To get a better understanding of air pollution, reduce emissions and manage its impacts in Africa, there is the need to improve the relevance and quality of current emission inventories and future emission scenarios. This could be achieved through the development of more focused emission scenarios that are bespoke for African nations (van Vuuren et al. 2011) and have achievable country-specific mitigation measures. In this study, the 'current' (i.e. base-year 2010) emission inventories created for each of the three West Africa countries considered – Cote d'Ivoire, Ghana and Nigeria - were described in Chapter Two. Emission sources covered include those categorised as fuel combustion and non-fuel combustion sources and the pollutants covered are those already listed in Chapter Two. The development of emission scenarios out to 2030 and 2050 is described in this Chapter. This requires some key assumptions regarding the driving forces behind the changes in emissions. These emission drivers are described in Section 3.1 below. The methods used in developing these scenarios are described in Section 3.2 and the results presented in Section 3.3. Section 3.4 include a discussion of the resulting emission projections, comparison with existing literature, uncertainties in the results and identification of the key pollutants and source sectors to be managed for future air quality.

The scenarios explored in this work give us estimates of future emissions in the absence of appropriate mitigation frameworks and how far the three mitigation scenarios can go in reducing emissions from the various source sectors. This is to give an understanding of how to manage future air quality to protect human health in West Africa as well and benefiting the global climate.

3.1.1. Key driving forces of emissions

There are four key driving forces which determine how emissions are likely to change over time and geospatial area: (i) population (ii) urbanisation (iii) economic growth, infrastructure and technological development and attainment of national development goals and (iv) motorisation. The characteristics of these driving forces specific to West Africa are described below. Section 3.2 then describes how particular aspects of these characteristics are quantified in the development of the scenarios used in this study.

3.1.1.1. Population

Increase in human population often leads to increase in activities that result in the emission of air pollutants (Amann et al., 2008). As population increases, the demand for energy also increases with population. So, does the need for food (possibly increasing agricultural activities) and housing. Waste generation (both domestic and industrial/commercial) increases and economic activities are also expected to increase, especially in Africa where economic growth is perhaps the most important government priority.

Increasing population is particularly important in Africa when it comes to the issues of atmospheric emissions. The population here is growing rapidly such that the region has been projected to be a major contributor to future global population growth. This is due to the predominantly high number of young people (60% of the population is less than 24 years of age) and high fertility compared to the rest of the world. Africa will account for more than half of the global population increase by 2050 (i.e. 1.3 of the 2.4 billion people that will be added to the global population by 2050). This will see an increase in Africa's share of global population to 25% in 2050 and then 39% by 2100 (UN 2015). Beyond 2050, Africa is projected to remain as the only world region with significant population growth (UNDECA 2015).

The contribution of West Africa to this projected population increase is significant with Nigeria playing a central role. Nigeria is projected to have one of the fastest growing populations of the largest countries of the world such that by 2050, total population of Nigeria would be third largest in the world, coming behind only India and China. By that time, Nigeria's population is projected to have double in size reaching almost 400 million people.

3.1.1.2. Urbanisation

Growing populations are often accompanied by the movement of people from rural to urban areas in search for jobs, social amenities and economic opportunities. The increasing concentration of people in urban areas will concentrate emissions in those areas (Amann et al. 2008) as the demand for energy and socioeconomic development rises. Consequently, Africa, whose urbanisation rate is increasing at the second fastest rate globally, with a value of 1.1% (just after Asia at 1.5%), and whose urban population is projected to increase to 56% by 2050 (from the current 40%) will likely experience increased pollutant emissions in urban areas.

The unplanned nature of urban development in Africa, the slow pace of public infrastructure development and the inadequate maintenance of existing infrastructure often result in an increase in negative externalities associated with urbanisation such as road traffic congestion, overcrowding, atmospheric pollution, high living cost, and so on. The impacts of these are expected to be greater in the West Africa sub-region. This sub-region has the highest number of urban dwellers in Africa at 33% (in 2014), set to rise to 36% and 38% by 2030 and 2050 respectively (UNDESA 2017). Furthermore, the burden of these impacts would also be shared differently across the West African countries. For instance, Nigeria alone accounts for 55% of the urban population in West Africa in 2014. Nigeria is projected to contribute the third highest number of people living in urban areas with an additional 212 million people by 2050. This means that by mid-century, the urban population would account for 67% of the total population in Nigeria, with even higher proportions of urban population projected for Cote d'Ivoire and Ghana at 71% and 70% respectively.

Although urbanisation is a key emission driver, its influence is not specifically included in the scenarios developed in this study as the focus here is on national emissions. However, it is an important factor that needs to be considered with respect to the emission of pollutants (especially when exploring atmospheric emissions of a smaller geographical area such as a city) as it leads to increased demand for motorisation and infrastructural development (IPCC 2000).

3.1.1.3. Economic Growth and National Development Goals

Economic growth is a priority for governments all over the world. Historically, economic growth has been strongly coupled with increases in greenhouse gas and air pollutant emissions. However, due to advancement in the technologies used in undertaking these activities, the relationship between pollutant emissions and economic growth in recent times is not necessarily linear depending on various factors, some of which are influenced by societal concerns about air pollution (Amann et al., 2008). In most developing countries of Asia, economic growth is still strongly linked to air pollution (Lyu et al., 2016). This can also be said for Africa as traditional technologies with higher emissions are still largely used in spite of there being more advanced and cleaner technologies now available. For instance, traditional wood stoves are still largely used for cooking and most vehicles in use in Africa are imported used cars with high emissions.

Since 2016, there has been a drop in Africa's economic growth due to weak global economic conditions and low prices of commodities (such as crude oil, coffee, tea, solid minerals). Among all Africa sub-regions, West Africa suffered the greatest decline in economic growth from a rate of 4.4% (in 2015) to 0.1% in 2016 becoming the slowest growing sub-region in the continent. This was mainly due to a decline in Nigeria's economic growth by 1.6% in 2016, whereas, some countries like Cote d'Ivoire experienced growth of 8% in the same year.

However, medium term economic forecasts show improving economies in all the sub-regions of Africa. This is mainly due to economic reforms together with the gradual recovery of the global economy. For instance, economic growth in West Africa is projected to increase to 4.1% in 2018 with Nigeria, Ghana and Cote d'Ivoire playing major roles.

Over the longer term, economic growth in Africa looks more promising (UNECA, 2017). This is due to the strong fundamentals which underpin this growth. Africa has a predominantly young population, a growing working class and a high urbanisation rate. The continent is still rich in natural resources and abundant in unused cropland (it potentially has about 60% of world's unused cropland. This could lead to job creation and foreign income if well managed, e.g. by adding value to the natural resource rather than exporting in the raw form (UNECA, 2017). Most national governments have identified the need to diversify the economy and add value to raw natural resources. For instance, the world's largest single-line crude oil refinery with an integrated petrochemical and fertiliser plant is being built in Lagos, Nigeria. When completed (in 2019) it is expected to produce high quality (Euro V standard) refined petroleum products large enough to more than meet daily national requirements. This will potentially reduce prices of petroleum products in the country and stop the import of refined petroleum products (which accounts for over 80% of refined products supply in the country annually (PricewaterhouseCoopers Ltd (PWC), 2017). Also, local production of urea from the fertiliser plant will boost crop production by increasing farmer's accessibility to fertilisers through the removal or reduction of import costs.

3.1.1.4. Motorisation

In sub-Saharan Africa, the use of gasoline and diesel fuelled road vehicles dominates other forms of transport (IEA 2014). Consequently, emissions resulting from the use of these vehicles are the most significant of all transport sector emissions. Road transport in Africa is markedly different from developed countries due to reduced availability of good transport infrastructure and affordability of transport services (IEA, 2014). In various sub-Saharan countries, vehicle ownership is low due to low income earnings of a large percentage of the population compounded by the high cost of vehicle importation (IEA, 2014). For instance, the number of vehicles per 1 000 people (i.e. the motorisation rate) in Cote d'Ivoire, Ghana and Nigeria was estimated as 41, 31 and 20 respectively for 2012 (OICA 2015). Most vehicles sold are second-hand (i.e. used) imports such that in Nigeria second-hand vehicles account for 90% of total fleet (Delloitte 2016). Poor fuel quality, high cost of vehicle maintenance relative to income and the percentage composition of the various types of road vehicles (i.e. gasoline-fuelled or diesel-fuelled vehicles) comprising the fleet will all influence the type of pollutants emitted from the transport sector in West African nations. For example, a country with a greater percentage of diesel cars, especially old ones, will expect to have high transport related BC and NO_X emissions. In Nigeria, there is a relatively high number of two-wheeled vehicles (estimated in this study in Chapter Two) compared with four-wheeled vehicles. Most of the two-wheeled vehicles are 2-stroke motorcycles known to emit a considerable amount of NMVOCs and PM (see Chapter Two). In addition, the majority of the roads used for transport are unpaved resulting in the resuspension of road dust from vehicular movement. Despite government fuel subsidies such as those that are provided in Nigeria, the import of a large fraction of refined petroleum products required in a country also means fuel costs are still high relative to income, a situation that as the case in Nigeria.

The growth of vehicle ownership in a country has been found to relate to income GDP per capita (Dargay et al. 2007). When GDP per capita is low (that is, below $3, 000), growth rate is slow; but at middle income levels ($3, 000 - $10, 000), vehicle ownership grows two times faster; and at higher levels, the growth rate of vehicles ownership is about the same rate as the per capita income before reaching the saturation point at the highest income level ($20,000 per capita) (Dargay J et al., 2007). African countries have not reached this saturation point but policies have been introduced that will likely influence vehicle ownership; for example, Nigeria has increased its duty on imported cars from 20% to 70% in order to discourage vehicle importation and stimulate local production. However, there is no evidence to show that the policies are effective. Importation of refined petroleum products to the country may also drastically reduce if the new private oil refinery being constructed in Lagos becomes fully operational. If that is the case, refined petroleum products may become affordable to more people potentially increasing per capita fuel consumption in Nigeria's transport sector and rapidly increasing the rate of vehicle ownership. With such projected rapid increase in population and economic growth as well as high urbanisation rates for Africa, increased demand for motorised road transport (both private and commercial) is expected for several decades.

3.1.1.5. Technological development

The impacts of advances in technology on everyday human life cannot be underestimated. It is a phenomenon which plays conflicting roles especially in relation to its effect on human beings and the environment. While most people see technological advancement as a positive and easily adopt the use of new technologies, others see it as a source of air pollution through human activities causing one of the main problems the world face today, i.e. global warming (Wang et al., 2016; Li, Y and Perkins, A., 2007). In the developed countries, it is a large source of air pollution by driving human activities that results in the emission of pollutants, for instance, emission of pollutants from transport sources, industrial processes, solid waste treatment and disposal, among others (Webster, 1999). Conversely, lack of access to services created through technological advancement (Webster, 1999) e.g. sanitation services, good roads, is a problem (for instance resuspension of road dust). While technological advancement has its downside, it is increasingly being used to design approaches that help reduce the impacts of air pollution. This could be in form of creating monitoring devices to assess air pollutants, or creating cleaner fuels and stoves to cook and light the house, or creating better houses and ventilation to reduce human exposure (WHO, 2018). Therefore, it is fair to say that it contributes to both environment pollution and environmental protection and future emissions would be determined by how sustainable technological development will be.

3.2. Scenarios

For each of the three countries studied (Cote d’Ivoire, Ghana and Nigeria), four emission scenarios were developed, all scenarios start from the 2010 base-year emissions and end in 2050. The base-year emission inventories are bespoke national emissions and are described in Chapter Two). These inventories contain both standard emission sources as well as emissions from the five key sources identified in Chapter Two as being particular to these West African countries and which are poorly characterised in existing global/regional inventories (illegal oil refining, backup generators, 2-stroke motorcycles, unpaved road dust, simple kerosene wick lamps). Understanding how national emissions might change in future, including emissions from these five particular sources, is key in estimating the future impacts of emissions in each of the three countries. The end date of 2050 for the scenario period provides an estimate of the impact of emissions in the longer term, however it is recognised that emission projections will become more uncertain the farther into the future that they are made and therefore care has to be taken in interpreting the results. The scenarios developed are:

(i) Baseline or Business-As-Usual scenario (BAU) scenario.
(ii) Combined Five Key Sources (COM) mitigation scenario.
(iii) Fully Implemented National Policies (FIN) scenario.
(iv) Maximum Feasible Reduction (MFR) scenario.

The BAU scenario describes potential future trends in emissions from 2010 to 2050 assuming there are no further interventions to mitigate emissions beyond those that exist already in 2010. The other three scenarios can be termed mitigation scenarios that build on the BAU scenario. This is to allow relative assessments of the impact of each of the mitigation scenarios against a common baseline scenario as well as each other. Figure 3.1 describes the development and relationship of the four emission scenarios (BAU, COM, FIN and MFR) to the 2010 Base-line emission inventory (see Chapter Two); the key drivers of changes in emission (population and GDP) and the emission sources that are targeted for mitigation. The use of population and GDP data to develop the BAU Scenario is described in Section 3.2.1.

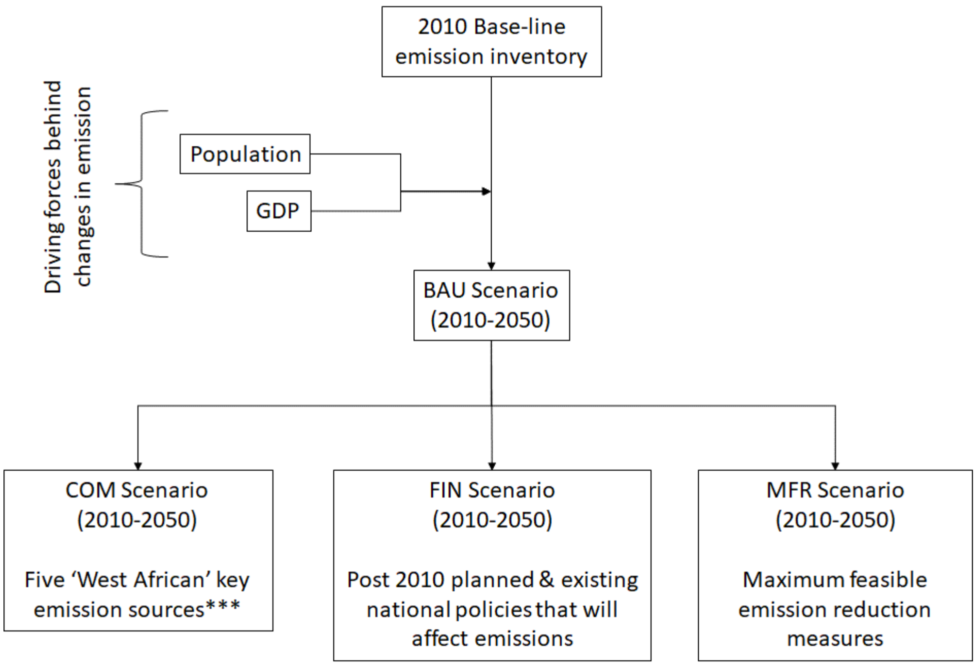


Figure 3.3: Flow chart describing the development and relationship of the four emission scenarios (BAU, COM, FIN and MFR) to the 2010 Base-line emission inventory (see Chapter 2); the key drivers of changes in emission (population and GDP) and the emission sources that are targeted for mitigation. ***COM scenario does not include emissions from illegal oil refining for Cote d'Ivoire and Ghana, and from backup generators for Cote d'Ivoire (see Section 3.2.3).

The FIN scenario was developed on consideration of a comprehensive assessment of planned government policies that will directly influence atmospheric emissions. This is described in Section 3.2.2.

The COM scenario was developed to describe the effect of eliminating emissions from the five emission sources that were either not at all, or only poorly, characterised in existing emission inventories as identified in Chapter Two. These sources are backup generators (BUGs); simple kerosene wick lamps (SIM); illegal crude oil refining (ILL); two-stroke motorcycles (TWO); and unpaved road dust (UNP). This is described in Section 3.2.3.

The MFR scenario was used to quantify total emissions that could be avoided based on the implementation of specific measures which target the largest source sectors (i.e. residential, transport and public electricity generation) in the three countries. This is described in Section 3.2.4.

All four scenarios were developed using the LEAP-IBC modelling tool (https://www.energycommunity.org/Default.asp). LEAP-IBC is a software tool that can be used to quantify atmospheric emissions in a country and subsequently estimate the impacts of air pollution on human health, crop yield and climate. The tool is built with gridded emissions (obtained from IIASA GAINS model) for the whole world but allows a user to substitute with alternative national emissions inventory. The emissions are then converted to concentrations from which impacts are then estimated.

3.2.1. Business-As-Usual scenario (BAU)

The business-as-usual (BAU) or baseline scenario was developed as the reference scenario. It shows how emissions would evolve assuming no further mitigation actions (i.e. policy changes or emission reduction actions) are implemented other than those already existing by 2010. Section 3.1 described the key drivers of emissions in the context of the West African countries studied. However, in developing the scenarios, only two of the four key drivers were used, namely: population and economic development (henceforth referred to as Gross Domestic Product, GDP). The assumptions used in the development of the BAU scenario for these two key drivers are described for each country in Table 3.1. Urbanisation was not included because the scope of the study is national, and this emission driver is more suited for the smaller demographic scale of cities or metropolitan areas. Motorisation mainly deals with vehicle ownership which was estimated in this study based on GDP for each country. Vehicle ownership for each of the categories of road vehicles was assumed to grow with the GDP per capita in line with earlier work by Dargay et al (2007). It was assumed that as people have more disposable income, more people would be able to afford a vehicle.

The two main steps involved in developing the baseline scenario are as follows:

1. Calculation of national emissions for the base-year 2010 - The 2010 bespoke inventories compiled (in Chapter Two) for Cote d'Ivoire, Ghana and Nigeria were used as the basis for making the future projections.
2. Projection of 2010 national emissions up to 2050 – To project emissions in a BAU case, the main variable that requires changing is the activity data based on assumptions concerning the two key drivers of emissions used in this work (population and GDP). It was assumed that total population for each of the three countries will grow according to future estimates provided by the United Nations Department of Economic and Social Affairs (UNDECA) population division. The

medium projection variant of these population estimates was used on the assumption that it best represents expected future changes in population growth (UNDESA, 2015c). The data are available from 2010 for every five years until 2030, then, every ten years until 2100. GDP was assumed to change according to future estimates provided by the United States Department for Agriculture Economic Research Service (USDA). These data have both real GDP values (in billions USD) and annual growth rates (%) from 2010 for every year till 2030. In this work, the estimated GDP values were used till 2030 and the average of the annual growth rates for the 2010 to 2030 period was used to make the emissions projections from 2031 to 2050. In general terms, GDP has three sectoral components: Agriculture, Services and Industry. The 2010 percentage share of these components was used for the entire projection period due to the difficulty in accurately predicting how these sectoral contributions to GDP will change in the future (IIACA, 2005).

Emissions were projected from both fuel combustion and non-fuel combustion sources using the emission drivers, population and GDP. Depending on the source sector, emissions were projected using either of these two drivers. Table 3.2 below gives the details of the drivers used for each emission source sector. The emission drivers were actually used to project the activity data of an emitting source or sector, i.e. the growth rate in the activity for a particular source sector was assumed to be the same as the growth rate in either population or GDP. For instance, the amount of waste generated is one of the key variables used in estimating emissions from waste incineration (or open waste burning). Waste generated is calculated based on population and while other variables remain the same, waste generated changes. This future change in waste generation was projected based on future changes in population. Also, in the agriculture sector, specifically enteric fermentation (for CH_4 emission), savanna burning and rice cultivation (for CH_4 emissions), FAO provides projections of the required activity data for 2030 and 2050. These were used instead of estimating based on either of the two emission drivers used in this study.

As for all other emission sources or source sectors, linear interpolation was used to estimate the activity data for the years in-between. For some sources or source sectors, the activity data for the projection period remains unchanged from the 2010 values because of lack of data on how they might likely change. These sources are illegal oil refining and coal mining (fugitive emissions sector), crops produced (agriculture sector), vegetation fires and forestry and animal husbandry (agriculture sector).

Details on the assumptions on population and GDP can be found in Table 3.1 while Table 3.2 gives the assumption(s) made for each source or source sector. In creating the BAU scenario, it was assumed that the distribution of fuels and technologies used in each sector remains the same as the 2010 values. For example, the percentage of people cooking with different fuels and technologies was the same as in 2010 for the future projections.

Table 3.1: Assumptions on the emission drivers (i.e. population and GDP) used to project national emissions from the base year 2010 to 2050 for Cote d'Ivoire, Ghana and Nigeria

Country	**Emission drivers**	**Years**						
		2010	**2015**	**2020**	**2025**	**2030**	**2040**	**2050**
Cote d'Ivoire	Population (millions) [a]	20	23	26	30	33	41	51
	GDP (billions USD) [b]	25	34	47	55	64		
	Contribution to GDP	Agriculture (25%); Services (53%); Industry (22%)						
Ghana	Population (millions) [a]	25	28	31	34	37	44	51
	GDP (billions USD) [b]	32	47	59	73	89	159	259
	Contribution to GDP	Agriculture (31%); Services (49%); Industry (20%)						
Nigeria	Population (millions) [a]	159	181	206	234	264	333	410
	GDP (billions USD) [b]	369	464	505	613	746	1,164	1,723
	Contribution to GDP	Agriculture (24%); Services (51%); Industry (25%)						

Sources: [a] **UNDECA (2015),** [b] **USDA (2017)**

Table 3.2: Assumptions used to project emissions from each source or source sector for the 2010 inventories for Cote d'Ivoire, Ghana and Nigeria.

Sectors	Sub-sectors	Emission driving forces
1. Combustion in the energy industries	1. Public Electricity and Heat 2. Petroleum Refining 3. Manufacture of Solid Fuels and Other Energy	1. Industry GDP 2. Industry GDP 3. Industry GDP
2. Combustion in manufacturing industries and construction	1. Iron and Steel 2. Non-ferrous metals	1. Industry GDP 2. *Not applicable*
3. Transport	1. Civil Aviation (Detailed) 2. Road transport (Detailed - exhaust) 3. Road transport (Detailed - unpaved road dust only) 4. Railways 5. Navigation 6. Pipeline transport 7. Non-specified transport	1. GDP 2. GDP 3. GDP 4. Industry GDP 5. Industry GDP *6. Not applicable* 7. GDP per capita
4. Combustion in other sectors	1. Commercial/Institutional a. Commercial BUGs use 2. Residential a. Domestic BUGs use 3. Agriculture/Forestry/Fishing 4. Non-specified "Other sectors"	1. GDP services a. GDP services 2. Population a. GDP per capita and population 3. GDP Agriculture 4. GDP
5. Fugitive emissions from fuels	1. Production of coke 2. Oil exploration and crude oil production and transport 3. Oil refining a. Illegal oil refining	*1. Not applicable* 2. Industry GDP 3. Industry GDP

	4. Distribution and handling of gasoline a. Refinery dispatch stations b. Transport and depots c. Service stations 5. Production and distribution of natural gas. 6. Coal mining	a. Unchanged from 2010 value (no idea how that might change) 4. a. Industry GDP b. Population c. Population 5. Industry GDP 6. Unchanged from 2010 value (due to lack of data)
6. Industrial processes	1. Mineral products 2. Chemicals 3. Metals 4. Pulp and paper 5. Food and drink (Food production) 6. Food and drink (Alcoholic beverages) 7. Major construction site activities (Fugitive PM only)	1. Industry GDP 2. Industry GDP 3. Industry GDP 4. Industry GDP 5. Industry GDP 6. Industry GDP 7. *Not applicable*
7. Solvent and product use		*Not applicable*
8. Agriculture	1. Manure management 2. Animal husbandry 3. Methane form enteric fermentation 4. Application of N-containing fertilizers 5. Savanna burning 6. Burning of agricultural crop residues 7. Methane emissions from rice cultivation.	1. Agriculture GDP 2. Unchanged 3. Actual estimates from FAO for 2030 & 2050 were used 4. Agriculture GDP 5. Actual estimates from FAO for 2030 & 2050 were used 6. Agriculture GDP

		7. Actual estimates from FAO for 2030 & 2050 were used
9. Vegetation fires and forestry	On-site burning of forests and grasslands	Unchanged from 2010 value (due to lack of data)
10. Waste	1. Waste incineration 2. Waste landfill (methane) 3. Domestic wastewater (methane) 4. Human excreta	1. Population 2. Population 3. Population 4. Population

3.2.2. Fully Implemented National Policies Scenario (FIN)

The FIN scenario was created to account for reduced emissions because of government interventions in each of the three countries. These interventions are national policies or emission reduction actions already implemented after the year 2010 or planned for future implementation. Policies included are those specifically designed to improve air quality (AQ) and those that indirectly benefit air quality through emission reduction. This scenario is based on the BAU scenario but includes the interventions identified for each country.

In the process of identifying air quality relevant policies, it was discovered that implemented actions or policies were not primarily established to improve air quality. Available interventions have only recently been developed (i.e. from year 2010) with a focus on sustainable energy generation and use. This is because they were facilitated by the Sustainable Energy for All initiative of the United Nations established in 2011 to achieve the Affordable and Clean Energy goal (number 7) of the Sustainable Development Goals (see Tables 3.3a-c). These energy interventions target the reduction of dirty fuel for cooking and the increase in the use of renewables for energy. The FIN scenario assumes that all interventions would be achieved by the end of the time proposed for their implementation, usually 2020 or 2030. For Nigeria, cooking interventions (as seen in Table 3.3a) are intended to replace half of the wood fuel consumed using traditional cook-stoves by 2020. In LEAP-IBC, this scenario was incorporated by halving the share of people cooking using traditional wood cook-stoves (i.e. from approx. 91%, in 2010, down to 45% in 2020) and increasing the share of people cooking with improved cook-stoves by half (from zero to 45% in 2020). Nuclear energy's contribution to the national energy generation mix is planned to be 2.5% by 2025, increasing to 4% by 2030. This was implemented in LEAP-IBC by increasing the share of nuclear energy used for electricity generation accordingly.

In 2016, Nigeria's Federal Minister of Environment together with the United Nations Environment Programme, UNEP, Economic Community of West African States (ECOWAS), Climate and Clean Air Coalition (CCAC) and Partnership for Clean Fuels and Vehicles (PCFV) organised a meeting to promote sulphur reduction in fuels. With the support of Environment Ministers from Ghana, Cote d'Ivoire, Benin Republic and Togo, it was agreed that sulphur content in fuels be reduced to 50 parts per million by 2020. However, Ghana already achieved this by August 2017. In LEAP-IBC, this was implemented by changing the sulphur contents of both gasoline and diesel to reflect this intervention.

Table 3.3a-c shows a summary of relevant polices applied in the FIN scenario for each country. Due to the modelling methodologies that were used to estimate emissions, only a subset of the current policies and measures highlighted in Table 3.3 could be included in the FIN scenario. The modelling methodologies used for each sector were based on the data available in those sectors to estimate emissions and create future projections. Therefore, the FIN scenario likely represents an underestimate of the total emission reduction potential of current policies and measures within each of the three countries. In Table 3.3a-c, the measures highlighted in ***red*** are the ones actually implemented in LEAP-IBC. As at the time the study was conducted, these other policies could not be implemented due to the limitations of the modelling tool or lack of sufficient data to actually implement the policies. Obtaining additional data that would allow the full suite of current policies to be represented is a key aspect of future work as discussed in Chapter 5.

Table 3.3: Policies or action plans relevant to air quality management in different sectors in Nigeria. Highlighted in red are the actual policies implemented in this study.

<table>
<tr><td colspan="3">Nigeria</td></tr>
<tr><td colspan="2">Coordinating authorities for the Environment:
• Federal Ministry of Environment
• National Environmental Standards and Regulations Enforcement Agency (NESREA)
• State Ministries of Environment

Other relevant Ministries:
• Federal Ministry of Power, Works and Housing</td><td>Policies relevant to AQ:
• Constitution of the Federal Republic of Nigeria, 1999; Section 20
• NESREA Act, 2007
• National Energy Policy, 2003
• National Renewable Energy and Energy Efficiency Policy (NREEEP), 2015
• Nigeria Climate Change Policy Response and Strategy, 2012
• (Intended) Nationally Determined Contribution, 2015
• Petroleum Industry Bill (PIB), 2017
• The Harmful Waste Act, 1988
• Environmental Impact Assessment Act, 1992
• National Environmental (Control of Vehicular Emissions from Petrol and Diesel Engines) Regulations, 2011
• National Environmental (Air Quality Control) Regulations, 2013</td></tr>
<tr><td colspan="3">National development goals
Vision 20:2020</td></tr>
<tr><td>Sectors</td><td colspan="2">Policies / Actions</td></tr>
<tr><td rowspan="2">Energy</td><td colspan="2">• Developed SE4All Action Plan Agenda in 2016 – targets set to be achieved by 2020 and 2030</td></tr>
<tr><td colspan="2">SE4All targets</td></tr>
</table>

	• *Electricity access to increase to 60% by 2020 and 90% by 2030* • *Replace 50% traditional firewood consumption for cooking by improved cook stoves by 2020* • *Nuclear energy expected to contribute 2.5% by 2025 and 4% by 2030 to the nation's energy mix* • Efficient lighting – replacement of incandescent lamps with those that are 5 times more effective, expected to cover 20% of households by 2015, 40% by 2020 and almost 100% by 2030 (Not included in the scenario, more data needed to implement policy) • Energy efficiency for high-energy consuming sectors (transport, power and industries) to increase to 20% by 2020 and 50% by 2030 (Not included in the scenario, more data needed to implement policy) • *Renewable energy to account for 30% of the energy mix by 2030 (wind – 2.5%; solar – 20% (2020), 19% (2030)*
Transport	• *Fuel Sulphur reduction to 50ppm by 2020 (together with other ECOWAS countries) (UNEP, 2016)* • Car to bus transport shift (INDC, 2015) (Not included in the scenario, more data needed to implement policy) • Policy recommendation to develop uniform vehicular emissions standards by 2020 in the ECOWAS region (UNEP, 2016) (Not included in the scenario, more data needed to implement policy)
Fugitive emissions	*Ending of gas flaring by 2030 (INDC, 2015)*

Table 3.4: Policies or action plans relevant to air quality management in different sectors in Ghana. Highlighted in red are the actual policies implemented in this study.

<table>
<tr><td colspan="2">Ghana</td></tr>
<tr><td>Coordinating authorities for the Environment:
• Ministry of Environment, Science, Technology and Innovation
• Ghana Environmental Protection Agency
Other relevant Ministries:
• Ministry of Power
• Ministry of Transport</td><td>Policies relevant to AQ:
• National Energy Policy, 2010
• National Transport Policy, 2008
• Strategic National Energy Plan 2006 – 2020
• Energy Efficiency Standards and Labelling Regulations, 2009
• No vehicular emissions control, guidelines and standards</td></tr>
<tr><td colspan="2">National development goals:
• Ghana Shared Growth and Development Agenda (GSGDA II) 2014 - 2017
• Long-term National Development Plan for Ghana (2018 – 2057)</td></tr>
<tr><td>Sectors</td><td>Actions</td></tr>
<tr><td>Energy</td><td>• Country adopted Sustainable Energy for All (SE4All) in 2012 and subsequently developed SE4All action agenda
• Renewable energy in the national energy mix to increase from 0.31% (in 2010) to 10% by 2020 (National Energy Policy, 2010)
• Installed electricity capacity - 5 000 MW by 2020 (additional or total?) (Not included in scenario due to more data needed and modelling tool limitation)
• Household access to LPG – 18% by 2015, 24% by 2020 (SE4All targets)
• Reduce demand of wood fuel from 72% to 50% by 2020 (SE4All targets)
• Renewable energy to account for 10% of the energy generation mix by 2020 (SE4All targets)</td></tr>
</table>

	• 20% energy efficiency of industrial facilities (to be achieved between 2020 & 2030) (Not included in scenario, more data needed to implement policy)
Transport	• *Fuel Sulphur reduction to 50ppm by 2020 (together with other ECOWAS countries)* • Bus Rapid Transit (BRT) (Not included in scenario, more data needed to implement policy) • Vehicular emissions testing programme done in 2015 to inform the development of emission standards • Policy recommendation to develop uniform vehicular emissions standards by 2020 in the ECOWAS region (UNEP, 2016) (Not included in scenario, more data needed to implement policy)

Table 3.5: Policies or action plans relevant to air quality management in different sectors in Cote d'Ivoire. Highlighted in red are the actual policies implemented in this study.

Cote d'Ivoire				
Coordinating authorities for the Environment: • Ministry of Safety, Environment and Sustainable development (Ministère de la sécurité, de l'environnement et développement durable) • Ministry of Petroleum and energy (Ministère du Pétrole et de l'Energie)		**Relevant (AQ) policies:** • Sustainable Energy for All		
National development goals: • National Development Plan 2016 - 2020				
Sectors	**Policies / Actions**			
Energy	SE4All targets • *Renewable energy to account for 16% of total energy mix by 2030* • *Reduce industrial energy consumption by 25% by 2030*			
Transport	• *Fuel Sulphur reduction to 50ppm by 2020 (together with other ECOWAS countries)* • Policy recommendation to develop uniform vehicular emissions standards by 2020 in the ECOWAS region (UNEP, 2016) (Not included in the scenario, more data needed to implement policy)			

3.2.3. Combined Key Five Sources Scenario (COM)

The COM scenario was developed to show emission reductions that could be achieved by eliminating future emissions of the five key emission sources described earlier in Chapter Two (that is, BUGs, ILL, SIM, TWO and UNP). This COM scenario inherits all the properties of the BAU scenario but phases out emissions from these five sources. The assumption here is that, by 2030, pollutants will no longer be emitted from these sources. Using linear interpolation, a certain amount or percentage of the relevant activity was reduced annually from the 2010 value such that by 2030, no emitting activity occurs from each of the key five sources. Table 3.4 shows the algorithm used to achieve this. There are some key differences between countries; in Cote d'Ivoire and Ghana, illegal refining of crude oil does not take place. Also, in Cote d'Ivoire, BUGs are not used to a significant extent in the country due to the steadier supply of power in the country. However, in Nigeria, all the five key sources are applicable.

Table 3.6: Assumption made to adjust the activity data of the 5 key sources when developing the COM scenarios.

5 Key sources	Cote d'Ivoire	Ghana	Nigeria	Activity reduction assumptions that result in zero emissions by 2030 for the 5 key sources
Two-stroke motorcycles (TWO)	√	√	√	The TWO 90% share of the total motorcycle fleet was reduced annually by 4.5%, replaced by equivalent increases in the share of four-stroke motorcycles.
Simple kerosene wick lamps (SIM)	√	√	√	The use of SIM accounts for 3% of total fuel used in the residential sector in 2010. This was reduced yearly by an average of 0.15%.
Unpaved road dust (UNP)	√	√	√	The UNP driven fraction was reduced by 0.8% annually from 16.2% in 2010.

Backup generators (BUGs)	Not applicable	√	√	BUGs use in the residential sector made up 76.9% of energy use (electricity) in 2010 in Nigeria. This was reduced annually by an average of 3.85%. BUG use in the commercial sector was reduced annually by 4.5% from a fuel share of 89.8% in 2010. In Ghana, residential BUGs use accounted for 8% fuel share in 2010. This was reduced by 5 % annually.
Illegal oil refining (ILL)	Not applicable	Not applicable	√	Illegal oil refined in 2010 was 2054 kt. This was reduced annually by 102.7 kt.

3.2.4. Maximum Feasible Reduction Scenario (MFR)

The Maximum Feasible Reduction (MFR) Scenario explores the potential for substantial emission reductions by focussing on the most substantial emission source sectors - residential, transport and energy. Three mitigation measures were developed to be in line with developmental policies set out to achieve the UN Sustainable Development Goals (SDGs). The potential implementation of these measures is consistent with the fact that each of the three West African countries studies are signatories to the SDGs which advocate the need for good health and well-being (goal 3), affordable and clean energy (goal 7) and climate action (goal 13). This MFR scenario also incorporates the COM scenario except for the mitigation for unpaved roads. The fraction of unpaved roads in all three countries (92% in Cote d'Ivoire, 87% in Ghana and 85% in Nigeria) is so high that it is considered unlikely that the national government in each country would be able to pave all roads before 2030 when the MFR measures are expected to be fully implemented.

The first of the three new measures focus on the residential sector where cooking is the largest emission source. This is called the Further Cooking Measure (FUR1). The aim of this measure is to change from the use of high emitting fuels (mainly wood) to cleaner fuels (see Table 3.7). All three countries use the same mix of cooking fuels, that is; wood (using traditional wood cook-stoves), charcoal, kerosene, liquefied petroleum gas (LPG) and electricity. However, the percent share of people using the different fuel types is different among countries. Wood fuel is the most widely used cooking fuel in all three countries (by 54% of people in Cote d'Ivoire, 59% in Ghana and 90% in Nigeria), almost all wood fuel is burnt in traditional stoves. However, traditional wood cook-stoves are the least energy efficient (at 7.5% efficiency) compared with traditional stoves fuelled by charcoal (10%), or kerosene (35%), LPG (65%) and electric (75%) stoves. Improved wood cook-stoves have an efficiency of 21.5%. A change from the use of high emitting fuels to cleaner fuels means moving to the use of more efficient fuels such as electricity, LPG, improved wood cook-stove and kerosene. Based on IEA data used to develop the 2010 emissions inventory for each country, the fractions of people using various cooking fuels were calculated in LEAP and presented in the third column of Table 3.7. On the assumption that by 2030, the economy would have improved, and more people would be able to afford to use cleaner fuels to cook, the 2010 shares of people cooking using various fuels were changed to favour the use of more efficient fuels thereby reducing the use of wood (in traditional wood cook-stoves). For instance, in Ghana, 59% of people were estimated to cook using wood in 2010. The adoption of cleaner cooking fuels in 2030 reduced the use of wood to 22 (as seen in the second column of Table 3.7, FUR1 - cooking).

The second measure was directed at the road transport sector. It is called Further Transport Measures (FUR2). Road vehicles in all three countries are dominated by second-hand vehicles with high emissions. National governments of these countries are taking steps to ensure good vehicles with lower emissions are used. For example, in Nigeria, the importation of vehicles older than 10 years were banned and, high vehicle import levies were enacted to encourage local production and use of new vehicles in the country. Also, in Ghana, vehicle emissions testing was conducted to establish vehicle emissions standards. Therefore, for this measure, a more holistic approach was used whereby all types of vehicles were changed from one vehicle emission class or standard (e.g. uncontrolled or conventional) to a less emitting one (e.g. Euro 5 or 6) based on EMEP/EEA (2016) emissions inventory guidebook. Since this measure is meant to be fully implemented by 2030, it is expected that vehicles imported into Nigeria, for instance, from 2020 onwards will adhere to higher emission standards while existing older fleet vehicles are assumed to gradually get scrapped. In the 2010 inventory, all vehicle categories are classed as uncontrolled or unconventional. For 2030, it was assumed that about half of all vehicle fleet should be Euro 5 and the other half

Euro 6 emission standard. By 2050, 90% of all vehicles are assumed to be of Euro 6 emission standard (see Table 3.7, FUR2 - Road transport).

The last mitigation measure was directed at the energy sector, specifically, electricity generation. This is referred to as Further Electricity Generating Measures (FUR3). Although, emissions from national grid electricity generation are much lower than both residential and road transport sectors, a significant portion of electricity demand is met using private BUGs in residential and commercial settings in Nigeria. With the phase-out of BUGs in the future, sustainable electricity demand will have to be met by the national grid. The other two countries also want to generate energy more sustainably, so, a shift to the use of cleaner fuels to generate electricity was also implemented for them (Table 3.7, FUR3 – Electricity generation).

Therefore, the measure here aims to promote the use of more efficient and cleaner fuels such as hydro, renewables and natural gas. This was done by minimising or eliminating the use of inefficient fuels in generating electricity. For instance, in 2010, Ghana generated electricity using hydro (57%), crude oil (27%) and natural gas (16%). Crude oil is inefficient at generating electricity and sometimes, there is the issue of low water levels influenced by rainfall patterns thereby reducing the capacity of the hydro plants. For FUR3 it is assumed that by 2030, the energy share will change to hydro (50%), natural gas (30%) and renewables (20%). This reduces dependence on hydro plants, increases the use of natural gas to generate electricity and promotes the development of renewable energy which is in line with Ghana government's framework on renewable energy (National Energy Policy, 2010; Sustainable Energy for all Action Plan, 2012)

Table 3.7: Assumptions made when adjusting the activity data (fuel types, number of vehicles) when developing the MFR scenario in LEAP-IBC.

<table>
<tr><td rowspan="5">Cooking [a] (FUR1)</td><td colspan="4">This measure aims to reduce the percentage of people who cook with wood fuel while promoting the use of other cleaner cooking fuels (in brackets are the percent share of people using various fuel types. For 2010, these are based on IEA energy balance for each country.)</td></tr>
<tr><td></td><td>Base-year (2010)
Share of people using various fuel tyres to cook</td><td>MFR
2030</td><td>2050</td></tr>
<tr><td>Cote d'Ivoire</td><td>• Kerosene (4%)
• LPG (13%)
• Charcoal (14%)
• Wood (using Traditional wood stoves) (54%)
• Electricity (15%)</td><td>• Kerosene (10%)
• LPG (20%)
• Charcoal (14%)
• Wood (16%)
• Improved wood cook stove (20%)
• Electricity (20%)</td><td>• Kerosene (10%)
• LPG (30%)
• Charcoal (14%)
• Wood (6%)
• Improved wood cook stove (20%)
• Electricity (20%)</td></tr>
<tr><td>Ghana</td><td>• Wood (using Traditional wood stoves) (59%)
• LPG (26%)
• Charcoal (11%)
• Kerosene (3%)
• Electricity (0.4%)</td><td>• Traditional wood cook-stove (22%)
• LPG (30%)
• Charcoal (8%)
• Kerosene (10%)
• Electricity (5%)
• Improved biomass stove (25%)</td><td>• Traditional wood cook-stove (5%)
• LPG (35%)
• Charcoal (5%)
• Kerosene (15%)
• Electricity (10%)
• Improved biomass stove (30%)</td></tr>
<tr><td>Nigeria</td><td>• Wood (using Traditional wood stoves) (90%)
• Electricity (5.7%)</td><td>• (Traditional) Wood cook-stoves (35%)
• Electricity (15%)</td><td>• (Traditional) Wood cook-stoves (4%)
• Electricity (20%)
• Charcoal (1.2%)</td></tr>
</table>

		• Charcoal (1.2%) • Kerosene (2.2%) • LPG (0.1%)	• Charcoal (1.2%) • Kerosene (15%) • LPG (15%) • Improved wood cook stoves (10%)	• Kerosene (20%) • LPG (30%) • Improved wood cook stoves (25%)
Road transport [b] (FUR2)	***This measure aims to reduce emissions by a shift from the use of high emitting vehicles to more efficient ones at reducing emissions** (figures with percentages are the share of vehicles)*			
		Base-year (2010)	MFR	
			2030	2050
	Cote d'Ivoire, Ghana and Nigeria	• Passenger cars (Uncontrolled) • Light commercial vehicles (Conventional) • Heavy duty vehicles (Conventional) • Motorcycles (Uncontrolled)	• Passenger cars ○ Gasoline & diesel (50% Euro V, 50% Euro VI) ○ Electric (4%) • Light commercial vehicles (50% Euro V, 50% Euro VI) • Heavy duty vehicles (40% Euro V, 50% Euro VI) • Motorcycles ○ No 2-stroke by 2030. ○ All motorcycles are 4-stroke (80% Euro II, 20% Euro III)	• Passenger cars ○ Gasoline & diesel (10% Euro V, 90% Euro VI) ○ Electric (8%) • Light commercial vehicles (10% Euro V, 90% Euro VI) • Heavy duty vehicles (20% Euro V, 80% Euro VI) • Motorcycles ○ All 4-stroke motorcycles are (20% Euro II, 80% Euro III)

Electricity generation [c] ***(FUR3)***	***This measure aims to promote cleaner and more sustainable electricity generation*** *(figures in brackets are the share of energy from a fuel)*		
	Base-year 2010	MFR	
		2030	2050
Cote d'Ivoire	• Natural gas (77%) • Hydro (23%) • Diesel (0.08%) • Heavy fuel oil (0.04%)	• Natural gas (50%) • Hydro (30%) • Renewables (20%)	• Natural gas (40%) • Hydro (40%) • Renewables (20%)
Ghana	• Hydro (57%) • Crude oil (27%) • Natural gas (16%)	• Hydro (50%) • Natural gas (30%) • Renewables (20%)	• Hydro (50%) • Natural gas (30%) • Renewables (20%)
Nigeria	• Natural gas (67%) • Heavy fuel oil (3.8%) • Diesel (4.2%) • Hydro (25%)	• Natural gas (26%) • Hydro (40%) • Nuclear (4%) • Renewables e.g. wind, solar (30%)	• Natural gas (26%) • Hydro (40%) • Nuclear (4%) • Renewables e.g. wind, solar (30%)

Note:

[a] Percentage refers to the percentage of people cooking with a fuel type

[b] Percentage refers to share of vehicles

[C] Percentage refers to the share of energy from a particular fuel

3.3. Results

Scenarios developed to show future emissions of air pollutants were described in Section 3.2. In this section, future changes in emission of these pollutants according to the BAU scenario are first presented in Section 3.3.1. Then, the reduction in emissions from the implementation of the different mitigation scenarios (COM, FIN and MFR) are presented in Section 3.3.2. These estimated emission reductions were further analysed to assess the magnitude of the reductions attributable to various sources or source sectors targeted by the mitigation scenarios in Section 3.3.3. Finally, in Section 3.3.4, emission reduction measures (from all scenarios) were assessed to identify those measures that are most effective at the sectoral level.

3.3.1. Future emissions of atmospheric pollutants in the BAU scenario.

In the BAU scenario, where there are no further emission reduction measures apart from those already implemented by 2010, results obtained for all three countries show that emissions of air pollutants increase continuously from 2010 until 2050 (see Figure 3.2 (a-c)). In each country, some pollutants show more rapid increase than others and the average annual rate of increase in pollutant emissions can range between 2 and 6% in Cote d'Ivoire, 1 and 10% in Ghana, and 3 and 6% in Nigeria. The rate of increase of each pollutant also differs among the three countries, essentially due to differences in values of the key assumptions used to estimate future emissions. For instance, the estimated GDP values for Ghana in 2030 is approximately three times the 2010 values, while for Nigeria, it is only two times (Table 3.1). Consequently, the projected increase in SO_2 emissions, for instance, relative to the 2010 value of 56 kt in Ghana, was as high as 133% by 2030 and 411% by 2050. Whereas, for Nigeria, the SO_2 emission increase relative to the 2010 value of 392 kt is 74% by 2030 and 202% by 2050. Based on the average annual rate of increase of pollutant emissions, important pollutants (i.e. those with 5% or more rate of increase) are SO_2, NO_X and VOC in Cote d'Ivoire and Nigeria, and SO_2 and NO_X in Ghana.

Other observations were also made from the results. In Nigeria, all pollutants increased by at least 50% by 2030 and more than 100% in 2050 with NO_X and SO_2 increasing by more than 200% in 2050. Projected emissions for Cote d'Ivoire show more than 3 times increase in emissions for most pollutants by 2050 while the others increase by a factor of two, except for OC which increased by 76%.

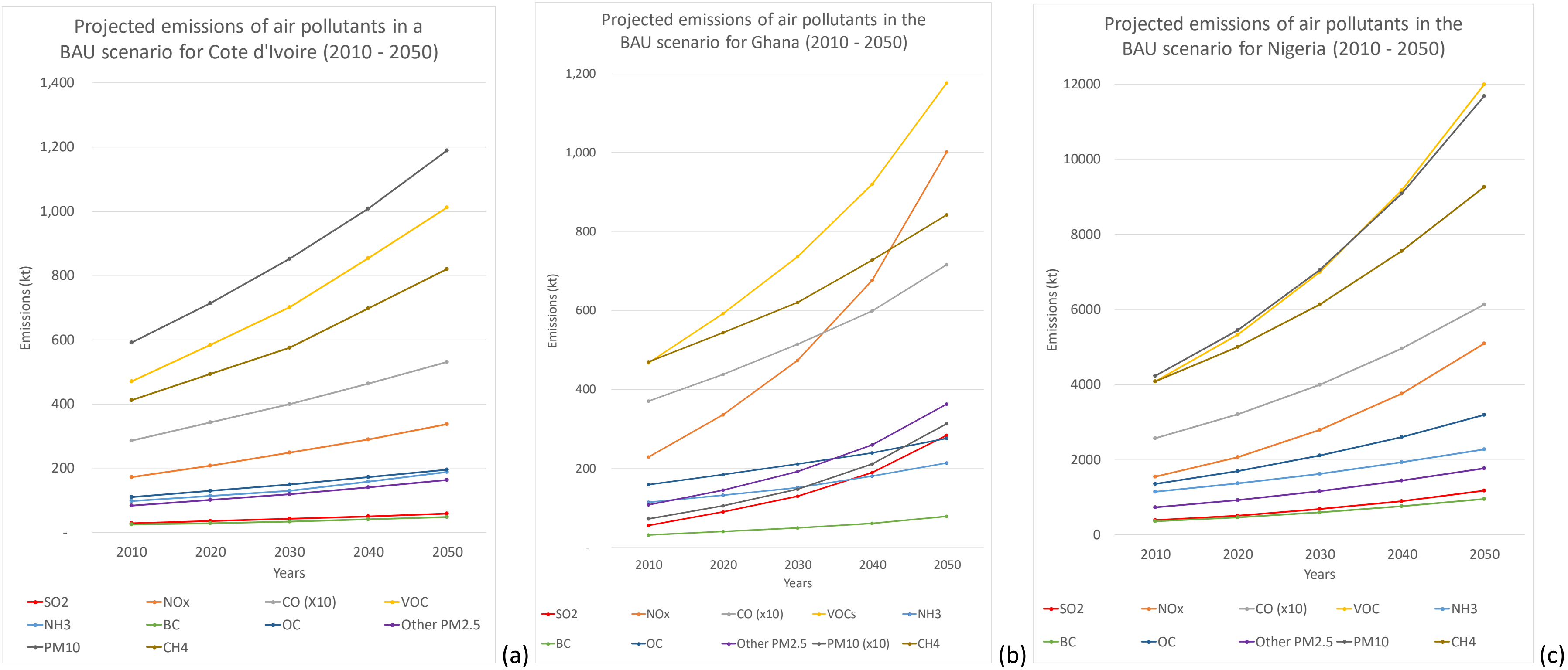


Figure 3.4 (a-c): Graph shows projection of national emissions in the in the Business-As-Usual scenario for Cote d'Ivoire, Ghana and Nigeria from 2010 to 2050.

Following the general overview of future emissions presented above, emissions of each pollutants were examined based on the contributions from various source sectors. For some pollutants, the largest emission source change over the projection period, so, highlighting this might be useful in informing potential mitigation measures in the future.

3.3.1.1. Sulphur dioxide

SO_2 emissions were projected to increase in all three countries from 2010 to 2050 in the BAU scenario. In 2010, SO_2 estimates for Cote d'Ivoire, Ghana and Nigeria were 29 kt, 56 kt and 392 kt respectively. However, the projected increase shows that the annual rate of increase of this pollutant differs among the countries. In Cote d'Ivoire, SO_2 emissions increased by approximately 3% annually while in Ghana and Nigeria, the rate is 10% and 5% respectively. Also, the largest sources of SO_2 differ slightly among the three countries with the residential sector being the only large emission source common to all three (see Figures 3.3 (a – c)).

Apart from Ghana, the residential sector is the largest source of SO_2 in 2030 for Cote d'Ivoire (28%) and Nigeria (34%), this can be attributed to the use of biomass (wood) for cooking. Although wood is the most widely used cooking fuel in all three countries with wood-fuel used by 59% of people in Ghana, 54% in Cote d'Ivoire and 91% in Nigeria there are other larger sources of SO_2 in Ghana. The largest source of SO_2 in Ghana is electricity generation from thermal power plants for the national grid (29%) followed by road transport (23%), manufacturing and construction industries (15%) and the residential sector (8%). In Ghana, thermal power plants fuelled by crude oil and natural gas are used in addition to hydro power plants to produce electricity. However, crude oil has a high sulphur content of 1.2% and it contributes approximately 24% of total energy requirement in Ghana's power sector. The resulting SO_2 emission of 37 kt (in 2030) and 92 kt (in 2050) are significantly higher than any other single emission source in the country.

Besides the residential sector, other large SO_2 emission sources in Nigeria in 2030 include the use of backup generators, BUGS (domestic BUGS, 18%; commercial BUGs; 9%), road transport (13%) and electric power plants (6%). The inadequacy of the national grid to meet the demand for electricity resulted in the prolific use of BUGs.

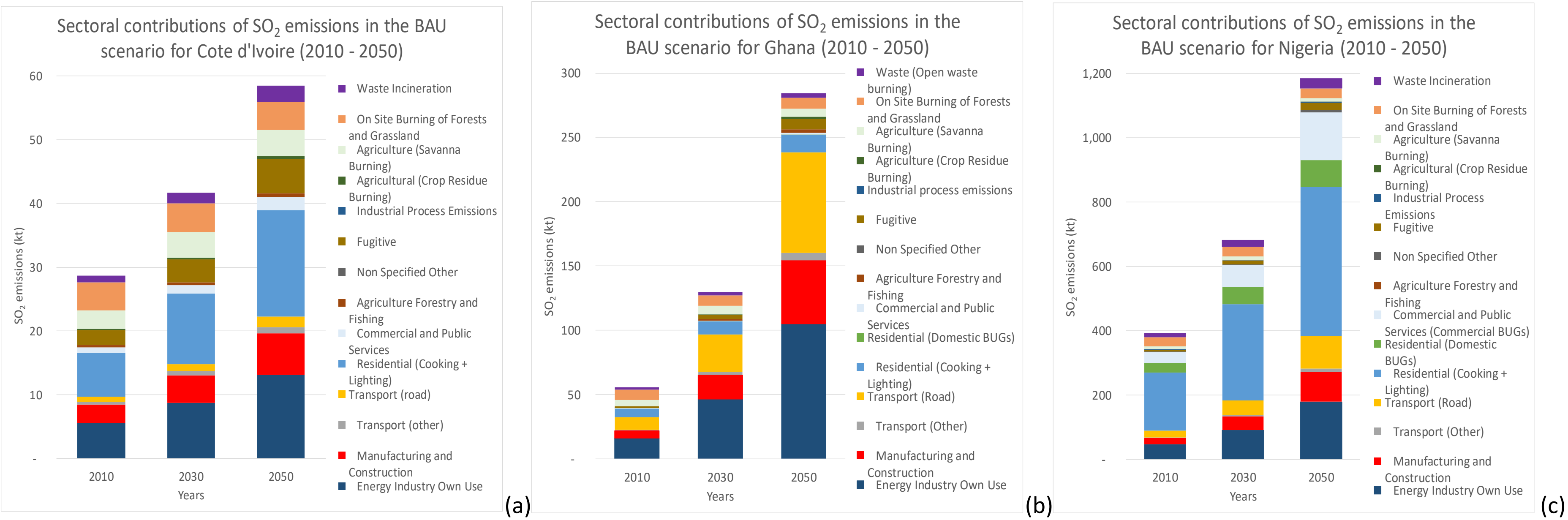


Figure 3.5 (a-c): Projected emission of SO_2 by source sectors in Cote d'Ivoire, Ghana and Nigeria for 2010, 2030 and 2050

This is an inefficient way of generating electricity which among other factors involves the combustion of diesel and gasoline. These fuels have high sulphur contents of 1% and 0.1% respectively compared to 0.001% for natural gas which, in 2010, accounted for 67% of the energy requirement of the thermal power plants in Nigeria. Assuming BUGs were not widely used in Nigeria and most of the demand for electricity were to be met by the national grid, SO_2 emissions from a power generation would still be likely to be rather low as 25% of the energy requirement for power generation is met using hydro power plants. Furthermore, the significant emission of SO_2 from domestic BUGs in Nigeria leads to a large projected increase in the share of emissions from the residential sector from 34% into 52% in 2030 and from 30% to 46% in 2050, in the BAU scenario.

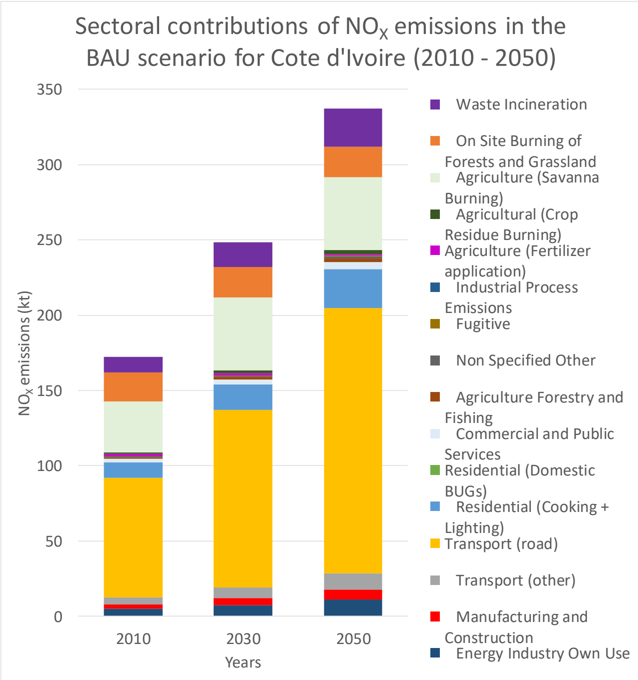
Heavy duty vehicles burning diesel are large road transport SO_2 emission sources in all three countries. Even until 2050, road transport emission of SO_2 are not important in Cote d'Ivoire, at least in relative terms, since on-site burning of forests and grasslands as well as savannah burning are the substantial SO_2 emission source for this country.

3.3.1.2. Nitrogen oxides

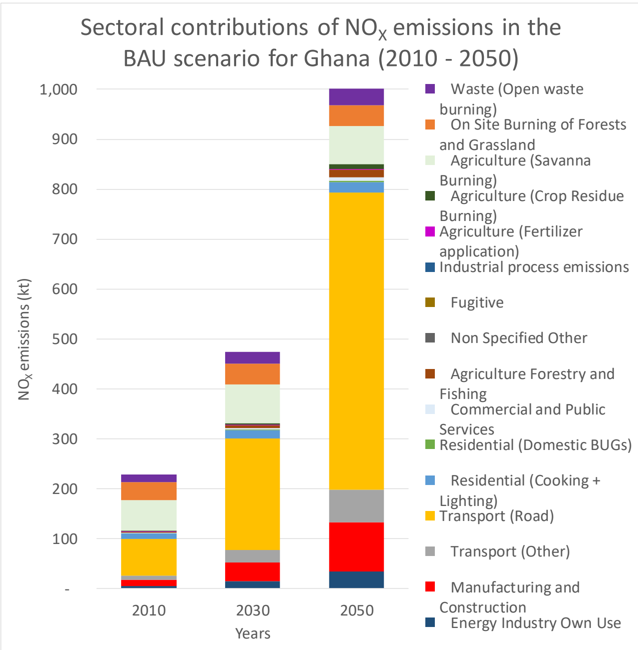
Results obtained for NO_X emissions show that, in the absence of effective emission control measures on fossil fuel combustion assumed for the BAU scenario, NO_X emission will progressively increase up to 2050. In all three countries, the major sources of NO_X involve fuel combustion, although, from different sources (see Figures 3.4 (a – c)). Projected NO_X emissions for Cote d'Ivoire and Ghana show remarkable similarities in both the main NO_X source sectors and the share of emission from those sources. Road transport accounts for the largest share with 48% in Cote d'Ivoire and 44% in Ghana followed by savanna burning with 20% and 22% respectively. On-site burning of forests and grasslands is the third largest source with 8% in both cases for 2030. However, this is completely different for Nigeria where the use of BUGs in the commercial sector accounts for the largest share of emissions at 27% in 2030. Other big sources are residential cooking using wood, domestic use of BUGs and road transport each at approximately 15%.

A common feature to all three countries is the increase in share of NO_X emission from road transport due to projected increase in the number of vehicles. This hides the fact that NO_X emissions from other sources are still increasing, but have a decreasing share of total emissions. An example is savanna burning in Cote d'Ivoire and Ghana which increase until

2030; with improved data on annual area burnt for 2050 these increases might actually have higher emissions than estimated in this study (and take a larger share of the total NO_X emissions).



(a)



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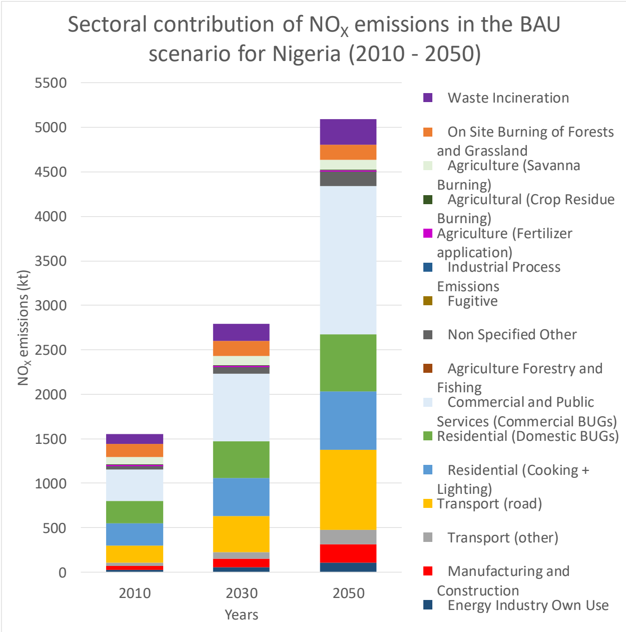


(c)

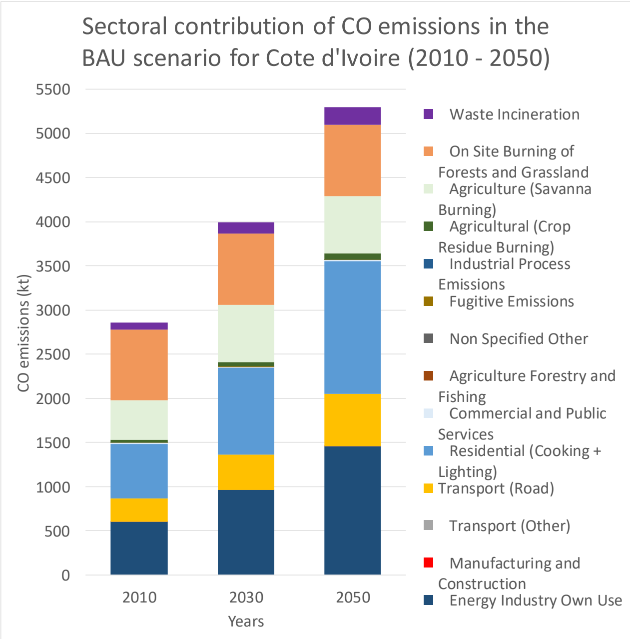
Figure 3.6 (a-c): Projected emission of NO_X by source sectors in Cote d'Ivoire, Ghana and Nigeria in 2010, 2030 and 2050.

3.3.1.3. Carbon monoxide

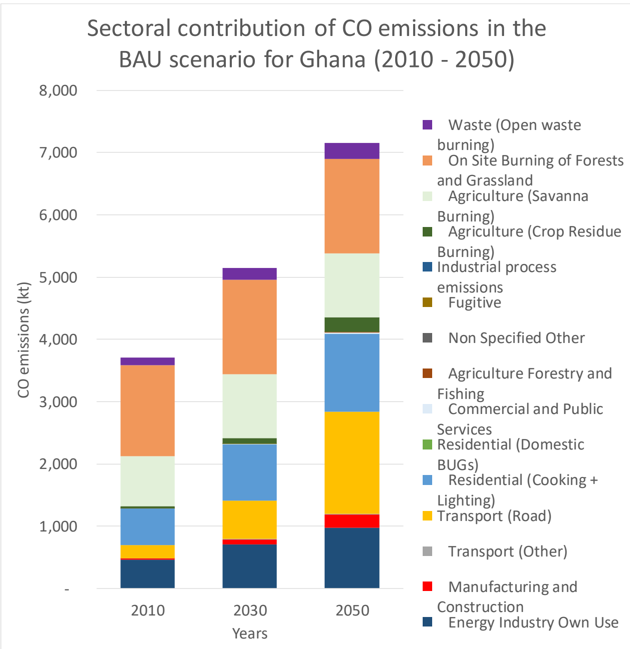
Over the next few decades, dependence on residential use of solid fuels (wood and charcoal) and vegetation fires (savanna burning; and on-site burning of forest and grasslands) will continue to account for major CO emissions. While the share of residential emissions increased in all three countries; that of vegetation fire emissions decreased although only in absolute emission values, emissions here increased until 2030 as the activity data required to project emissions (i.e. annual area burnt) is not available beyond 2030.

The residential sector is overwhelmingly the biggest CO source in Nigeria accounting for 58%, 62% and 64% of total emissions in 2010, 2030 and 2050. It will be the largest source in Cote d'Ivoire, although, to a lesser degree when compared with Nigeria at 25% by 2030 and 30% by 2050. In Ghana, vegetation fires are bigger emission source than the residential sector which only show a gradual increase in their contribution to future CO emissions (15% (2010) - 17% (2050)).

By 2050, road transport will be the biggest CO emitter in Ghana at 22%. This is a sharp increase from its 5% share in 2010 due to the projected increase in the number of vehicles. This was also observed for Nigeria though with a lower margin of 7% (2010) – 13% (2050). Emissions from motorcycles dominate road transport emissions in Nigeria (58% in 2050), however, passenger cars dominate road transport emission in Ghana (43%) reflecting the diversity of vehicle types among the three countries. Road transport CO emissions in Cote d'Ivoire will also rise fast from 9% in 2010 to 21% by 2050 similar to the fraction from residential cooking and charcoal production.



(a)



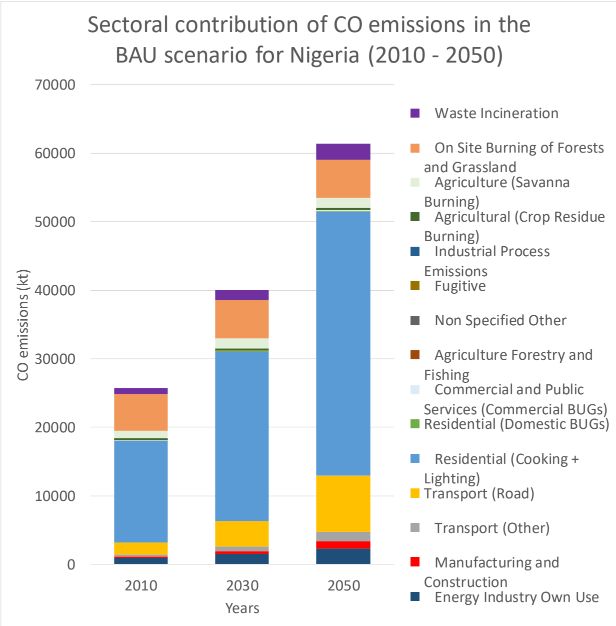


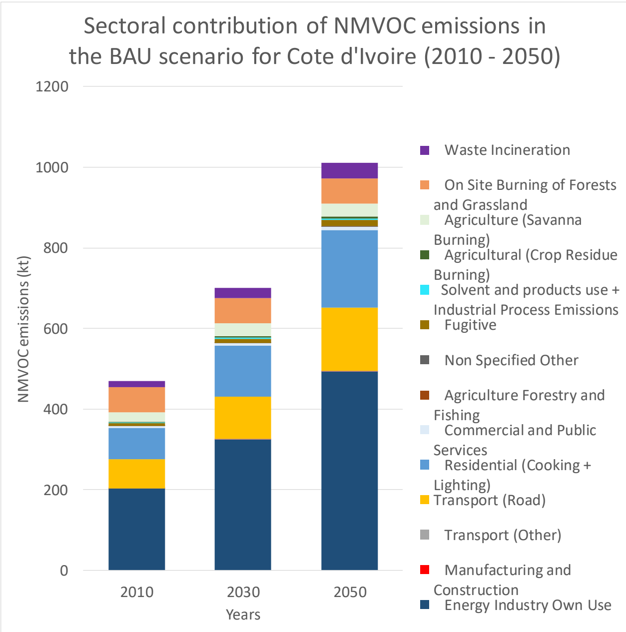
Figure 3.7 (a-c): Projected emission of CO by source sectors in Cote d'Ivoire, Ghana and Nigeria in 2010, 2030 and 2050.

3.3.1.4. Non-methane volatile organic compounds (NMVOC or VOC)

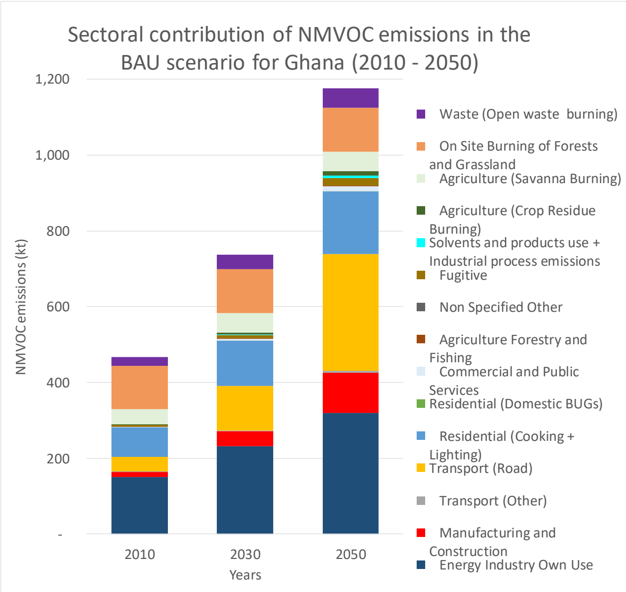
According to the BAU scenario, total national NMVOC emissions are expected to increase in coming years with the road transport sector being a particularly important source in all three countries. By 2050, total national NMVOC emissions would have increased from the 2010 values by approximately 3 times in Cote d'Ivoire and Nigeria, and 2 times in Ghana. However, road transport is the only source where its share of total emissions continues to increase in all three countries while contribution from other sources are about the same or reduced. This is predominantly due to the projected increase in motorcycles and passenger cars. In 2010, road transport accounted for 11%, 8% and 16% of total in Cote d'Ivoire, Ghana and Nigeria. By 2050, these were projected to increase to 17%, 26% and 26% respectively.

While the share of road transport NMVOC emission increases, there are still larger sources in each of the countries. In Cote d'Ivoire, the use of diesel in railways for transport and charcoal making are the biggest sources representing 33% and 28% of total national NMVOC emissions in 2030 becoming 38% and 25% respectively by 2050. Similarly, charcoal making is a large NMVOC source in Ghana where it accounts for the largest share of national emissions at 30% in 2030 reducing to 26% by 2050. In Nigeria, residential use of wood for cooking remains the largest source of NMVOC throughout the projection period at 51% in 2010 reducing to 45% by 2050 due to increased road transport emissions.

It is important to note that although NMVOC emissions are projected to increase in this study, there could still be further increases than estimated in this study. Apart from the big sources already identified above, solvents and other products (like paints, adhesives) are well known sources of NMVOCs. Lack of reliable data on their production and use hinders the estimation of NMVOC emissions from this source. Furthermore, the projected increase in NMVOC emissions could also mean a proliferation of other pollutants, such as ozone, due to its importance in its formation.



(a)



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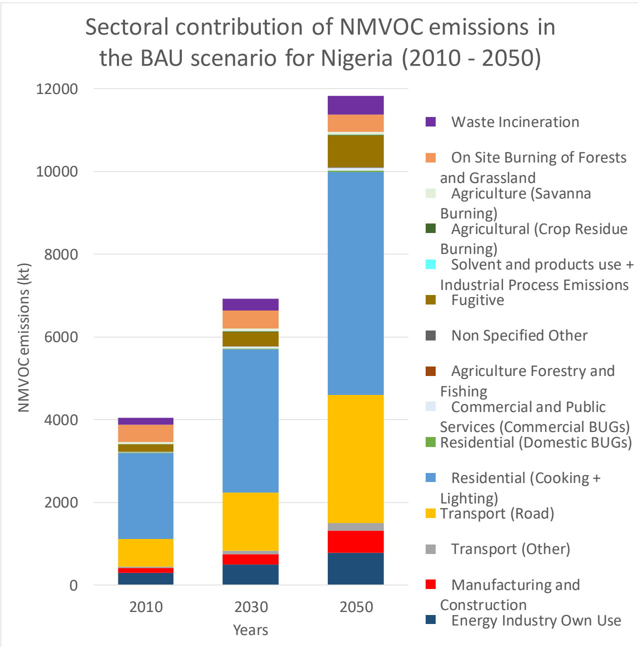


(c)

Figure 3.8 (a-c): Projected mission of NMVOC by source sectors in Cote d'Ivoire, Ghana and Nigeria in 2010, 2030 and 2050.

3.3.1.5. Black carbon and Organic carbon

Under the BAU scenario, the residential sector is the dominant source of carbonaceous particulates of BC and OC. Cooking using wood fuel is the largest BC source in all three countries and emission from this source for the projection period can account for an average of 47%, 29%, 72% of total emissions in Cote d'Ivoire, Ghana and Nigeria. While residential cooking remained the largest source for OC in Nigeria at an average of 60% for the projection period, it rose to become the largest OC source in Cote d'Ivoire at 32% in 2030 further increasing to 36% by 2050. In Ghana, vegetation fires (on-site burning of forests and grasslands; and savanna burning) on average account for more than half of OC emissions at 57% for the 2010 – 2050 period.

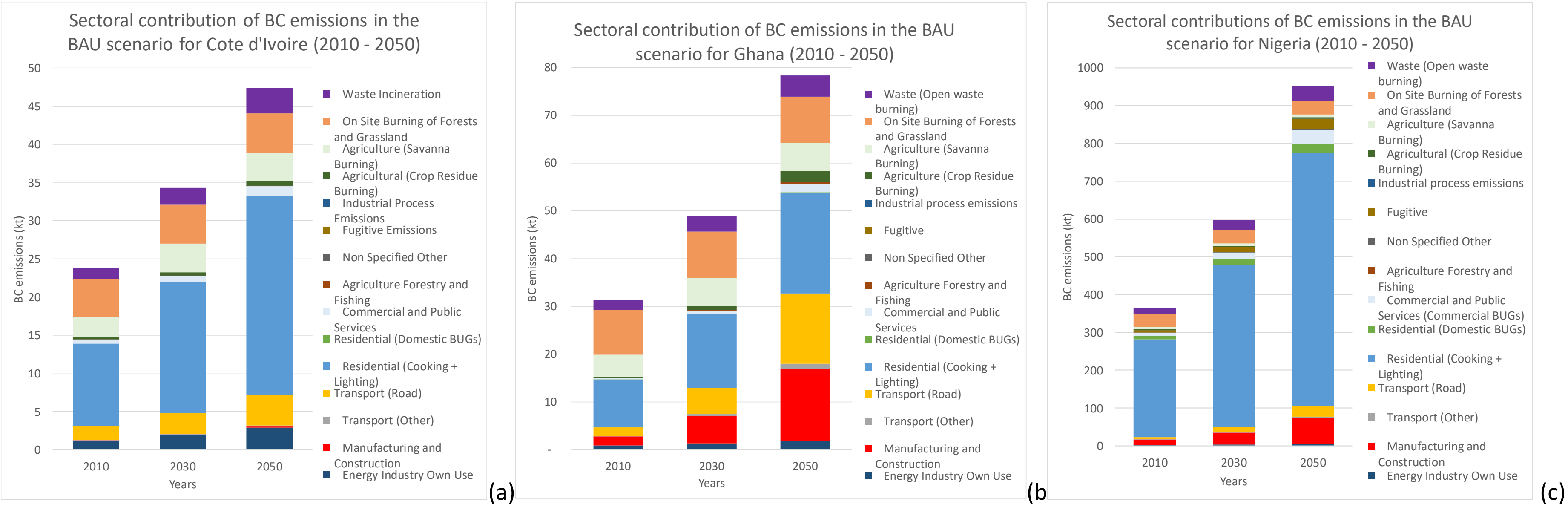


Figure 3.9 (a-c): Projected emission of BC by source sectors in Cote d'Ivoire, Ghana and Nigeria in 2010, 2030 and 2050.

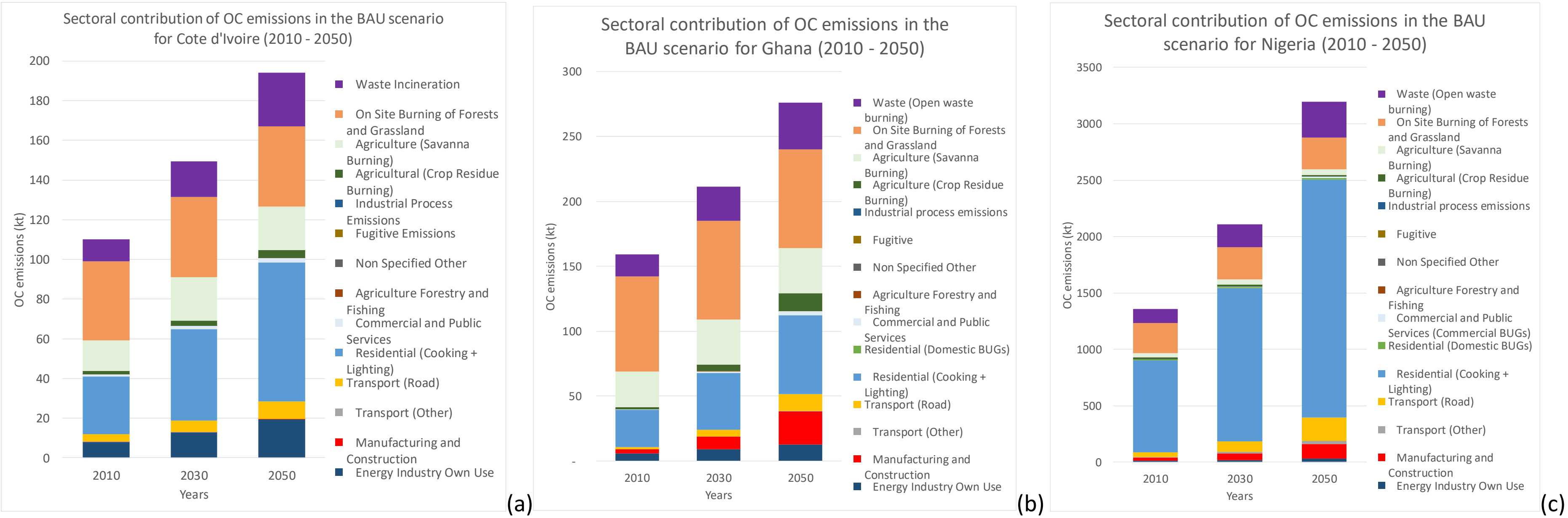


Figure 3.10 (a-c): Projected emission of OC by source sectors in Cote d'Ivoire, Ghana and Nigeria in 2010, 2030 and 2050.

3.3.1.6. Methane

The BAU projection of methane emissions shows an increase in each of the three countries, although at different annual average rates. Emissions in both Cote d'Ivoire and Nigeria increased at an average of 3% per year resulting in net increases of 47% and 52% respectively by 2030, relative to 2010 emissions. By 2050, the two countries show increases of more than 100% compared to 2010 values. This is, however, not the case in Ghana. Although, CH_4 emissions increased over the projection period, the average rate of increase over the entire projection period of 1% per year is much lower compared to that of Cote d'Ivoire and Nigeria. Only a 4% increase was projected by 2030 relative to 2010 emissions and by 2050, the emissions increased by 41%.

The largest emission sources in each of the three countries differs from one another. In Cote d'Ivoire, charcoal-making and domestic waste water maintain their status all through the projection period as the biggest sources of CH_4 in the country. Their share of total CH_4 emissions increased by 4% (by 2050) each relative to their shares in 2010. Although, charcoal is the third most popular fuel used for cooking in Cote d'Ivoire, it is still more widely used here than in Ghana and Nigeria, hence, the increase in charcoal production and consequently, CH_4 emissions. Increasing population in all three countries also mean increase in the generation of domestic wastewater and CH_4 emission. As in Cote d'Ivoire, domestic waste water is a major source of CH_4 emission in Ghana. Share of emission from this source increased from 16% in 2010 to 23% of total CH_4 emissions by 2030 and 24% BY 2050. In addition to domestic waste water, charcoal production is also a large CH_4 source in Ghana with its share of total emissions increasing from 10% in 2010 to 15% by 2030 and 2050.

However, a common large CH_4 source to all three countries is the agriculture and specifically, CH_4 emissions from livestock enteric fermentation and manure management. It is not the biggest source but, an important one as it remains the third largest CH_4 source in Cote d'Ivoire, and second in both Ghana and Nigeria over the projection period. In Nigeria, residential use of wood for cooking dominates other CH_4 sources as it accounts for about one-third of all total CH_4 emissions resulting from the predominant use of wood for cooking in the country.

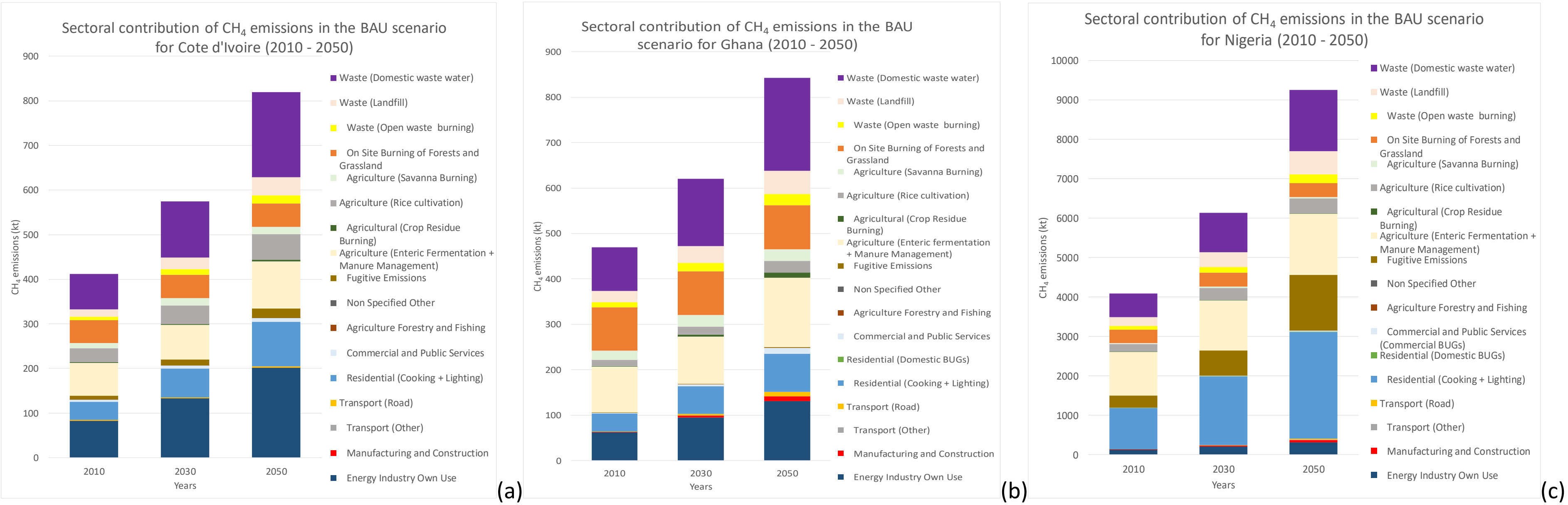
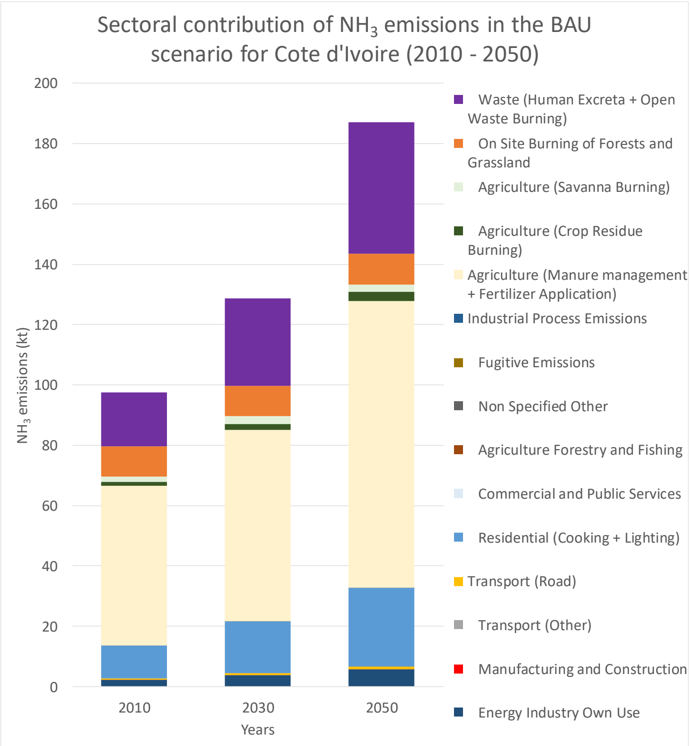
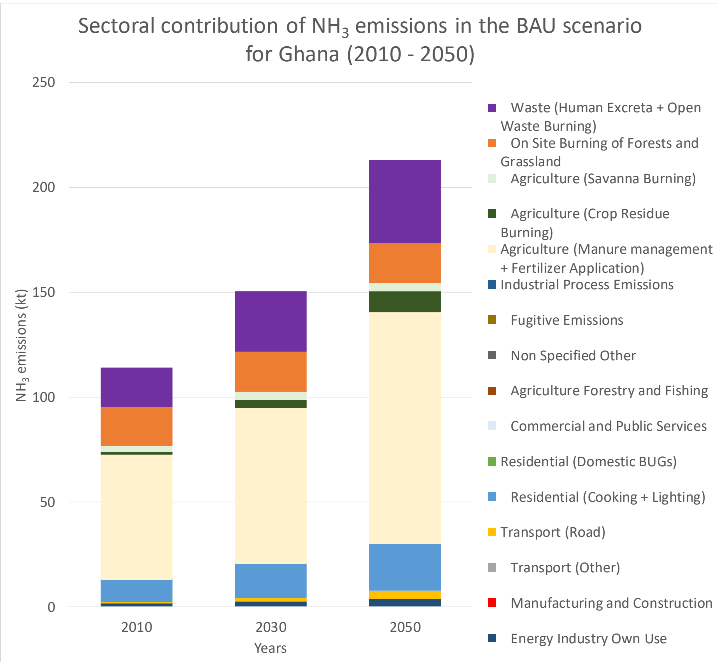


Figure 3.11 (a-c): Projected emission of CH_4 by source sectors in Cote d'Ivoire, Ghana and Nigeria in 2010, 2030 and 2050.

3.3.1.7. Ammonia



(a)



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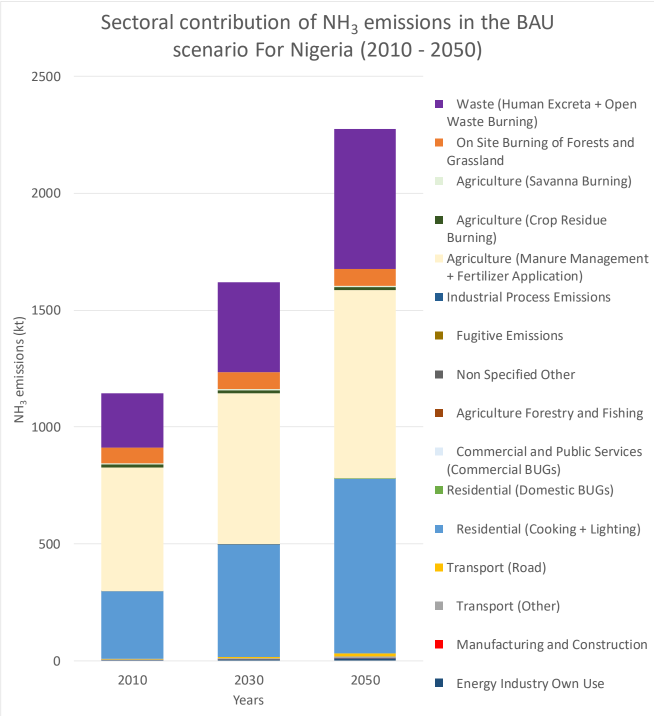


(c)

Figure 3.12 (a-c): Projected mission of NH_3 by source sectors in Cote d'Ivoire, Ghana and Nigeria in 2010, 2030 and 2050.

The BAU projection of ammonia emissions shows an increase in each of the three countries, although at different annual average rates.

The largest emission sources in each of the three countries was agriculture, specifically, fertilizer application and manure management. The other largest sources of ammonia emissions were the waste sector and residential cooking. However, the relative importance of these sectors differs between countries. The residential and waste sectors made the largest contribution to total CH_4 emissions in Nigeria, which had the smallest contribution from agriculture. In Ghana and Cote d'Ivoire, waste sector CH_4 emissions were the second largest source while residential sector CH_4 emissions made a smaller contribution.

3.3.2. Emission reduction potential of mitigation scenarios

The BAU scenario has shown possible future emissions of atmospheric pollutants for Cote d'Ivoire, Ghana and Nigeria in the absence of additional regulations besides those already existing in 2010. This section assesses the level of emission reduction that could be achieved by each of the three mitigation scenarios (COM, FIN and MFR) in reference to the BAU scenario. Although, the analysis described here covers all three countries, only the figures showing the analysis for Nigeria are presented. Similar figures for Cote d'Ivoire and Ghana are found in Appendix 4.1.

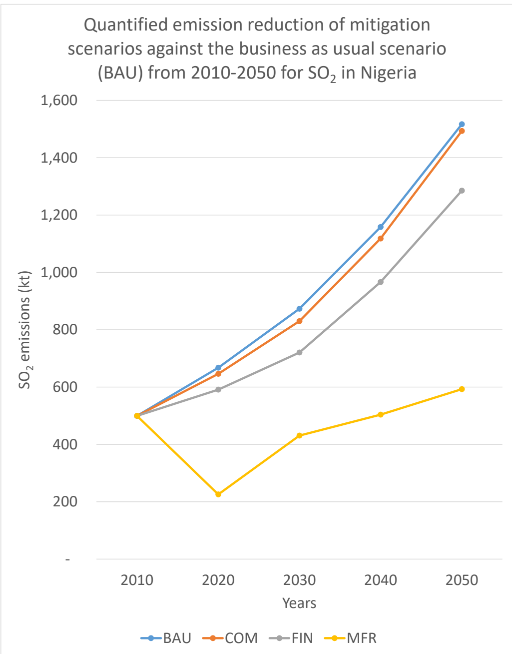
Figures 3.11 (i-ix) below show that all three scenarios will reduce the emission of all pollutants in Nigeria for the period 2020 – 2050 with the largest reduction achieved by the MFR scenario. However, there are a few of exceptions. First, the reduction of CH_4 and NH_3 by COM scenario are negligible at 0% share of total emissions. Second, between 2020 and 2030, the FIN scenario shows greater emission reduction than the MFR for certain pollutants. This is due to the implementation of an ambitious government policy (in the FIN scenario) which aims to halve the use of wood fuel for cooking through the adoption of improved cook stoves by 2020. The pollutants with larger 2030 emission reductions in the FIN compared to MFR scenario are CO, BC, OC, $PM_{2.5}$ and CH_4 at 40%, 52%, 43%, 50% and 19% reduction in emissions in 2030 compared to the BAU respectively, compared with 38%, 44%, 42%, 40% and 14% for MFR in 2030. Third, the phase out of BUGs in the COM scenario led to increased demand for electricity from public electricity generating plants (also called national grid). This increased emission of all pollutants from the national grid in the COM scenario. However, overall emission reduction achieved by the COM scenario is limited. Conversely, in Ghana, this caused an increase in total emissions for the COM scenario by approximately 1% for SO_2 and BC throughout the projection period.

Furthermore, the COM scenario for Nigeria shows the emission reduction that can be achieved by gradually phasing out the 5 sources that are particular to the West African region (described in Chapter Two). The extent of this reduction is limited as observed by the range of the fraction of emissions reduced, which is 1-18% in 2020, 4-38% in 2030 and 2-41% by 2050. By contrast, the MFR scenario includes progressive emission reduction measures (i.e., further cooking (FUR1), further road transport (FUR2) and further electricity generating measures (FUR3)) resulting in large emission reductions of pollutants with a range of 14-60% of total emissions in 2030 increasing to 26-79% for 2050.

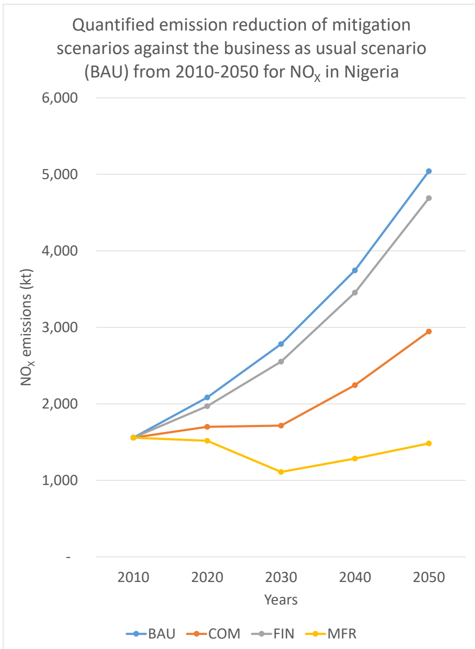
For Ghana, emission reduction of all pollutants is mainly greater in the FIN and MFR scenarios than in the COM scenario. The COM scenario is most relevant for reducing PM_{10} emissions where 59% of total emissions would be avoided by 2030 increasing to 75% by 2050 due to the large contribution to PM_{10} emissions from road dust which is substantially reduced in the COM scenario. While the fraction of total emissions reduced by FIN is constant, at 2-10% (for 2020 to 2030) and 3-11% (2030 - 2050) depending on the pollutant, MFR achieved larger and increased emission reductions from 2020 to 2050 at 2-22% by 2020 to 7-79% by 2050. A similar emission reduction pattern to Ghana's is also observed for Cote d'Ivoire. The COM scenario is only important for PM_{10} and $PM_{2.5}$ reducing both by 66% and 20% respectively by 2030 to 74% and 26% by 2050 while MFR scenario shows increased reductions over the projection period for all pollutants.

The COM and FIN scenarios are limited both in the fraction of emission reductions achievable between 2010 and 2050, as well as in the number of pollutants that can achieve a significant reduction. By contrast, the MFR scenario demonstrates the possibility of reducing pollutant emissions by 2030 to values that are equivalent to or less than 2010 values for all pollutants in Nigeria apart from CH_4 and NH_3 whereas, for Ghana, only PM_{10} can achieve this value. For Cote d'Ivoire, this is only possible for PM_{10} and BC. However, if the emissions threshold is increased to 2020 values (i.e. higher emissions) the MFR scenario will reduce the emission of all pollutants in Ghana to 2020 values or less by 2030. For Nigeria, this is also applicable to all pollutants except CH_4 and NH_3 while for Cote d'Ivoire, this is applicable to NO_X, CO, OC, $PM_{2.5}$, PM_{10} and BC.

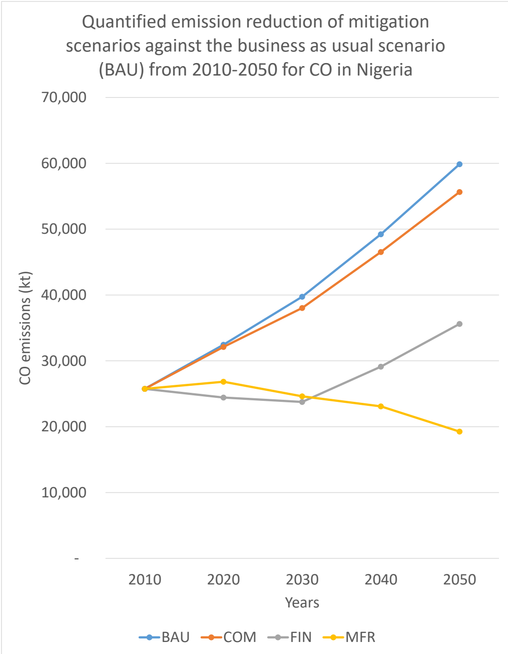
By 2050, the MFR scenario can reduce emissions to BAU 2020 values for all pollutants in Nigeria except CH_4 and NH_3. This is also true for CO, $PM_{2.5}$ and PM_{10} for Ghana and NO_X, BC, $PM_{2.5}$ and PM_{10} for Cote d'Ivoire. If the threshold is lowered to BAU 2010 values (that is, lower emissions), MFR scenario will only reduce 2050 emissions for NO_X, CO, BC, OC, $PM_{2.5}$ and PM_{10} for Nigeria; PM_{10} for Ghana and Cote d'Ivoire.



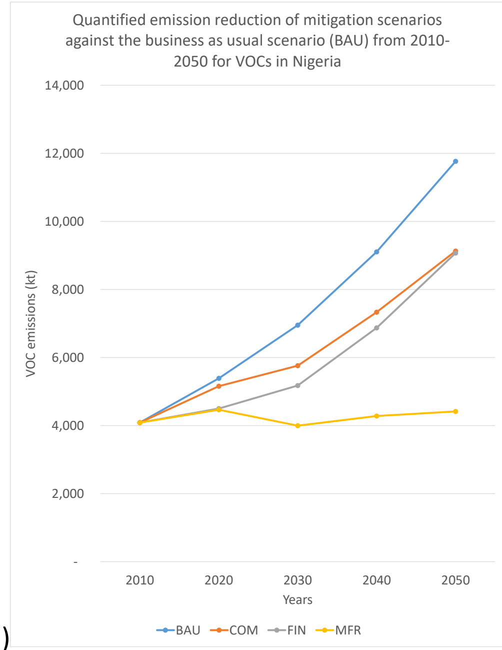
(i)



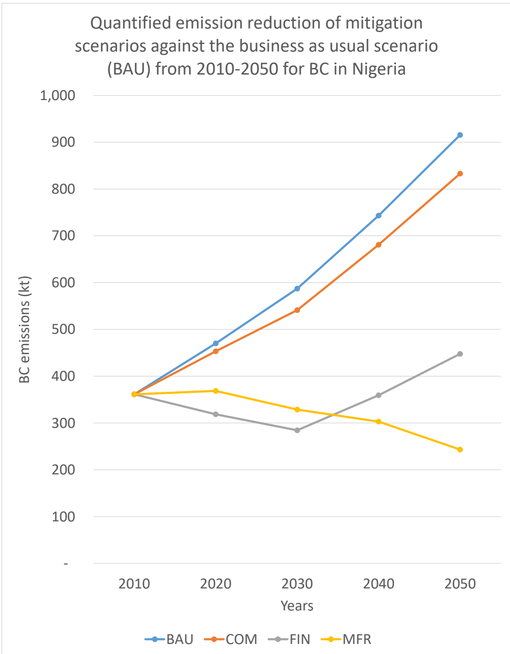
(ii)


Quantified emission reduction of mitigation scenarios against the business as usual scenario (BAU) from 2010-2050 for CO in Nigeria
CO emissions (kt)
70,000
60,000
50,000
40,000
30,000
20,000
10,000
-
2010
2020
2030
2040
2050
Years
BAU
COM
FIN
MFR

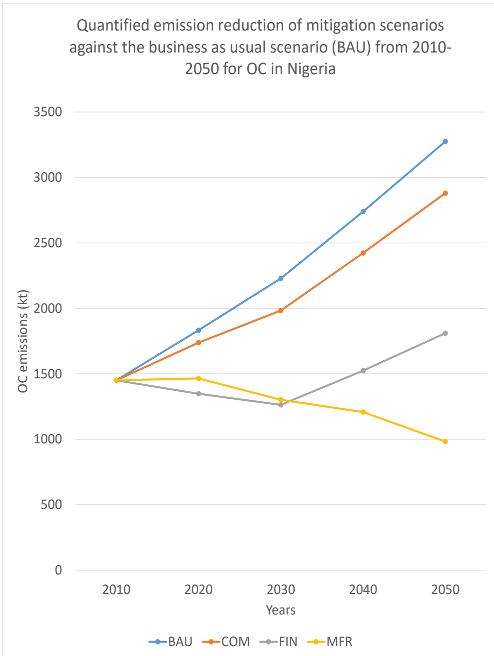
(iii)


Quantified emission reduction of mitigation scenarios against the business as usual scenario (BAU) from 2010-2050 for VOCs in Nigeria
VOC emissions (kt)
14,000
12,000
10,000
8,000
6,000
4,000
2,000
-
2010
2020
2030
2040
2050
Years
BAU
COM
FIN
MFR

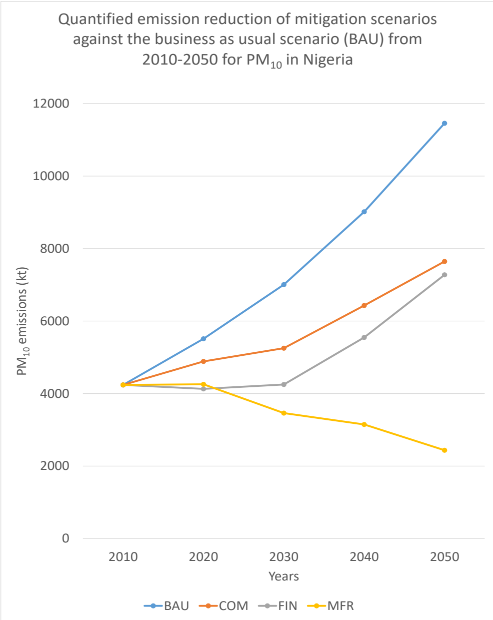
(iv)


Quantified emission reduction of mitigation scenarios against the business as usual scenario (BAU) from 2010-2050 for BC in Nigeria
BC emissions (kt)
1,000
900
800
700
600
500
400
300
200
100
-
2010
2020
2030
2040
2050
Years
BAU
COM
FIN
MFR

(v)


Quantified emission reduction of mitigation scenarios against the business as usual scenario (BAU) from 2010-2050 for OC in Nigeria
OC emissions (kt)
3500
3000
2500
2000
1500
1000
500
0
2010
2020
2030
2040
2050
Years
BAU
COM
FIN
MFR

(vi)



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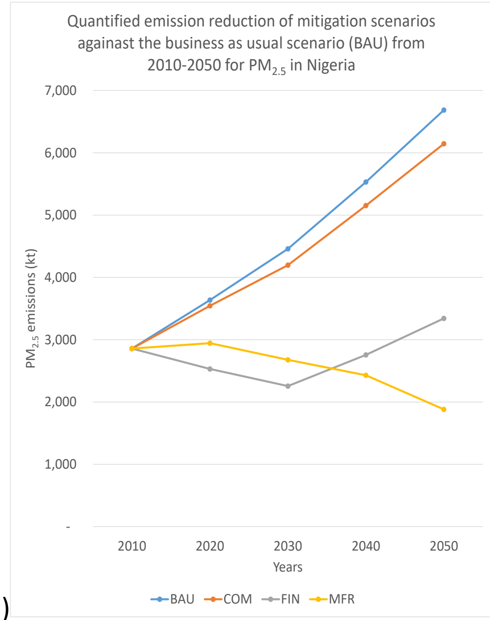
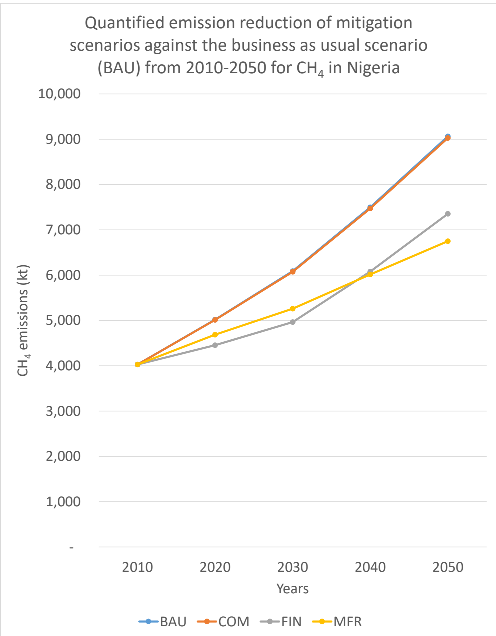


(viii)



(ix)

Figure 3.13 (i-ix): Comparison of emission reduction of the three mitigation scenarios (COM, FIN and MFR) against the Business-AS-Usual (BAU) scenario for Nigeria for the projection period (2010 – 2050).

3.3.3. Magnitude of emission reductions for specific mitigation measures

The three mitigation scenarios developed in this study have been shown to reduce the emission of pollutants to varying degrees in each of the countries. However, it is also important to understand which of the mitigation measures (within each scenario) are most effective at reducing emissions. Table 4.5 summarises the fraction (in percentage) of total emissions reduced by the mitigation scenarios (Appendix 4.2).

In Nigeria, for the COM scenario, the majority of the emission reductions come from phasing out the use of backup generators (BUGs) in both domestic and commercial settings. For instance, by 2030, the COM scenario reduces NO_X emissions by 1070 kt (38% of the national total NO_X emissions). Phasing out BUGs reduced NO_X emissions from these generators by 1177 kt, although this was then partially offset by an additional 115 kt NO_X emissions from grid electricity generation. BC and OC were also reduced in 2030 by 46 kt (8% of total national BC emission) and 247 kt (11% of total OC emissions) respectively. Phasing out BUGs accounts for 70% and 95% of these reductions. National total NMVOC emission was reduced by 1191 kt (17%) in 2030 by the COM scenario. 1131 kt of this reduction comes from road transport. For Ghana and Cote d'Ivoire, the COM scenario only reduced emissions of PM_{10} and $PM_{2.5}$, and BC for Cote d'Ivoire. In both countries, eliminating the resuspension of road dust from unpaved roads (UNP) accounts for the main PM emissions. The COM scenario reduced $PM_{2.5}$ emissions by 92 kt (17% of national total emissions) in Ghana. 91 kt is attributable to reduction from unpaved roads. In Cote d'Ivoire, $PM_{2.5}$ was reduced by 80 kt (20% of total national emissions) of which 78 kt was from unpaved road dust.

For the MFR scenario, the most effective mitigation measure is the further cooking measure (FUR1) in all three countries. This is because it accounts for the greatest share of the emissions reduced for several pollutants. However, there are also other measures with significant emission reduction for certain pollutants. For instance, $PM_{2.5}$ emission for Ghana in 2030 was reduced by 160 kt (29% of national total), 62 kt of that reduction is from FUR1 while 81 kt is from UNP (unpaved road. Similarly, in Cote d'Ivoire, 150 kt (37% of national total $PM_{2.5}$ emissions) was reduced, 73 kt was from FUR1 and 69 kt from UNP. In Nigeria, $PM_{2.5}$ reduction of 1800 kt (40% of national) mainly come from FUR1 (1549 kt). VOC emission was reduced by 2971 kt (42% of national total) in Nigeria, FUR1 accounts for 1588 kt while further road transport measures (FUR2) accounts for 1321 kt. FUR1 (at 67 kt) and FUR2 (at 163 kt) accounts for most of the 229 kt VOC reduced in Cote d'Ivoire. While most reduction in NO_X emissions in 2030 were obtained from FUR2 in Ghana and Cote d'Ivoire (38% and 49% of national total NO_X emissions respectively), NO_X emission reduction of 1677 kt in Nigeria was mainly from (BUGs), although, FUR2 and FUR1 also reduced NO_X emissions significantly (324 kt and 194 kt respectively).

3.3.4. Sectoral significance of mitigation measures

This section shows the effectiveness of various mitigation measures at sectoral level. This will allow the identification of the mitigation measure or a combination of measures that is most beneficial at reducing emissions in a sector. Apart from the BAU scenario, the other three scenarios (i.e. COM, FIN and MFR) are made up of emission reduction measures (Sub-Section 3.2.2-3.2.4). These measures were drawn out from all three scenarios and then categorised based on the sector from which they reduce emissions. The main sectors identified are the residential sector and the road transport sector. Under the residential sector, emission reduction measures compared are further cooking measures (FUR1), simple wick lamp elimination (SIM) and domestic backup generator phase-out (D.BUGs). A fourth measure which combines all three measures (i.e. FUR1+D.BUGs+SIM) was also included in this comparison. For road transport sector, emission reduction measures included are further road transport measures (FUR2), two-stroke motorcycle elimination (TWO) and unpaved road dust (UNP).

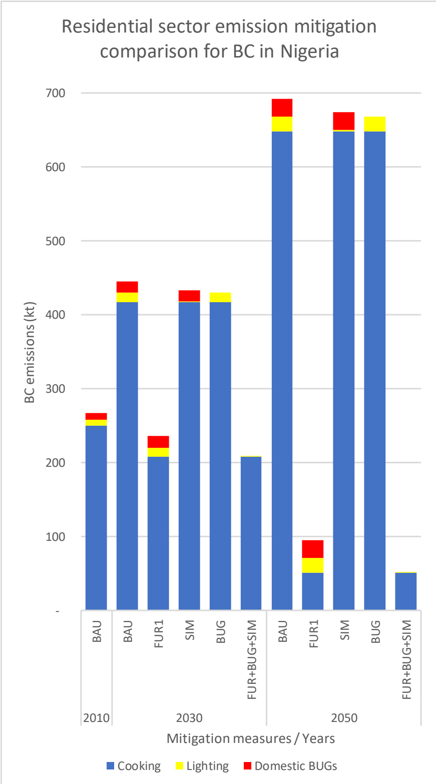
3.3.4.1. Residential sector

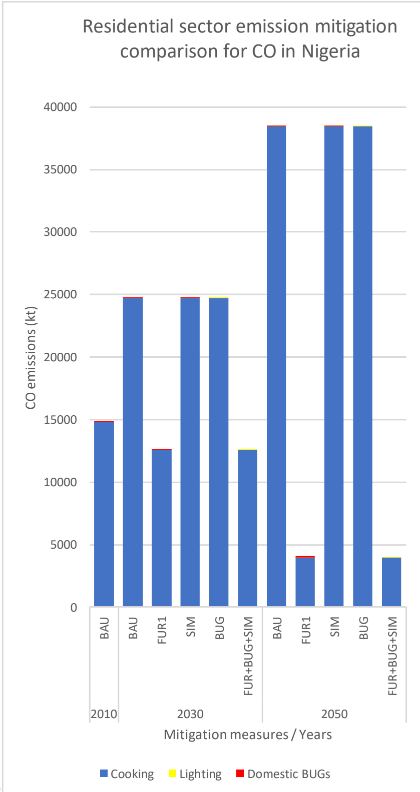
In the BAU scenario, cooking and the domestic use of backup generators contributes approximately 50% each to residential NO_X emissions in Nigeria between 2030 and 2050. Cooking also contributes virtually all residential CO emissions and most of residential BC (94%), OC (86%) and SO_2 (65%) while domestic use of backup generators is responsible for 35% residential SO_2 emissions and 14% of OC emissions. Lighting only contributes 3% of residential BC emissions in Nigeria. With exception to OC where approximately half of the residential emissions come from cooking and the other half from the domestic use of BUGs, all other pollutants considered here are predominantly from cooking – BC (93%), NO_X (99%), SO_2 (98%) and CO (approx. 100%).

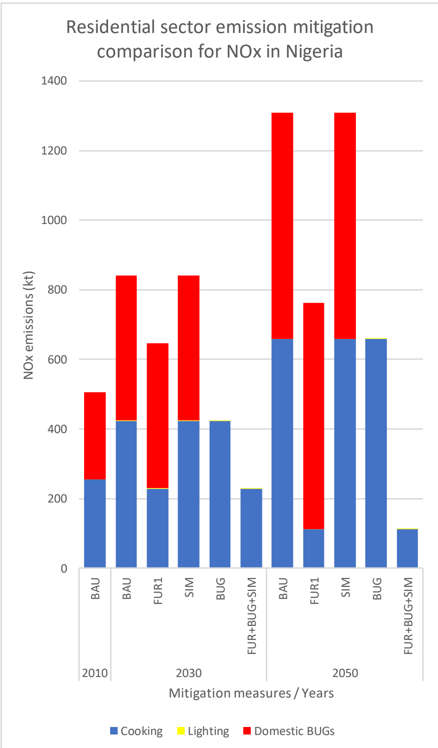
The comparison of the mitigation measures show that D.BUGs (i.e. domestic backup generator phase-out) is the single most effective measure for reducing residential NO_X emissions in Nigeria, reducing it by 50% in both 2030 and 2050. This is followed by FUR1 (i.e. further cooking measures), reducing NO_X emissions here by 23% in 2030, then increasing to 42% by 2050. Overall, FUR1+D.BUGs+SIM achieved a 73% NO_X reduction in 2030, increasing to 91% by 2050 (see Figures 3.12(a-e)). Conversely, NO_X emissions from domestic use of BUGs in Ghana is not large enough to account for a significant NO_X reduction by implementing emission reductions from D.BUGs. Here, FUR1 is best for reducing Ghana's residential NO_X emissions by 44% (in 2030) and 68% (2050) (Figure 3.12 h).

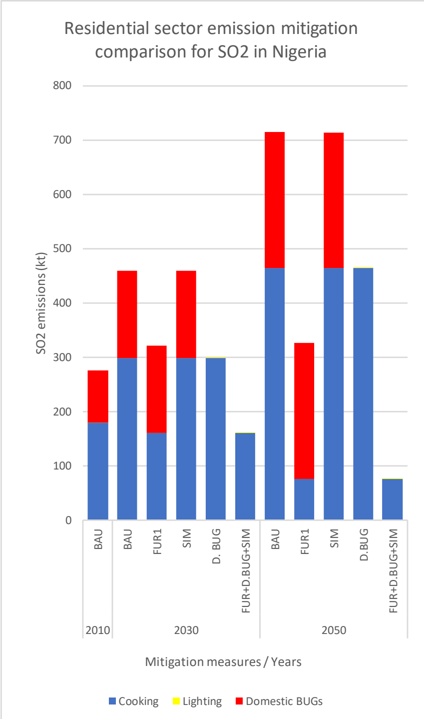
Residential cooking is the predominant source of CO and BC in residential homes in Nigeria, so SIM and D.BUGs did not achieve any significant BC reduction, only 3% each. FUR1 on the other hand, reduced residential CO and BC emission by 49% and 47% respectively in 2030 and by 2050 almost doubles emission reductions to 89% and 86%. This is also true for Ghana. Residential CO and BC reduction by FUR1 achieved 52% reduction for both pollutants in 2030 further increasing to 79% and 78% respectively (Figures 3.12 f and g).

In Nigeria, FUR1 reduced residential OC emissions by 44% in 2030 increasing to 80% by 2050 while D.BUGs were more effective for residential SO_2 reduction in 2030 (at 35% compared with 30% by FUR1). By 2050, however, FUR1 increased the SO_2 reduction to 54% while D.BUGs remained at 35%. Conversely, in Ghana, FUR1 was effective for reducing residential SO_2 emissions at 45% in 2030 and 69% by 2050 while D.BUGs (at 50% reduction in both 2030 and 2050) was more effective than FUR1 in reducing OC emissions which accounts for 29% reduction in 2030 and 43% by 2050.

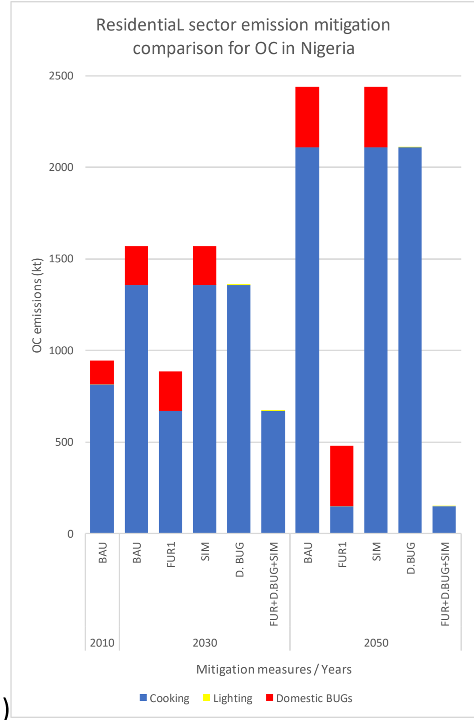

Residential sector emission mitigation comparison for BC in Nigeria
BC emissions (kt)
700
600
500
400
300
200
100
-
BAU
BAU
FUR1
SIM
BUG
FUR+BUG+SIM
BAU
FUR1
SIM
BUG
FUR+BUG+SIM
2010
2030
2050
Mitigation measures / Years
Cooking
Lighting
Domestic BUGs
(a)


Residential sector emission mitigation comparison for CO in Nigeria
CO emissions (kt)
40000
35000
30000
25000
20000
15000
10000
5000
0
BAU
BAU
FUR1
SIM
BUG
FUR+BUG+SIM
BAU
FUR1
SIM
BUG
FUR+BUG+SIM
2010
2030
2050
Mitigation measures / Years
Cooking
Lighting
Domestic BUGs
(b)

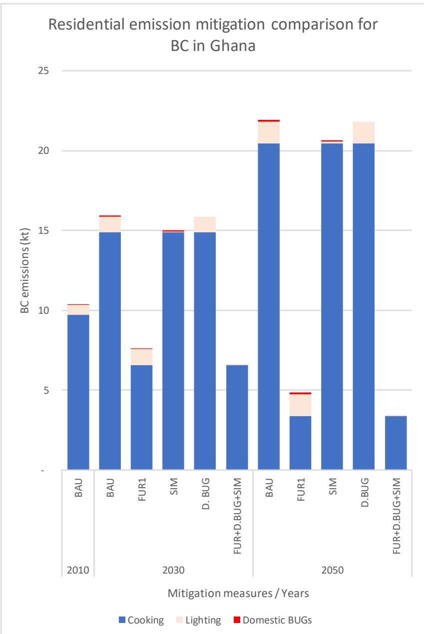

Residential sector emission mitigation comparison for NOx in Nigeria
NOx emissions (kt)
1400
1200
1000
800
600
400
200
0
BAU
BAU
FUR1
SIM
BUG
FUR+BUG+SIM
BAU
FUR1
SIM
BUG
FUR+BUG+SIM
2010
2030
2050
Mitigation measures / Years
Cooking
Lighting
Domestic BUGs
(c)


Residential sector emission mitigation comparison for SO2 in Nigeria
SO2 emissions (kt)
800
700
600
500
400
300
200
100
0
BAU
BAU
FUR1
SIM
D. BUG
FUR+D.BUG+SIM
BAU
FUR1
SIM
D.BUG
FUR+D.BUG+SIM
2010
2030
2050
Mitigation measures / Years
Cooking
Lighting
Domestic BUGs

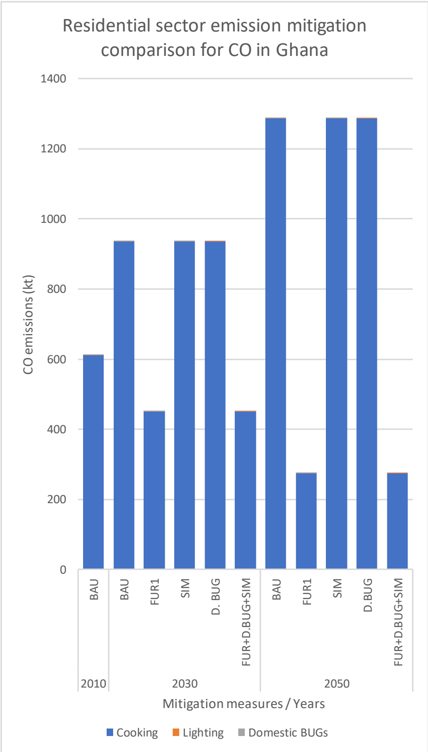
(d)


ResidentiaL sector emission mitigation comparison for OC in Nigeria
OC emissions (kt)
2500
2000
1500
1000
500
0
BAU
BAU
FUR1
SIM
D. BUG
FUR+D.BUG+SIM
BAU
FUR1
SIM
D.BUG
FUR+D.BUG+SIM
2010
2030
2050
Mitigation measures / Years
Cooking
Lighting
Domestic BUGs

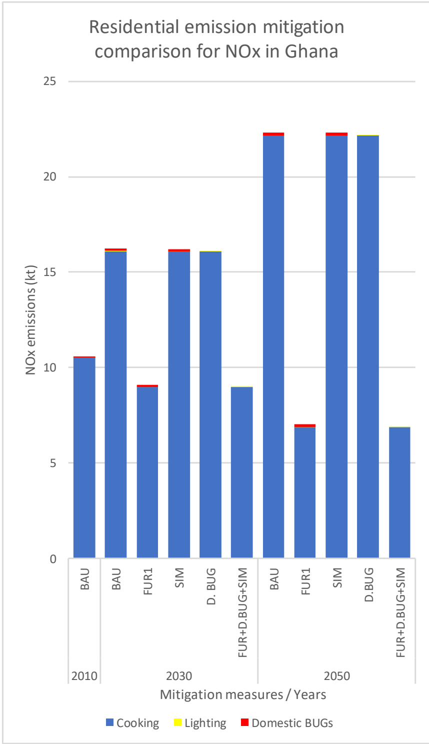
(e)


Residential emission mitigation comparison for BC in Ghana
BC emissions (kt)
25
20
15
10
5
-
BAU
BAU
FUR1
SIM
D. BUG
FUR+D.BUG+SIM
BAU
FUR1
SIM
D.BUG
FUR+D.BUG+SIM
2010
2030
2050
Mitigation measures / Years
Cooking
Lighting
Domestic BUGs

(f)



(g)



(h)

Figure 3.14 (a-h): Comparison of mitigation measures for BC, OC, CO, NO_X and SO_2 in the residential sector in Nigeria between 2010 – 2050 while (f – h) is the same comparison for Ghana for BC, CO, NO_x

3.3.4.2. Road transport

The road transport sector is important for the emission of NO_X, VOC and PM_{10} in Cote d'Ivoire, Ghana and Nigeria. In 2010, it contributed a range of 12 – 66%, 8 – 17% and 38 – 74% to national emissions respectively. A comparison of the three mitigation measures for reducing emissions from this sector (i.e. FUR2, TWO and UNP) shows that the effectiveness each measure depends on the pollutant in question. In all three countries, PM_{10} from road transport is predominantly emitted or released into the atmosphere as re-suspended dust from vehicular use of unpaved roads, the size of exhaust particles predominantly being sub-micron. So as expected, UNP, which assumes that all roads would be paved by 2030 is the most effective measure to reduce PM_{10} emissions from road transport.

On the other hand, VOC emissions from road transport largely come from the use of motorcycles compared to other vehicle types like passenger cars, light commercial vehicles and heavy-duty vehicles. However, the 'TWO' measure did not achieve any reduction in VOC emissions by simply changing from the use of 2-stroke motorcycles to 4-stroke ones (when both are classed as uncontrolled vehicles based on exhaust emissions as they were assumed to have the same emissions factor). But when the change is from the use of 2-stroke motorcycles (uncontrolled) to 4-stroke motorcycles (Euro II and III), a level of VOC emission reduction was observed. In Cote d'Ivoire, this reduction amounts to 60% of total road transport emissions in 2030, 33% in Ghana, and 82% in Nigeria.

FUR2 is the only road transport emission reduction measure that is significant for more than one pollutant (i.e. NO_X and VOC). This measure assumes a shift from the use of highly polluting uncontrolled vehicles to the use of cleaner ones as described in Section 3.2.4 (Table 3.5). As a result, a reduction of 79% of total road transport NO_X emissions is possible by 2030 in Cote d'Ivoire and Ghana, and 82% in Nigeria. Maintaining this shift to the use of cleaner fuels proves to remain effective as the fraction of total road transport NO_X emissions reduced by 2050 increased to 88% in both Cote d'Ivoire and Ghana, and 90% in Nigeria. For VOC emissions from road transport, FUR2 seems to be even more effective going by the fraction of VOC emission reduced from the sector in comparison to NO_X. In Cote d'Ivoire, 90% of total road transport VOC emissions were prevented by implementing the FUR2 measure by 2030. For Ghana and Nigeria, it is 87% and 90% respectively.

Therefore, to achieve significant emission reduction of the three identified pollutants from the road transport sector in all three countries, a combination of the shift from the use of dirty vehicles to cleaner less polluting ones (i.e. FUR2 for NO_X and VOC) plus the paving of all roads used for vehicular transport (UNP for PM_{10}) would be highly effective, especially from 2030 to 2050.

3.4. Discussion

3.4.1. Key results

The results of the projected emissions for all three countries show that in the absence of any regulatory framework, emissions of all air pollutants increased continually throughout the projection period (from 2010 – 2050). This is mainly due to the projected increase in population and economic growth which are the main underlying drivers of emissions. However, the rate at which the emissions increased differs by pollutant and by country. The largest source of each of the pollutants also differs by country except BC where the residential sector is the largest source in all three countries. For instance, although fossil fuel combustion is the major source of NO_X in all three countries by 2030 and 2050, fuel combustion in road transport is the largest source in Cote d'Ivoire and Ghana, while fuel combustion by BUGs in the commercial sector is the largest in Nigeria (see Appendix 3.2, 3.3, 3.4). In Cote d'Ivoire, charcoal making is the leading source of CH_4 while in Ghana, it is domestic water and residential cooking in Nigeria. The results for the BAU scenario highlights the specific and differing major source sectors of pollutants between West African countries. This emphasises the need for detailed and bespoke emissions inventories for modelling of future atmospheric pollutants in countries within the region. It also suggests the need for the development of country-specific approaches in reducing emissions of a pollutant.

As seen in Section 3.3.2, each of the three mitigation scenarios reduced emissions to varying degrees with the least reduction from COM scenario in all three countries. In fact by 2050, there is net gain in total emissions for certain pollutants in the COM scenario for Cote d'Ivoire and Ghana, although, this is less than 1%. These pollutants are NH_3 for Cote d'Ivoire; SO_2, VOC and BC for Ghana; and NO_X and CH_4 for both countries. The net gain is a consequential increase in emission from another source sector due to the removal of emissions from one or more of the 5 key sources of the COM scenario. For instance, increases in emissions from grid electricity as domestic Bugs are phased out.

In general, pollutants significantly reduced by the COM scenario by 2030 are NO_X (38% of national total emissions), NMVOC (17%) and PM_{10} (25%) in Nigeria; whereas in Ghana and Cote d'Ivoire, they are PM_{10} and $PM_{2.5}$. These are theoretical outcomes assuming all the measures that make up the scenario are implemented. However, this may be challenging to achieve. For instance, the major share of PM_{10} emissions reduced by COM scenario is attributable to the paving of all or most of the unpaved roads in each country. Likewise, the

FIN scenario shows substantial emission reduction for certain pollutants in Ghana and Nigeria. For Ghana, these are SO_2, BC, OC and $PM_{2.5}$; and for Nigeria, they are SO_2, CO, VOC, PM_{10}, BC, OC, $PM_{2.5}$ and CH_4. However, all emissions reduced by the FIN scenario in Nigeria, for example, can be traced back to the reduced use of wood fuel for cooking which the Nigerian government plans to halve by 2020 (SE4all, 2016). The possibility of that happening is low because as of 2017, of people in the country still use wood fuel to cook.

Sectoral analysis of the mitigation measures shows that among the three countries, there are also common strategies and mitigation measures that would likely be effective in reducing the emission of certain pollutants. In the residential sector, CO and BC are effectively reduced by further cooking measures (FUR1) in all three countries while this is not the case for residential NO_X emissions. In Ghana, the FUR1 mitigation measure is best for reducing NO_X emissions in the residential sector while for Nigeria, D.BUGs is the most effective residential NO_X emission reduction measure because of the significant use of backup generators in Nigerian houses. Differences are also seen in residential SO_2 emissions between Ghana and Nigeria.

3.4.2. Comparison with other emission projection studies for Africa

Of the few available studies that made future projections of emissions for Africa, only GAINS Eclipse v5a provides a basis whereby results obtained in this work can be quantitatively compared. GAINS provide country estimates of future emissions for the main or common air pollutants (NO_X, SO_2, CO, BC, OC, NH_3, CH_4, VOC, $PM_{2.5}$ and PM_{10}) for 2030 and 2050. Other studies, namely: Liousse et al. (2014); Cofala et al. (2007), Streets et al. (2004) and Kram et al. (2000) present either global or regional forecast of emissions under various scenarios. As a result, they are included in this work for descriptive purposes. Liousse et al estimated future emissions of pollutants from combustion sources only in Africa from 2005 to 2030. Cofala et al assess future global emissions of air pollutants and methane until 2030 while Streets et al. (2004) presented future emissions of carbonaceous aerosols (BC and OC) for 2030 and 2050. Although Kram et al. (2000) estimated future greenhouse gas emissions, results are only available as global or regional estimates with Africa, Latin America and Middle East grouped together as a region. Consequently, this is not considered suitable for comparison in this work.

	GAINS Eclipse - 2010			This study - 2010		
	CIV	GHN	NGR	CIV	GHN	NGR
BC	29	33	149	24	31	364
CH_4	319	285	437	412	470	4091
CO (x10)	183	224	1030	286	371	2574
NH_3	69	65	657	98	114	1144
NO_X	58	86	598	172	229	1555
OC	69	78	346	110	159	1358
OM	121	135	590			
PM_{10}	185	212	996	591	720	4239
$PM_{2.5}$	168	195	883	250	346	2858
SO_2	33	48	120	29	56	392
VOC	296	337	2250	470	468	4052

(a)

	GAINS Eclipse - 2030			This study - 2030		
	CIV	GHN	NGR	CIV	GHN	NGR
BC	33	32	103	34	49	597
CH_4	447	398	552	475	621	6136
CO (x10)	221	231	676	399	515	4004
NH_3	102	89	850	129	150	1620
NO_X	67	145	414	248	474	2791
OC	83	77	254	149	211	2107
OM	145	133	413			
PM_{10}	221	227	759	853	1470	7052
$PM_{2.5}$	201	201	643	348	516	4497
SO_2	37	83	168	42	130	681
VOC	361	395	1465	701	736	6922

(b)

	GAINS Eclipse emissions (kt) - 2050			This study emissions (kt)- 2050		
	CIV	GHN	NGR	CIV	GHN	NGR
BC	33	34	109	47	78	952
CH_4	598	541	757	820	842	9259
CO (x10)	247	267	779	530	716	6136
NH_3	151	125	1160	187	213	2276
NO_X	89	206	581	337	1002	5096
OC	91	86	272	194	276	3194
OM	160	147	458			
PM_{10}	251	276	936	1189	3140	11689
$PM_{2.5}$	224	236	764	463	800	6874
SO_2	47	112	224	59	284	1185
VOC	414	492	1792	1011	1176	11831

9c)

Table 3.8 (a-c): Shows the comparison of projection emissions results between this study and GAINs Eclipse estimates for Cote d'Ivoire, Ghana and Nigeria for 2010, 2030 and 2050.

In absolute emissions values, the results of emission estimates obtained in the BAU scenarios of this study (i.e. for Cote d'Ivoire, Ghana and Nigeria) are generally higher when compared with the total of gridded national emissions of GAINS Eclipse v5a (baseline or current legislation scenario) for any year within the projection period (2010 – 2050). This is likely a result of differences in emission source sectors included in the Eclipse inventory and those developed in this work. This study includes emissions from sources not previously quantified in existing inventories such as gasoline BUGs, illegal oil refining, and unpaved road. In addition, there is no database of emission factors for African countries, so, the choice of emission factors in this work compared to the Eclipse inventory could further contribute to the disparities between the two results (see Appendix xx Table xx). Another clear observation in GAINS results is the initial decline in the projected emissions of all pollutants except CH_4, NH_3 and SO_2 until 2030 for Nigeria. After 2030, emissions started to increase again until 2050 but despite this latter increase, the 2050 emission for Nigeria were still projected to be less than the 2010 values. Conversely, projected GAINS emissions for Cote d'Ivoire and Ghana increased over the projection period, however, at a small annual rate of increase, between 0 and 3%. The increasing trend in GAINS results for Cote d'Ivoire and Ghana is similar to results obtained in this work for all three countries although both absolute values of emissions and the rate of increase are higher than GAINS' result. Although, the background paper which describes the emissions projections is still being prepared (Klimont, Z., Höglund-Isaksson, L., Heyes, C., Rafaj, P., Schöpp, W., Cofala, J., Purohit, P., Borken-Kleefeld, J., Kupiainen, K., Kiesewetter, G., Winiwarter, W., Amann, M, Zhao, B., Wang, S.X., Bertok, I., Sander, R. Global scenarios of air pollutants and methane: 1990-2050. *In preparation*.), it is thought that the decline in GAINS emissions result for Nigeria is probably due to the implementation of measure(s) aimed at reducing emissions from the residential use of biomass suggested by the number and types of pollutants reduced (BC, OC, NO_X, CO, $PM_{2.5}$, PM_{10} AND VOC).

Results obtained in this work and the results of other studies such as Liousse et al. (2014) and Cofala et al. (2007) are all stating the same fact that African emissions are increasing and are projected to continue on the increasing pathway such that they will potentially account for a substantial part of future global emissions. However, it is not possible to make a quantitative comparison between results obtained in this study for country level emissions and the regional totals estimated in these previous two works. Emissions of SO_2 , NO_X, CO, BC and OC in Africa were projected to increase by 2030 despite a projected decrease in global estimates due to the implementation of emission reduction measures in other parts of the world (Europe, North America and certain parts of Asia) (Cofala et al. 2007). According to Liousse et la. (2014), OC from Africa could account for 50% of global emissions by 2030 in the absence of any legal obligations to reduce emissions. In this study, the already high estimates for 2010 are projected to increase all through to 2050 if no significant emissions reduction measures are implemented. Depending on the country, SO_2 emissions is projected to increase by a range of 5 – 10%, NO_X by 6 – 8%, CO by 2 – 3%, VOC by 4- 6%, BC by 3- 4%, OC by 2 -3%, CH_4 by 1 – 3%, $PM_{2.5}$ by 3 – 4%. The inability to compare regional emission estimates for Africa with country level results inhibits both the translation of regional scale trends to the national scale and incorporation of country scale analysis into regional inventories. The development of a mechanism for the consistent development of emissions inventories at the national scale in Africa e.g. building on the national greenhouse gas emission inventories that most African countries already developed as part of their climate planning, would facilitate a consistent comparison of emissions across African countries and allow countries specific analysis to be aggregated to the regional scale for regional level planning and/or scenario level analysis.

Contrary to the global study by Streets *et al* (2004) which projects declining emissions for both BC and OC for Western Africa in 2030 and 2050, results obtained under the BAU scenarios shows an increase of a range of 137 - 160% by 2050 for BC depending on the country and 55 – 91% for OC. The increase projected in this work is similar with that obtained by Liousse *et* al (2014). However, results obtained here differ from those reported for the GAINS Eclipse Current Legislation (CLE) BC and OC projections for both Ghana and Nigeria. The largest decline was projected for Nigeria where the two pollutants will decrease by 31% and 27% respectively in 2030. (Klimont *et al., In preparation)*.

3.4.3. Key uncertainties

In addition to the uncertainty analysis conducted for the estimated emissions for year 2010 (as seen in Section 2.2.4), there are uncertainties associated with the development of emissions scenarios. In this work, the inability to precisely determine how the variables used in estimating future emissions will change makes it quite challenging to reasonably quantify the range of uncertainties inherent in the emission estimates obtained. The variables (activity data, emission factors, GDP growth rate and future population estimates) used in estimating emissions all inherently have significant sources of uncertainties which are compounded by the lack of country specific data that is available in the three West African countries. Future activity data required for both fuel combustion and non-fuel combustion emission sources were estimated based on either future projection of economic growth (GDP) or population growth. Future GDP estimates are often available as single values without the option of a range of possible upper or lower values. It is also rare to see future GDP estimate beyond 2030, meaning the GDP growth rate used here from 2031 to 2050 had to be derived. On the other hand, there are higher and lower population estimates besides the median estimates from the UNDESA. However, without the availability of the upper and lower limits for future GDP, it is probably impossible to estimate the uncertainties surrounding future national emissions estimated for the three countries. Furthermore, some of the data sources used in compiling the baseline emission for the year 2010 (e.g. IEA) do not account for some specific emission sources identified in this work such as the use of backup electricity generators (BUGs) and illegal oil refining and how these might change in the future.

To manage the effects of uncertainties on the results obtained in this study, values that best represent each of the variables required to develop the base year emissions inventory and make future emissions projections were used. For instance, the medium-variant of the population estimate (from UNDESA), for each country were used to project activity data where required. Doing this ensured that a more conservative approach was used to prevent an overestimation of activity data because the estimated population figures themselves were based on assumptions on mortality, fertility and international migration. For activity data which required GDP values for future projections, GDP values or growth rate were sourced from the United States Department of Agriculture Economic Research Service (USDA). This source provides both historic (dating back to 1969) and future projections (up to 2030) of international macroeconomic dataset with regular reviews for 189 countries. The regular review of the dataset and the long-term existence of this source suggest a reliable source of data. For the base year 2010 emissions, data required were sourced from reputable sources (as seen in Chapter Two) and where the required data had to be newly or independently estimated (as is the case for backup generator use in Nigeria and Ghana), they were done with caution to ensure there is no chance for overestimation.

Despite the existence of unquantified uncertainties around the absolute future emission estimates for each scenario, the relative differences in emissions (and their) impacts between scenarios are still likely to represent realistic estimates of the effects of the different scenario assumptions. This is because alternative estimates of the main drivers (e.g. population and GDP growth) would tend to affect all scenarios in more or less the same way. Thus, despite the possibly large uncertainties around projected emissions in absolute terms, the relative differences in impacts between the scenarios, the main focus of this chapter, are likely to be much less uncertain.

3.4.4. Recommendations

Given that human population figures are projected to continue to increase in all the three countries that were studied and economic development expected to continue, emission of air pollutants will continue to increase especially in the current unsustainable way as seen with the COM scenario. This scenario evidently shows that if things continue as they were in 2010, emissions will continue to be on the rise. The FIN scenario as well is either not great for substantial emission reduction or the policies (i.e. proposed policies by government) are not likely feasible at the time proposed for their implementation (see Section 3.2.2).

So, it is obvious that realistic actions need to be implemented now (or as soon as possible) in order to achieve meaningful emission reduction in the nearest future (for instance, by 2030), in line with the MFR scenario. Based on the MFR scenario, three sectors have already been identified as the largest ones in terms of emission sources – that is, residential, road transport and energy sectors. So, actions to reduce emissions should focus on these three sectors as they stand to achieve the largest emission reduction.

In the residential sector, the use of wood fuel for cooking is the singular biggest source of residential emissions in all three countries. Gradual and progressive departure from the use of this highly polluting fuel to cleaner ones like electricity or LPG will positively change the emission source structure of the residential sources in each of the countries. For instance, reducing the share of people using wood fuel for cooking such that by 2030, less than half of the 59% of people that used wood fuel for cooking in 2010, would half $PM_{2.5}$ emissions from the residential sector.

Reducing emissions from the road transport sector is also an important opportunity to reduce emissions especially NO_X. Implementing vehicle maintenance check which include emissions testing will go a long way in reducing emissions from this sector. Already, there a policy in place to prevent the importation of very old vehicles in Nigeria. This needs to be properly enforced as newer cars are expected to meet higher emission standards.

It is not enough to just agree on the right policies to bring about emission reduction, effective implementation is vital to achieve the desired outcome. So, it is important that all the relevant stakeholders are involved and informed, the appropriate government departments officials are well trained and equipped to enforce the emission reduction actions agreed and the effectiveness of the implemented actions evaluated regularly or at designated times.

Chapter 4

Impacts of air pollution

4.1. Introduction

It is well documented that air pollution has adverse impacts on human health, crops and climate (Fang et al. 2013; Shiraiwa et al. 2017; Lelieveld et al. 2015; Shindell 2012; Shindell et al. 2005; Dingenen et la. 2009). Most research has focussed on the human health impacts caused by air pollution. These are usually quantified in epidemiological studies as mortality from respiratory diseases, cardiovascular diseases, stroke, and lung cancer (Silva et al. 2016; Shiraiwa et al. 2017; Anenberg et al. 2010). They are based on exposure to the atmospheric concentration of particulate matter less than 2.5 µm in size ($PM_{2.5}$) and ozone (O_3) due to their significant effects on human health (Silva et al. 2013; Brauer et al. 2016; Lepeule et al. 2012; Bell et al. 2004; Jerrett et al. 2009; Cohen et al. 2005). $PM_{2.5}$ are so small that they can deeply penetrate respiratory organs causing significant health risks while ozone is secondarily formed in the atmosphere. $PM_{2.5}$ has been estimated to have the largest health burden globally, therefore, it is the pollutant considered here for human health impacts.

In the literature, evidence of these impacts is increasing but still relatively little is known of the scale and magnitude of these impacts across Africa due to lack of data and epidemiological studies that have quantified the relationship between air pollution exposure and negative health outcomes in Africa specifically. This is a result of a lack of data both on the health status of the population and air pollutants concentrations that they are exposed to. The geographical scope upon which the understanding of the relationship between air pollution and its impacts is based is predominantly limited to North America, Europe (Shiraiwa et al. 2017) and some developing countries of Asia such as China (REF). In Africa, air pollution impact studies are few, and mostly explore impacts on human health, using short-term studies that are generally limited in both the types of pollution sources investigated and the geographic area considered. Most studies have examined the human health impacts from air pollution due to the use of biomass for cooking. For instance, Oluwole et al. (2013) reported health effects from exposure to smoke such as difficulty in breathing, running nose and burning eyes. Dionisio et al. (2008) assessed the exposure of infants and children to indoor air pollution from biomass fuels as a risk factor for pneumonia in The Gambia while Nkosi et al. (2016) explored the acute changes in lung function and air pollution among asthmatic children in communities close to mine dumps in South Africa. Rehfuess et al. (2009) assessed the impact of fuel type and cooking practices on childhood mortality from Acute Lower Respiratory Infection, ALRI. Other available studies such as De Longueville et al. (2010) highlight the fact that despite West Africa being a major receptor of dust particles from the Sahara desert (up to 60% according to D'Almeida, 1986), little is known about the effect of mineral dust from the desert on air quality and human health in West Africa. Owili et al. (2017) also showed the importance of examining different types of $PM_{2.5}$ (mineral dust, anthropogenic pollutants, biomass burning and mixture aerosols) in relation to its impacts on the health of infants and mothers in orders to reduce mortality in low and middle-income countries.

Air pollution health impact assessments that have been conducted for this region are often examined as part of global assessment studies. In such assessments, Africa is either treated as an entity without further country level details, due to insufficient air quality monitoring data, or a continent broken down into sub-regions (Madaniyazi et al. 2015; Silva et al. 2016; Silva et al. 2016; Evans et al. 2013; Shiraiwa et al. 2017; Apte et al. 2015; Brauer et al. 2012; Apte et al. 2015). An exception to this is the global study by Lelieveld et al (2015) and the Global Burden of Disease (GBD) studies described by Brauer et al. (2016) and Lim et al. (2012). For example, the analysis of Lelieveld et al (2015) ranked the top 15 countries based on premature mortality due to outdoor air pollution in 2010. Nigeria was ranked 5th after China, India, Pakistan and Bangladesh. These are all countries with high population levels classified as developing nations by the United Nations. Such studies suggest that as population grows in African countries (currently Africa is home to the fastest growing population in the world), more and more people will be exposed to and affected by air pollution. The GBD studies make use of satellite-based estimates of $PM_{2.5}$ for regions or countries where monitoring data are not available or reliable. Africa lacks such monitoring data; however it has also been found that satellite-derived data do not always agree (both over and underestimating) with other sources of concentration data (Liousse et al. 2014).

Regulatory policies to improve air quality in countries are predominantly based on reducing its impact on human health (Monks et al. 2009). However, the lack of data for African countries of the levels of air pollution, and associated impacts mean that regulatory policies do not exist in many African countries. The regional and global studies that have attempted to quantify the health impact of air pollution across Africa have relied on global emission inventories and global modelling methods (e.g. the Global Burden of Diseases methodology (Lim et al. 2012) to quantify the impacts of air pollution. So, there is the need to know, on a national basis, how the atmospheric environment affects, and will in future affect, people residing in Africa. Consequently, the following questions must be answered: (i) What is the ambient concentration of $PM_{2.5}$ in each country and how will it likely change in future? (ii) How many premature deaths can we attribute to the changing concentrations of ambient $PM_{2.5}$ in each of the countries studied? (iii) Based on estimated mortality, how does air pollution affect various age groups in each country? (iv) What are the impacts of country emissions on local or global climate? (v) How can we improve air quality to benefit human health in these countries and potentially, the climate in the near-term through various policy instruments?

In this study, national emissions data that are derived, wherever possible, using national activity and emission factors and also include emission estimates for key 5 emissions sources not previously considered or well quantified in existing inventories, are used to quantify the impacts of air pollution in each of the three countries studied (Cote d'Ivoire, Ghana and Nigeria). The emissions data were converted into $PM_{2.5}$ concentrations and used to estimate impacts of human health for each country. The impact of all estimated emissions in each country was also assessed in terms of the contribution to near-term global climate change. Scenarios for emission projections (see chapter Three) were applied to explore the benefits of minimising national emissions on concentrations and subsequent impacts. The Long-range Energy Alternatives Planning system – Integrated Benefits Calculator (LEAP-IBC) tool was used for this analysis (Available at: https://www.sei.org/projects-and-tools/tools/leap-long-range-energy-alternatives-planning-system/). LEAP-IBC was used to develop national emissions inventory of atmospheric pollutants from all major emission sources for the base year 2010 (as described in Chapter Two). As described in Chapter Three, this tool was also used to make future projections of national emissions from the base year (2010) to 2050 and also under various mitigation scenarios for all three countries. With the inclusion of other parameters, specifically, linear atmospheric transfer coefficients and concentration-response functions, the tool allows the estimation of ambient concentrations of $PM_{2.5}$ from which impact on human health was quantified. Climate impacts were calculated by first estimating the change in global radiative forcing of pollutant emissions and then converting these forcing to absolute global temperature change. The next Section (Section 4.2) describes the methods used to assess air pollution concentrations and their impacts on human health and near-term climate change, followed by the results in Section 4.3. The discussion of the results is found in Section 4.4 and finally, the concluding remarks in Section 4.5.

4.2. Methodology

The impacts of air pollution on human health and near-term climate were assessed for Cote d'Ivoire, Ghana and Nigeria in this part of the study. In previous chapter, bespoke emissions inventories developed for all three countries were projected from 2010 to 2050 under a business-as-usual scenario (BAU) and 3 mitigation scenarios (i.e. COM, FIN and MFR). Here, the impacts of emissions under each of the four scenarios were quantified based on their contribution to changes in ambient concentrations of $PM_{2.5}$. Ambient concentrations of $PM_{2.5}$ calculated from national emissions were used together with concentration-response functions to allow the estimation of human health impacts for each country using the LEAP-IBC tool.

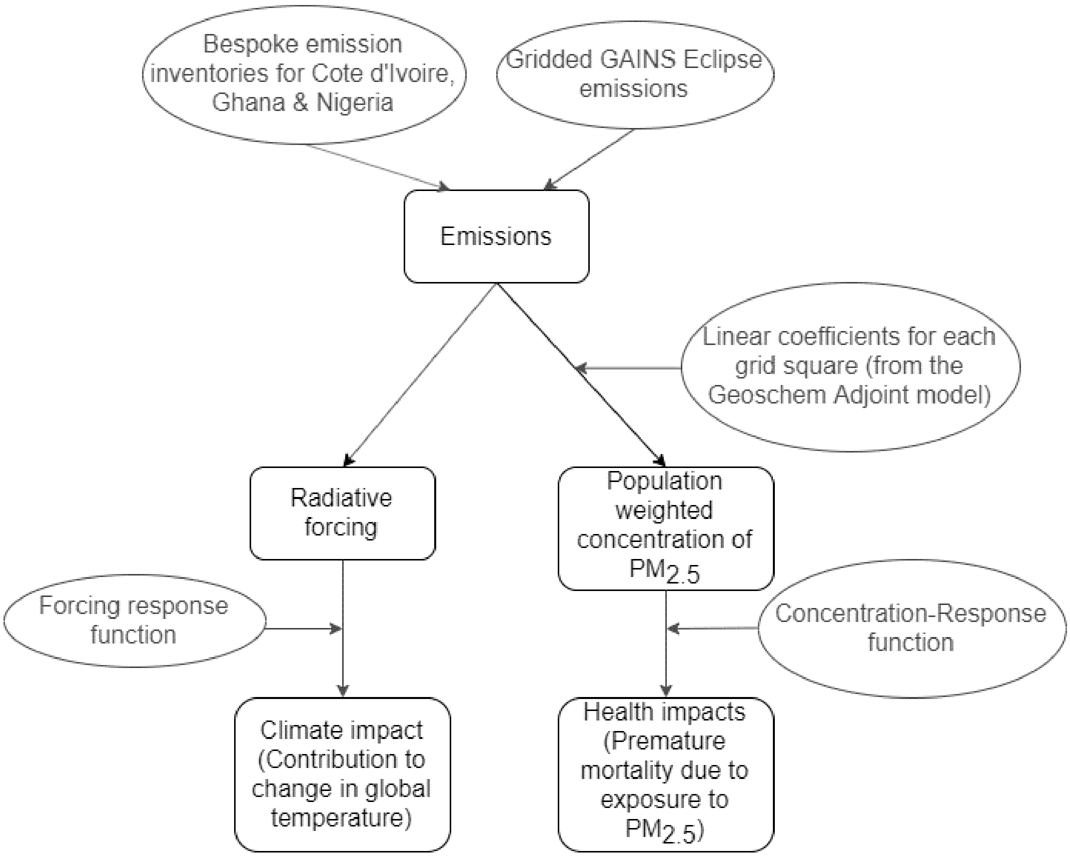


Figure 4.1: Flow diagram describing how the analyses of the impacts were done. From the emission estimates (bespoke national emission + girdded GAINs emissions), populated $PM_{2.5}$ concentration was calculated and used to calculate the health impacts while radiative forcing and subsequently, the national contribution to global temperature change.

4.2.1. Deriving air pollutant concentrations

Ambient concentrations of $PM_{2.5}$ were derived by combining i) national emissions for each country for each scenario ii) emission estimates from all other countries from default, international emission estimates to characterise transboundary impacts, and iii) outputs from a global atmospheric chemistry transport model that quantify the transport and chemical reactivity of these pollutants in the atmosphere. Total $PM_{2.5}$ concentrations in each country were not determined by national emissions alone, contribution of emissions from the "rest of the world" represented by the gridded IIASA Eclipse emission inventories are also included due to atmospheric transport of pollutants. Bespoke national emissions for each country (previously developed in Chapters 2 and 3 of this study) were spatially allocated to grids (2^0 x 2.5^0) based on the spatial distribution of emissions across the country within the Eclipse dataset. This provided a global gridded dataset of all relevant pollutants combining country specific emissions for the three West Africa States with the internationally derived emissions covering the rest of the globe.

In LEAP-IBC, atmospheric concentrations of $PM_{2.5}$ were obtained as a product of this global gridded emissions dataset and a series of linearised coefficients produced by a global atmospheric chemical transport model (GEOS-Chem Adjoint) developed at the University of Colorado, US (Henze et al. 2007). The GEOS-Chem Adjoint model output (hereafter referred to as 'coefficients') quantifies the relationship between emissions of a particular pollutant that contributes directly to $PM_{2.5}$ (i.e. BC, OC or other PM), or is a precursor to $PM_{2.5}$ (i.e. NO_x, SO_2 and NH_3) in any location, and the associated change in $PM_{2.5}$ in the target country. GEOS-Chem simulates the formation and fate of pollutants globally at a degree resolution of 2^o x 2.5^o, with 47 vertical intervals. These coefficients account for both the transport and chemical reactions of pollutants in the atmosphere and quantify the sensitivity of population weighted annual $PM_{2.5}$ concentrations in a target country to a change in primary emissions in each grid squares across the globe. The coefficients were calculated individually for each country and for five $PM_{2.5}$ direct or precursor pollutants (OC, BC, NO_X, NH_3 and SO_2) to account for the different contributions and formation mechanisms that these pollutants have in producing $PM_{2.5}$ concentration in the atmosphere. Hence, when applied with the gridded emission dataset for a particular year and scenario, they give information on the contribution of emissions (in grid squares of 2^o x $2.5°$ grids) across the globe to population weighted $PM_{2.5}$ concentration in the country of interest (in this case - Cote d'Ivoire, Ghana and Nigeria).

The relevant (precursor) emission in a grid is multiplied by the relevant coefficient for that grid. For instance, BC emission in Grid X is multiplied by the coefficient in Grid X for BC. This results in the contribution to the population-weighted concentration of $PM_{2.5}$ in the target country due to the emission of BC in Grid X, which when repeated for each grid square gives the contribution of all global BC emissions to $PM_{2.5}$ concentration in the target country. The tool then repeats this process for all other direct or precursor emissions used to estimate $PM_{2.5}$ concentrations (OC, other primary $PM_{2.5}$, NO_X, SO_2 and NH_3) to arrive at the final population-weighted annual mean $PM_{2.5}$ concentration for the target country.

The grid scale used to estimate $PM_{2.5}$ sensitivities in the GEOS-Chem Adjoint (2 x 2.5°) is substantially larger than the gradients in population and $PM_{2.5}$ concentrations. To overcome this, in 2010, $PM_{2.5}$ concentration value was then scaled to a finer grid resolution of 0.1° x 0.1° (i.e. downscaled) based on a population weighted $PM_{2.5}$ concentration that was estimated from a satellite-derived grid of $PM_{2.5}$ concentration by van Donkeler et al (2016). These were derived from a combination of satellite and modelled $PM_{2.5}$ data, calibrated to a global network on ground-based $PM_{2.5}$ measurement.

Total population-weighted $PM_{2.5}$ concentrations were apportioned between natural $PM_{2.5}$ (i.e. non-anthropogenic, desert dust, sea salt) and the contribution from different $PM_{2.5}$ and $PM_{2.5}$ precursor pollutants. Gridded (2x 2.5°) $PM_{2.5}$ concentrations from natural background emissions in 2010 were calculated from the GEOS-Chem model and combined with population density data from the Gridded population of the World v3 dataset to calculate population-weighted ''natural' annual $PM_{2.5}$ concentrations for the target country in 2010. The natural contribution to population-weighted $PM_{2.5}$ was assumed to stay constant for future years, i.e. the impacts of increasing desertification or other drivers of changes in natural $PM_{2.5}$ were not taken into account in the analysis.

The anthropogenic component was disaggregated into contributions from emissions of each primary $PM_{2.5}$ or precursor pollutant. It was also disaggregated into contributions from emissions in the target country, and from emissions from grid squares outside of the country (rest of the world emissions). For each pollutant, for the target country and the rest of the world emissions separately, the contribution to anthropogenic population-weighted $PM_{2.5}$ in 2010 was calculated by multiplying the adjoint coefficients parametised for that pollutant by the pollutant emissions in the girds covering the target country or the rest of the world emissions.

The impacts of changes in emissions for future scenarios on population-weighted $PM_{2.5}$ were calculated by multiplying the adjoint coefficients for each grid, for each $PM_{2.5}$ and $PM_{2.5}$-precursor pollutant, by the difference in emissions between 2010 and the future year in a particular scenario. The change in emission in the grids covering the rest of the world, in the baseline scenario, was estimated from the ECLIPSE current legislation scenario (Stohl et al., 2015). The change in emissions in the grids covering the target country were calculated by subtracting the emissions of each pollutant in the future year for a given scenario (baseline or mitigation) from the value in 2010.

4.2.2. Quantifying the impacts

4.2.2.1. On human health

The impact of air pollution on human health is estimated in LEAP-IBC as associated premature mortality using established concentration-response functions as used in the Global Burden of Disease study (Brauer et al. 2016).

In this study, only $PM_{2.5}$ related premature deaths were calculated because they are responsible for the largest health impacts (i.e. mortality) associated with exposure to $PM_{2.5}$. Premature deaths due to $PM_{2.5}$ exposure were estimated using the Integrated Exposure Response (IER) functions (Burnett et al., 2014). These IER functions quantify the relative risks (RRs) for premature mortality due to exposure to $PM_{2.5}$ up to very high levels (10,000 $\mu g m^{-3}$) by integrating relative risk estimate for $PM_{2.5}$ exposure from ambient, household, second-hand smoke and active smoking exposure. The IER functions were derived for the following health outcomes: (i) acute lower respiratory infection (ALRI), for children less than 5 years; and for adults of over 30 years, (ii) ischaemic heart disease (IHD), (iii) chronic obstructive pulmonary disease (COPD), (iv) lung cancer and (v) cerebrovascular disease. These IER functions assumed that the increase in the risk of mortality from different sources of $PM_{2.5}$ is only based on the mass of $PM_{2.5}$, and not the toxicity of the various components of $PM_{2.5}$ (i.e. all components of $PM_{2.5}$ here are assumed to be equally toxic). RR to $PM_{2.5}$ (RR_{IER}) was calculated using Equation 1 and the change in mortality (ΔMort) for a change in pollutant concentration for each of the PM related health outcomes was calculated using Equation 2:

$$RR_{IER} = 1 + \alpha(1 - \exp[-\gamma(z - z_{cf})^{\delta}]) \qquad \text{(Equation 1)}$$

Where:

z_{cf} = $PM_{2.5}$ low concentration cut-off. For the IER functions, the low concentration cut-off was set as a uniform distribution between 5.8 and 8.8 µg m^{-3},

$\boldsymbol{z}$ = $PM_{2.5}$ exposure (µg m^{-3}), and

α, γ, and δ = parameters derived by fitting the model to RRs across a large $PM_{2.5}$ concentration range.

$$\Delta Mort = y_0(RR_{IER}-1/RR_{IER})Pop. \qquad \text{(Equation 2)}$$

Where:

y_0 = baseline mortality rate for each PM related disease category, and

Pop. = exposed adult (>30 years) or child (<5 years) population exposed.

Premature deaths were estimated using Equation (2) for each country for each year and scenario. The $PM_{2.5}$ exposure is the population weighted $PM_{2.5}$ concentration described in Section 4.2.1. The exposed population is the adult population over 30 years estimated from the UN population division statistics and consistent with the population projection described in Chapter 3. The population over 30 was used here because the underlying epidemiological studies used to derive the IER functions did not assess adults below this age. Similarly, child mortality from $PM_{2.5}$ exposure was only for the population under 5 years because older children were not included in the epidemiological studies used to derive the child IER functions. The baseline mortality rate used were taken from the global burden of disease studies (Brauer et al. 2016).

4.2.2.2. On climate

The climate impacts of emissions of both short-lived and long-lived climate forcers for each of the three countries were estimated by calculating the average global temperature changes using the methodology described in Lacey et al (2017). This is a two-stage process. First, is the estimation of changes in the radiative forcing of emissions in four latitudinal bands – that is, arctic, northern-mid latitudes, tropics, southern-hemisphere extra-tropics due to emissions from a target country. The second step is the calculation of change in transient temperature for both short-lived climate pollutants (SLCPs) and long-lived greenhouse gases.

For well-mixed greenhouse gases (GHG) such as CO_2 that stay in the atmosphere for a long time, a change in radiative forcing due to their emissions is not restricted to the year they were emitted. Hence, the assumption that their emissions anywhere in the world contributes to the global GHG mix unlike the shorter-lived climate pollutants. Therefore, the change in the global concentration of these gases (i.e. CO_2 and CH_4), based on emission to concentration conversions from the IPCC (2013) assessment report, due to a change in emissions from each of the three countries was first calculated. Then, the change in radiative forcing due to the atmospheric concentration of these pollutants in a given year resulting from the emissions in a country is calculated followed by the change in temperature. In calculating the concentration, 1 Gt emission of CO_2 or CH_4 in a year is linked with 0.128 ppm (CO_2) and 0.360 ppm (CH_4) change in global concentration. Also taken into consideration is the decay in the concentration of the two gases which was represented by impulse response function (IRF) which quantifies the proportion of CO_2 or CH_4 left in the atmosphere multiplied by the number of years following their emission.

For shorter-lived climate pollutants: Change in radiative forcing was first calculated for the emissions of ozone precursors (i.e. NO_X, CO, NMVOCs) and pollutants which form aerosols (i.e. BC, OC, NH_3, NO_X, SO_2) using GEOSCHEM Adjoint coefficient that quantify the radiative forcing change for each of these pollutants.

For both long and short-lived species, having quantified the changes in radiative forcing from their emissions in the years between 2010 and 2050 after they were emitted, a forcing to global temperature response function was used to estimate the global average temperature change in the years 2011 – 2050. The temperature response in a given year is therefore the global average temperature change due to emissions in the target country of long-lived greenhouses gases and short-lived climate forces between 2010 and the year of interest. Temperature change was calculated for each of the three countries for all the future scenarios.

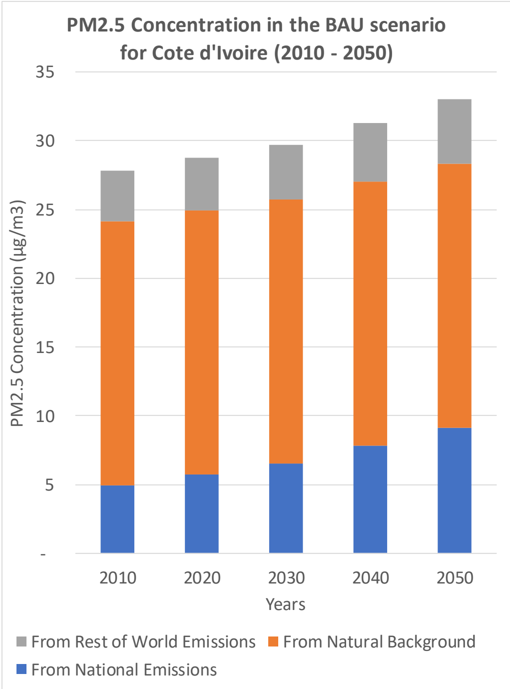
4.3. Results

This section is made up of two parts. The first part shows total ambient $PM_{2.5}$ concentration obtained for all three countries for 2010 to 2050 (Section 4.3.1). The share of the estimated concentration from national emissions, natural background emissions and transboundary emissions from other parts of the world is also presented here. The second part (i.e. Section 4.3.2) contains the health impacts attributable to ambient $PM_{2.5}$ exposure and the effects of national emissions on climate.

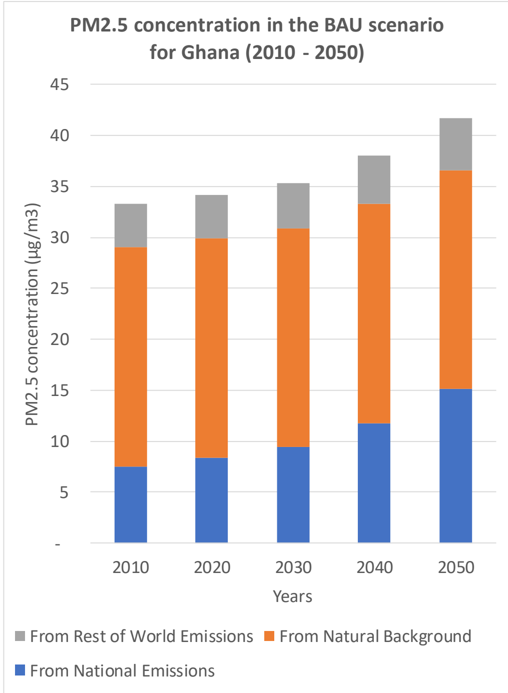
4.3.1. $PM_{2.5}$ concentration for health impact assessment

Results obtained for ambient $PM_{2.5}$ concentration clearly show that natural background emission is the largest source of $PM_{2.5}$ in all three countries. Depending on the year within the projection period and the country, it contributes between 48 – 69% of total $PM_{2.5}$ concentration. In absolute concentration values however, the model assumes that ambient $PM_{2.5}$ from natural background emissions stays the same in each of the three countries all through the projection period (i.e. 19, 21 and 31 μg/m^3 for Cote d'Ivoire, Ghana and Nigeria) as seen in Figures 4.1(a-c).

Notwithstanding, $PM_{2.5}$ concentration from national emissions is an important source. Without any regulatory measure (i.e. according to the BAU scenario), national contribution to ambient $PM_{2.5}$ concentration increased in all three countries between 2010 and 2050. In absolute values, the increase in $PM_{2.5}$ concentration could rise to equal the contribution from natural background emissions. In Nigeria, for instance, $PM_{2.5}$ concentration of 13 μg/m^3 from national emissions in 2010 increased by 135% by 2050 to 31 μg/m^3. The increase from national emission contribution is less for Cote d'Ivoire and Ghana attributable to the difference in the rate of growth of population and GDP. In Cote d'Ivoire, $PM_{2.5}$ concentration of 5 μg/m^3 in 2010 rose by 32% in 2030 to 7 μg/m^3 and by 86% to 9 μg/m^3 by 2050. In Ghana, $PM_{2.5}$ concentration of 8 μg/m^3 in 2010 rose by 25% in 2030 to 9 μg/m^3 and by 101% to 15 μg/m^3 by 2050. $PM_{2.5}$ contribution from the rest of the world is the least of all three $PM_{2.5}$ concentration sources. Nevertheless, there is considerable increase in its contribution between 2010 and 2050. The approximately 4 μg/m^3 $PM_{2.5}$ concentration from the rest of the world in 2010 increased by 28% in 2050 to 5 μg/m^3 in Cote d'Ivoire. In Ghana, 4 μg/m^3 in 2010 increased by 19% in 2050 while rest of the world emissions of 2 μg/m^3 in 2010 for Nigeria increased by 17% in 2050.



(a)



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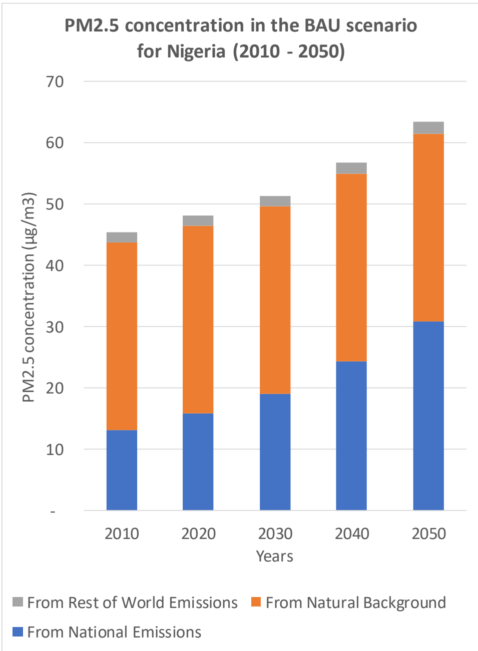


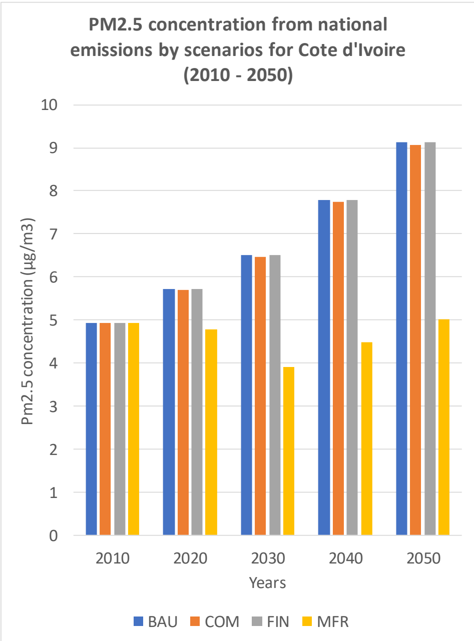
(c)

Figure 4.2(a-c): Total $PM_{2.5}$ concentrations for Cote d'Ivoire, Ghana and Nigeria for the projection period 2010 – 2050 according to the BAU scenario.

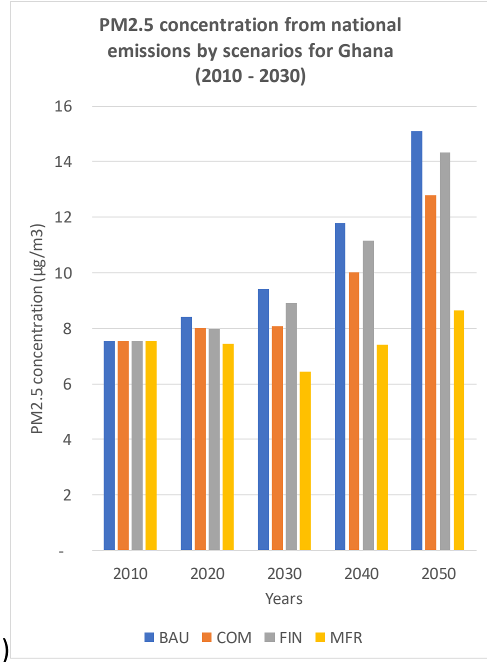
A comparison of the three mitigation scenarios (COM, FIN and MFR) described in Chapter 3 was used to assess their effectiveness at reducing ambient $PM_{2.5}$ concentration from national emissions in each country (Figure 4.2). Compared with the BAU scenario, all three mitigation scenarios achieved substantial reductions in the contribution of national emissions to population weighted $PM_{2.5}$ concentration in Ghana and Nigeria, although, to varying degrees. However, in Cote d'Ivoire, only the MFR scenario achieved significant reduction in the contribution of national emissions to $PM_{2.5}$ concentration in compared to its corresponding BAU values (by 40% in 2030 and 45% by 2050). For Nigeria, the MFR scenario reduced the contribution of national emissions to $PM_{2.5}$ concentration by 44% in 2030 and by 64% in 2050. Ghana has the least fraction of concentration reduction due to the MFR scenario compared to the other two countries at 32% and 43% for 2030 and 2050 respectively.

For the FIN scenario in Ghana and Nigeria, the fraction of$PM_{2.5}$ concentration from national emissions remained the same throughout the projection period, as was the case for Ghana (i.e. 5%) or reduced slightly in Nigeria (from 28% in 2030 to 27% in 2050). This is most likely due to government policies used to develop the FIN scenario for each country. The policies are planned to be implemented by 2030 after which there is no further knowledge on how the policies will evolve going forwards. The COM scenario was most effective at reducing $PM_{2.5}$ concentrations in Nigeria compared with either of the other two countries because all 5 key emission sources were important in Nigeria. This was not the case for Ghana and Cote d'Ivoire; illegal oil refining does not occur in either of these countries, and the use of BUGs in both countries is quite limited compared to Nigeria. As a result, Nigeria has higher relative emission from the 5 key emission sources resulting in a higher fraction of $PM_{2.5}$ concentration reduction in the COM scenario. In Nigeria, it accounted for a 19% reduction in ambient $PM_{2.5}$ in 2030 increasing to a 23% reduction by 2050 while Ghana maintained an average of a 15% reduction between 2030 and 2050.

A common observation in all three countries was found with the MFR scenario which produced an initial drop in $PM_{2.5}$ concentration from national emissions between 2010 and 2030. However, as mitigation measures were assumed to be fully implemented by 2030 in this scenario, $PM_{2.5}$ concentration subsequently rise in all three countries, although only gradually in Nigeria. This indicates that from 2030, the rate of increase in $PM_{2.5}$ concentration from national emissions is higher than the rate of reduction indicating that emission drivers (such as increase in population and GDP) in all three countries will outpace available technology to bring down emissions.



(a)



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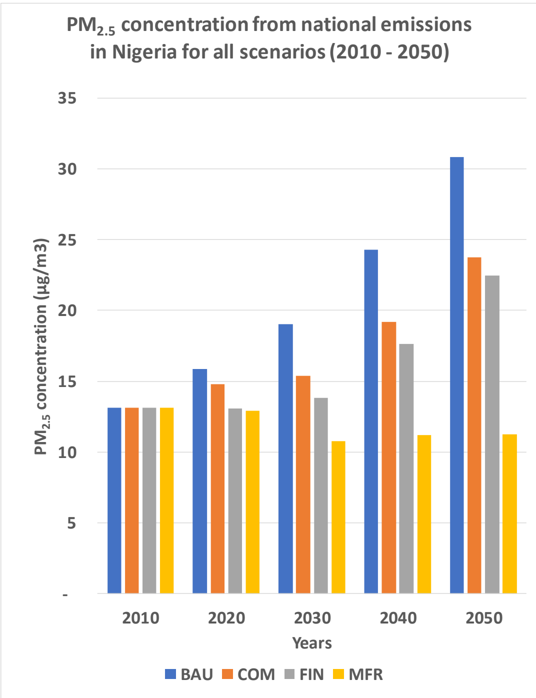


(c)

Figure 4.3(a-c): Comparison of $PM_{2.5}$ concentrations from national emissions from 2010 to 2050 according to the Business as Usual Scenario (BAU) and the three mitigation scenarios (Combined 5 key sources mitigation scenario (COM), Fully implemented national policies scenario (FIN) and Maximum feasible reduction scenario (MFR) for Cote d'Ivoire, Ghana and Nigeria.

4.3.2. Impacts

4.3.2.1. Human health

The impacts of ambient $PM_{2.5}$ concentrations on human health in Cote d'Ivoire, Ghana and Nigeria is quantified here as premature mortality resulting from exposure to $PM_{2.5}$ in each country. Just like the estimated concentration of $PM_{2.5}$ (as seen in Section 4.3.1), total premature mortality estimated for Cote d'Ivoire, Ghana and Nigeria is presented as mortality from national emissions, mortality from natural background emissions and mortality from the rest of the world emissions (see Figure 4.3(a-c)). These mortality estimates were further analysed to give an understanding of the population affected according to the age groups of the affected people, disease composition and precursor pollutants responsible.

In the BAU scenario, overall mortality due to ambient $PM_{2.5}$ exposure in 2010 for Cote d'Ivoire, Ghana and Nigeria was approximately 6,000, 9,000 and 42,000 premature deaths respectively. Relative to these estimates for 2010, mortality grew by approximately 35, 54 and 18% in 2030 in Cote d'Ivoire, Ghana and Nigeria, and yet further by 127, 188 and 75% in 2050 respectively. These future increases in mortality for each country as well as the difference in mortality among all three countries is a result of changes in exposure (that is, $PM_{2.5}$ concentrations), population and the underlining disease rates used to estimate the impacts. Although, in all three countries, the share of $PM_{2.5}$ concentration from national background emissions is high while $PM_{2.5}$ concentration from other parts of the world is low (see Figure 4.1 (a-c), increase in the share of $PM_{2.5}$ concentration from national emissions is the main cause of future increase in $PM_{2.5}$ concentration in all three countries. This suggests that increase in exposure (i.e. concentration), contributes a large part to the increase in mortality, meaning exposed population breadth in higher concentrations of $PM_{2.5}$. For instance, the increase in $PM_{2.5}$ concentration from national emissions between 2010 and 2030 accounts for approximately 84% of the total increase in $PM_{2.5}$ concentration in Cote d'Ivoire for the same period. Also, a look at Figure 4.3 (a-c) shows that the fastest growth in mortality results from exposure to $PM_{2.5}$ concentration from national emissions such that by 2050, mortality from this $PM_{2.5}$ source alone would have increased by around 3 ½ times in Cote d'Ivoire (i.e. approximately 4,000 deaths), 5 times in Ghana (approximately 10,000 deaths) and almost 3 times in Nigeria (36,000 deaths). It is important to note that, the number of premature deaths from all sources (national, rest of the world and natural) will also increase because more people are exposed as the population increases.

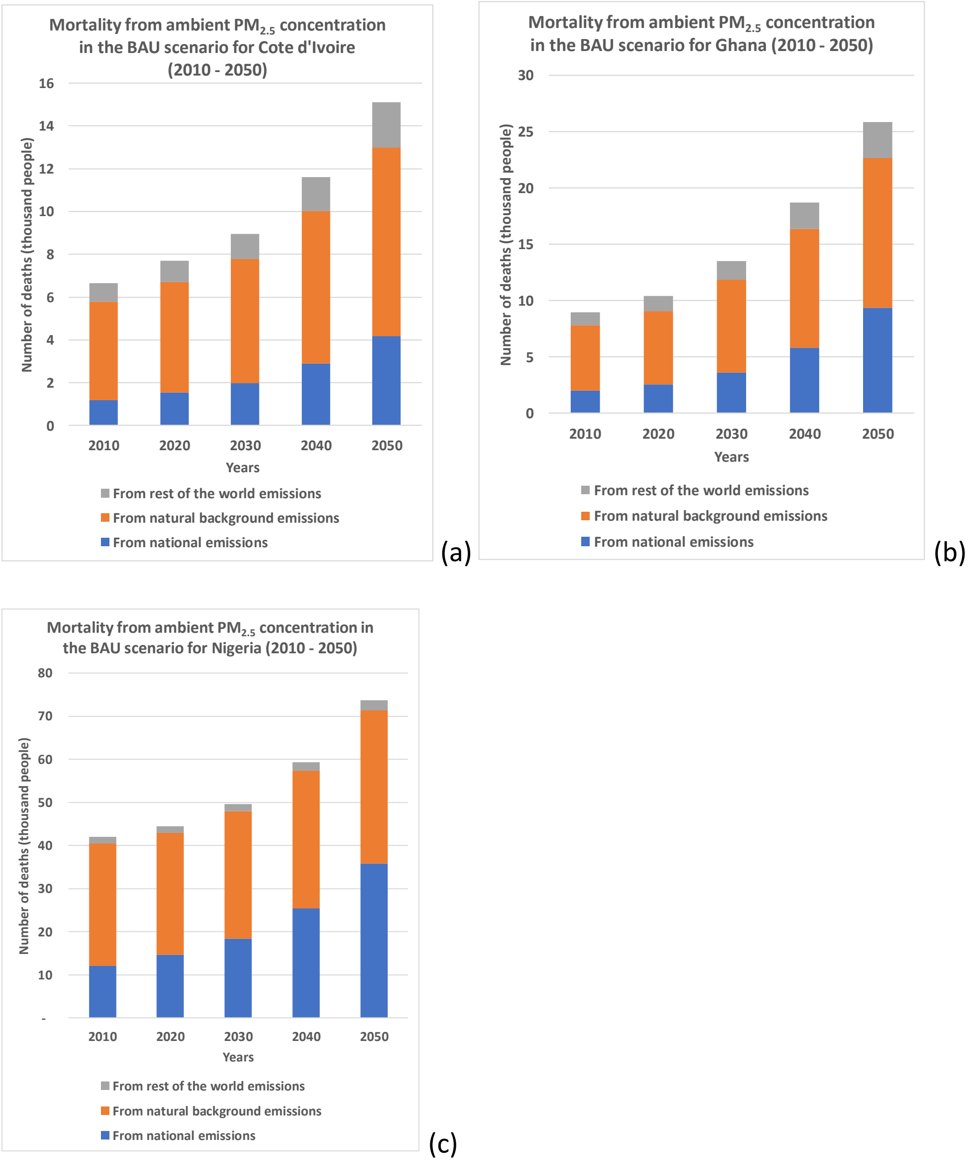


Figure 4.4(a-c): Premature mortality due to total $PM_{2.5}$ concentration in Cote d'Ivoire, Ghana and Nigeria for the projection period 2010 to 2050.

When the three mitigation scenarios were compared to know the number of premature deaths that can be avoided in each country, results show that the MFR scenario is the most successful one at slowing down the rate of increase in premature deaths relative to the BAU scenario (see Figures 4.4(a-c)). In Nigeria, the MFR scenario reduced mortality estimates in 2030 by 5% (i.e. approximately 592 premature deaths avoided), to a value less than the 2010 estimate of approximately 12, 000 deaths. After 2030, the number of premature deaths start to rise again (Figures 4.4a). This suggests that if aggressive emission reduction measures are implemented and sustained, premature death rates from national emissions can be kept relatively low. On the other hand, national population continues to grow rapidly thereby increasing the number of people that would be exposed to ambient $PM_{2.5}$. In Ghana, the MFR scenario reduces the percentage increase in mortality to a quarter of the increase shown in the BAU scenario by 2030 (i.e. a 77% increase in BAU premature deaths by 2030 is reduced to only a 25% increase).

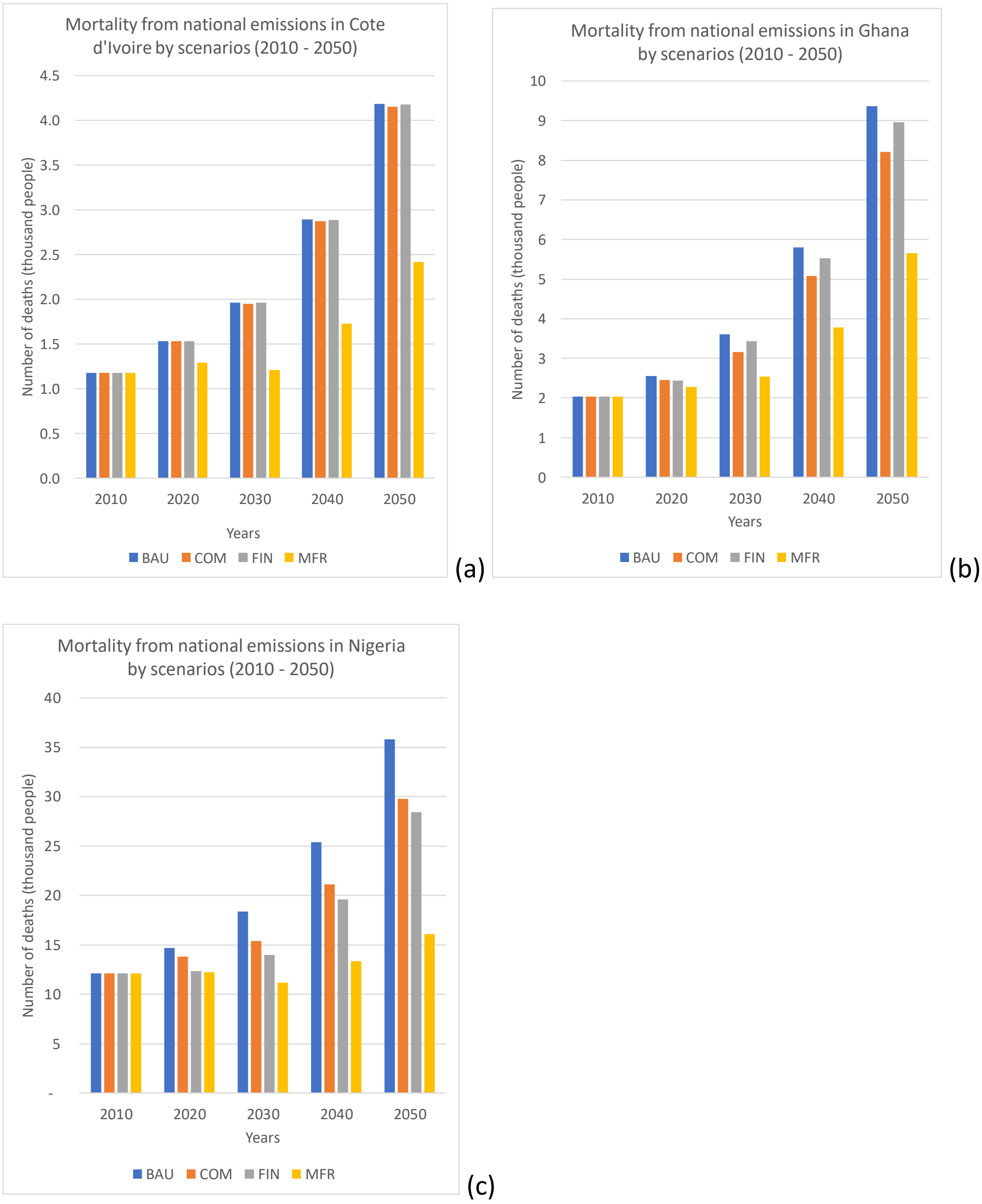


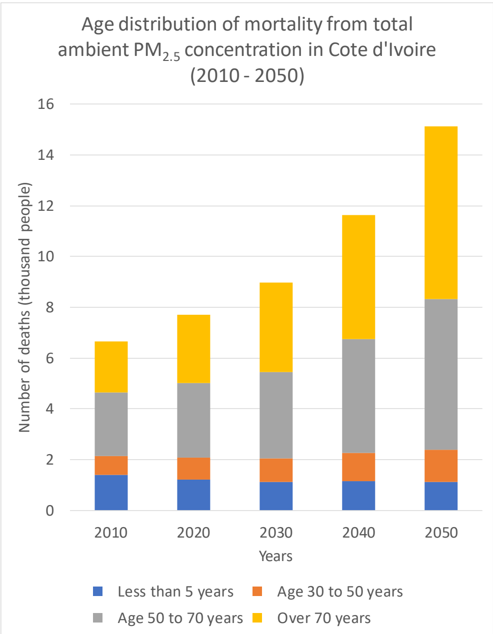
Figure 4.5 (a-c): Comparison of premature mortality from the three mitigation scenarios in reference to the Business-as-usual scenario for Cote d'Ivoire, Ghana and Nigeria.

4.3.2.1.1. *Age distribution of mortality from $PM_{2.5}$*

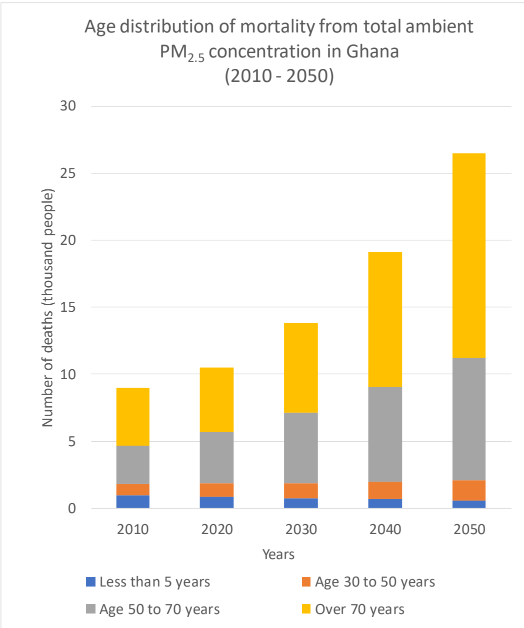
The three countries show differences in the age distribution of mortality attributable to total ambient $PM_{2.5}$ exposure. In 2010, the age groups that accounted for the biggest share of mortality in Cote d'Ivoire, Ghana and Nigeria are the 50 to 70 years old, the Over 70 years and the Less than 5 years old (or childhood) respectively. In percentage terms, this is 38%, 48% and 53% respectively. While mortality estimate is a function of exposure (i.e. $PM_{2.5}$ concentration), fraction of the population for each age group, concentration-response function and the baseline mortality rate for each country, this difference in mortality based on age group is mainly due to differences in the baseline mortality rate for the five diseases and the relative risk of death associated with exposure to $PM_{2.5}$ for each disease. This is on the assumption that everyone in each country is exposed to the same concentration of ambient $PM_{2.5}$. In addition, the fractions of total population for all age groups are about the same for all three countries. Premature mortality from exposure to $PM_{2.5}$ was not estimated for the 5 – 30 year age group because the epidemiological study by Burnett et al (2014) that was used to derive the IER functions did not derive the relative risk (RRs) for premature mortality due to exposure to $PM_{2.5}$ for this age group. It could be on the assumption that it is the least susceptible among all the age groups which suggests it is one of the limitations of the study.

In Nigeria, where childhood mortality account for the highest mortality from $PM_{2.5}$ exposure in 2010, the mortality rate of 274 deaths / 100000 people for ALRI is higher than that of either Cote d'Ivoire (at 242 deaths / 100000) or Ghana (129 deaths / 100000). Besides Nigeria has the highest fraction of children in total population at 17.5% compared with Cote d'Ivoire at 16.5% and Ghana at 14.8%. In Cote d'Ivoire, the baseline mortality risk for IHD is higher than any other disease. Although, the Over 70 age group has higher mortality risk (of 6320 deaths / 100000 people), the 50 -70 years age group (with a lower mortality rate of 1608 deaths / 100000 people) accounts for highest mortality from $PM_{2.5}$ exposure as this group make up a higher fraction of total population in 2010 (at 9%) compared with the Over 70 at just 2%.

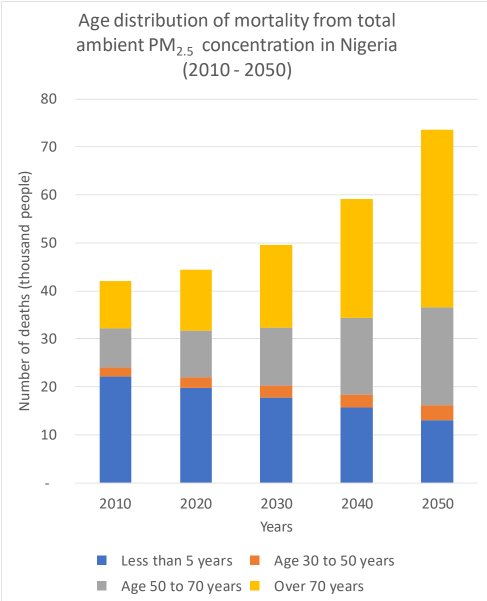
However, going forward into the future, it is clear from Figures 4.5(a-c) below that susceptibility to dying prematurely from exposure to $PM_{2.5}$ in all three countries is higher in the older age groups (i.e. the 50 to 70-year olds and the over 70 age group) because mortality rate increases with age among adults. The annual rate of increase in premature deaths over the entire projection period (2010 to 2050) due to exposure to $PM_{2.5}$ is highest among the over 70s at 6% for both Cote d'Ivoire and Ghana and 7% for Nigeria, making the over 70 age group the most susceptible group. Following this is the 50 to 70 age group at 3% for Cote d'Ivoire, 5% for Ghana and 4% for Nigeria. Life expectancy is increasing in Africa, meaning people are living longer than before and therefore, exposed to air pollution over a longer period of time. Conversely, estimated child premature deaths show a decline within the projection period with a death rate of either 0 (Cote d'Ivoire) or -1 (Ghana and Nigeria). Across all three countries, there is consistent reduction in absolute number of premature child deaths from 2020 such that by 2050, child premature deaths will be lower than 2010 estimates (Appendix 1). This is because the population growth rate is projected to reduce from the high of 2.6% per annum (between 2010 – 2015) down to 1.8% by 2045 – 2050 (World Population Prospects, 2017) despite Africa having the fastest growing population of any region in the world and remaining the biggest contributor to global population increase over the next few decades. It is also due to an assumed improvement in infant mortality rate over this time period. This is consistent with the study by Adhvaryu et al (2016) suggests that a decline in impacts might be expected from economic development and health-related improvement in public health infrastructures despite the absence of reduction in air pollution (dust in this case).



(a)



(b)



(c)

Figure 4.6 (a-c): Age distribution of mortality attributed to ambient $PM_{2.5}$ exposure in Cote d'Ivoire, Ghana and Nigeria for the 2010 – 2050 period in the BAU scenario.

4.3.2.1.2. Disease composition of mortality from ambient $PM_{2.5}$

Premature deaths from exposure to ambient $PM_{2.5}$ in all three countries were quantified as mortality from acute lower respiratory tract infection (ALRI), chronic obstructive pulmonary disease (COPD), ischaemic heart disease (IHD), lung cancer and stroke (see Figure 4.6). Child mortality is by ALRI, so the fraction of deaths by this disease equals the fraction of deaths for the less than 5-year age group.

For adults, mortality from $PM_{2.5}$ is associated with some diseases more than the others. Stroke and IHD account for the biggest fractions of premature deaths from $PM_{2.5}$ in all three countries. However, across the projection period from 2010 – 2050, while the fraction of premature deaths from stroke increases, IHD decreases in all three countries. Also, as age increases, that is, from 30-50 age group all the way up to the over 70 age group, the fraction of premature deaths from stroke decreases while the fraction from IHD increases. This suggests that people in the 30 – 50 age group are more prone to dying from stroke due to ambient $PM_{2.5}$ than any other age group in each country. Also, IHD becomes more common as the people in each country gets older.

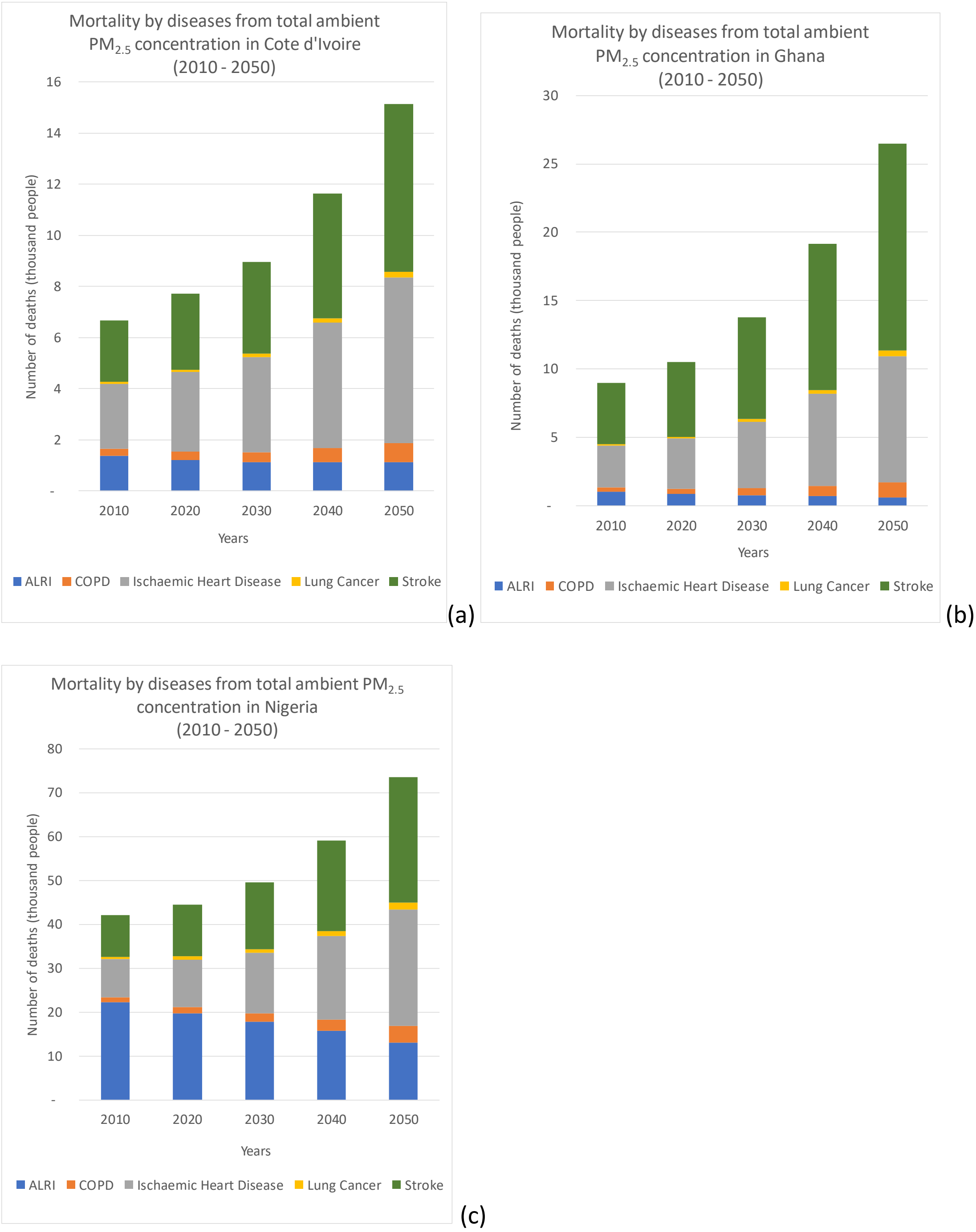


Figure 4.7 (a-c): Premature mortality by diseases from total ambient $PM_{2.5}$ for Cote d'Ivoire, Ghana and Nigeria for the projection period (2010 – 2050)

4.3.2.2. Impact on climate (global average temperature changes every year)

National emissions from each of the three countries cause an increase in global atmospheric temperature. However, this increase is very small. Temperature change was not measured for the base year 2010. The contribution of each of the three countries are so small that by 2050, Cote d'Ivoire, Ghana and Nigeria added only added an estimated 0.0015 degrees C, 0.0017 degree C and 0.017 degree C to global temperature change. Of the three mitigation scenarios, MFR achieved the largest reduction in national contribution to global temperature change for each country such that in Nigeria a 60% reduction was achieved by 2050, Ghana achieved 46% reduction and Cote d'Ivoire achieved a 40% reduction.

This shows that, although, the contribution to increase in global temperature is not significant for all three countries, the MFR scenario primarily developed to improve air quality through emission reduction has the co-benefit of reducing each countries contribution to global climate change.

4.4. Discussion

4.4.1. What changes are likely in pollutant concentrations in the future and how do these translate into impacts?

In this study, the impacts of air pollution considered are the impacts on human health, estimated as mortality associated with exposure to ambient $PM_{2.5}$, and the impact on climate estimated as the increase in global temperature due to national emissions from each country studied. So, future changes in the impacts of air pollution is dependent on how total ambient $PM_{2.5}$ concentration will change and how the emission of the pollutants that lead to increase in global temperature changes.

Total $PM_{2.5}$ concentration in a country is determined by national emissions, natural background emissions and transboundary emissions from the rest of the world. However, as described in Section 4.3.1, future changes in total $PM_{2.5}$ concentration is determined by the change in $PM_{2.5}$ concentration from national emissions. This is because absolute $PM_{2.5}$ concentration from natural background emissions were assumed to remain constant throughout the projection period and the change in $PM_{2.5}$ concentration from the rest of the world emissions is of little or no significance. As a result, in the BAU scenario, the share of $PM_{2.5}$ concentration from national emissions increased, for instance, from 29% in 2010 to 48% by 2050 for Nigeria, while the share of $PM_{2.5}$ concentration from natural background emissions decreased from 68% to 48% (i.e. from 2010 to 2050) and from 4% to 3% for the concentration from the rest of the world emissions.

Premature mortality from air pollution was estimated based on ambient $PM_{2.5}$ concentration among other variables like population, relative risk of death from exposure to $PM_{2.5}$ concentration (i.e. concentration-response function) and baseline mortality rate. Since there is no change in $PM_{2.5}$ concentration from natural background emissions and the change in concentration from the rest of the world emissions are negligible, future increases in mortality from these two $PM_{2.5}$ concentration sources are almost entirely due to increase in population as more people are exposed to about the same concentration from these two sources. On the other hand, major increase in $PM_{2.5}$ concentration is due to increases in national emissions, and as concentration increases so is mortality due to people inhaling higher concentration of $PM_{2.5}$. Increasing population also means more people are exposed to the increasing $PM_{2.5}$ concentration. In the BAU scenario, an increase of 18 $\mu g/m^3$ in $PM_{2.5}$ concentration from national emissions as seen in Nigeria between 2010 (13 $\mu g/m^3$) and 2050

(31 µg/m^3) will result in the premature mortality of approximately 24,000 more people. This means that for every 10 µg/m^3 increase in $PM_{2.5}$ concentration, approximately 13,000 people could die prematurely.

4.4.2. Sectors most likely contributing to changing ambient $PM_{2.5}$ concentrations and impacts for BAU scenario?

Projected changes in $PM_{2.5}$ concentration under the BAU scenario in Cote d'Ivoire, Ghana and Nigeria are mainly attributed to changes in national emissions. Chapter Two has identified that OC, NH_3 and NO_X are the largest contributors to $PM_{2.5}$ concentrations over the projection period (2010 – 2050). During this period they account for an average of 41%, 24% and 14% of total $PM_{2.5}$ concentration in Cote d'Ivoire; 39%, 25% and 20% in Ghana and; 36%, 23% and 23% in Nigeria respectively. Therefore, it is useful to explore the sources of these three pollutants since they contribute the most to ambient $PM_{2.5}$ concentrations, and hence premature mortality, in each country.

The sources of each pollutant are broadly similar across all three countries but there are slight changes in their order of relevance based on the share of emission from each source. For instance, OC emission in all three countries is mainly caused by combustion activities, with vegetation burning, residential cooking and open waste burning being the most significant sources in Cote d'Ivoire and Ghana. In Nigeria, residential cooking, vegetation burning, domestic use of BUGs and open waste burning are the most significant sources of OC. NH_3 is the second largest contributor to $PM_{2.5}$ concentration in all three countries, the main sources being manure management, latrines, residential cooking and vegetation burning. Whilst road transport and savanna burning are the biggest sources of NO_X in Cote d'Ivoire and Ghana (followed by vegetation burning, residential cooking and open waste burning); the use of BUGs (in both domestic and commercial settings) and residential cooking are larger sources of NO_X in Nigeria than road transport (although, this source is also important).

From the above, the sources of concern in all three countries are quite similar, so, coordinating efforts on a regional scale where practicable, might be more effective in reducing emissions from these sources.

$PM_{2.5}$ concentration from national emissions is determined by the emission of BC, OC, and other primary $PM_{2.5}$ as well as the emission of NO_X, SO_2 and NH_3 which form secondary $PM_{2.5}$.

By 2050, $PM_{2.5}$ concentration from national emissions would increase by 4 μg/m^3, 8 μg/m^3 and 18 μg/m^3 relative to 2010 concentrations in Cote d'Ivoire, Ghana and Nigeria respectively. This means a percentage increase in $PM_{2.5}$ concentration of 86, 101 and 135% respectively. Of all the pollutants contributing to ambient $PM_{2.5}$, OC, NH_3 and NO_X are the largest in decreasing order of magnitude (see chapter Three). Chapter Three also shows that over the projection period from 2010 to 2050, the percentage contribution from NO_X increases while those from OC and NH_3 decreases. This shows the importance of NO_X emission sources in future such as domestic and commercial BUGs use, road transport and residential cooking with wood in Nigeria; road transport and vegetation burning in Ghana and Cote d'Ivoire; the results from this chapter translate these changes in pollutant emission profiles into impacts.

4.4.3. Comparison with other studies

$PM_{2.5}$ concentrations estimated in this study for Cote d'Ivoire, Ghana and Nigeria together with the associated mortality from its exposure were compared with corresponding estimates in the literature. In this study, 2010 estimates of $PM_{2.5}$ concentration for each of the three countries studied were substantially higher than similar estimates from Brauer et al. (2016) used in the 2013 global burden of disease study. $PM_{2.5}$ concentration in this study is 50% higher than Brauer et al. (2016) concentration for Cote d'Ivoire in 2010, 45% higher for Ghana and 60% higher for Nigeria as seen in Table 4.1 below. Despite higher $PM_{2.5}$ concentration estimated in this study compared to Brauer et al (2016), premature mortality estimated in this study is lower than the average premature mortality estimates of the global burden of disease study according to the Institute of Health Metrics and Evaluation, IHME, 2018 (http://ghdx.healthdata.org/gbd-results-tool). Although, the estimated premature mortality in this study for all three countries is lower, they are still within the range estimated by IHME as seen in Table 4.1 below.

Table 4.1: Comparison of concentration and premature mortality between this study and Brauel et al

	Cote d'Ivoire (2010)	Ghana (2010)	Nigeria (2010)
$PM_{2.5}$ concentration (µg/m$^{3)}$ - This study	**28**	**33**	**45**
$PM_{2.5}$ concentration (µg/m^3) - (Brauer et al (2016)	19	23	28
Mortality (deaths) - This study	**6,661**	**8,979**	**42,045**
IHME Mortality (deaths) - average	8,046	8,881	53,857
IHME Mortality (deaths) - lower	6,373	7,078	41,568
IHME Mortality (deaths) - upper	9,835	10,760	69,661

The 2010 population weighted $PM_{2.5}$ concentration estimates used here are based on the satellite derived estimates in (Van Donkelaar et al. 2016). Both IHME, 2018 and Van Donkelaar et al combine satellite observations of aerosol optical depths with model derived conversions to surface $PM_{2.5}$ concentrations which are then calibrated against a global database of surface $PM_{2.5}$ point measurements. However, the calibration methodology and the monitoring data included in the calibration between both studies differ and included very few measurements in Africa which may contribute to the differences in estimates. The lower estimate of IHME suggests that the estimated mortality they obtained might be quite conservative. It therefore emphasises the need for long term monitoring of ambient pollutants in these three countries to verify concentration estimates sourced using other methods and to further improve emissions inventories for modelling work.

In another comparison, the results obtained from this study for Nigeria in 2010 (41,568 deaths) is markedly different from the 89,000 premature deaths estimated by Lelieveld et al. (2015). This could be due to various reasons. One possible reason for the difference could be their assumption of greater contribution from natural sources. Of the 89 000 deaths, 77% is due to natural sources, mainly attributed to desert dust, compared to 68% estimated from natural background emissions in this study. The estimates obtained by Lelieveld et al. also includes mortality from O_3 which is not included in this study. It is however not clear from their result what fraction of the total mortality is attributed to O_3 and which one is from $PM_{2.5}$. This study and Lelieved et al used different atmospheric model, so difference in the underlying assumption can also contribute to the difference in premature mortality, for instance, the $PM_{2.5}$ concentration below which health impact is assumed to be negligible.

Arku et al. (2008) conducted a short term (3-week) study measuring $PM_{2.5}$ concentration in low-income neighbourhood in Ghana. Results obtained in this work and those by Brauer et al (2016) both falls within the range (i.e. 22.3 – 40.2 $\mu g/m^3$) measured by Arku et al, though, the result of this study is closer to the upper limit while Brauer et al is closer to the lower limit. It is also important to note that $PM_{2.5}$ concentration by Arku et al is not population weighted and so, not ideally suitable for this comparison. The fact that it is not population weighted means that the $PM_{2.5}$ concentration measured is not the average concentration the entire country is exposed to. For example, Obioh et al. (2013) also conducted a screening exercise measuring $PM_{2.5}$ concentration for a day in six cities in Nigeria selected to represent all the geopolitical zones in the country. Results obtained show large variations in $PM_{2.5}$ from one city to another with a range of 14 to 100 $\mu g/m^3$. If this represents typical result for every day of the year, then, some fractions of the population are prone to suffer more from air pollution than others.

The values obtained in this study for Ghana falls within the range reported by Dionisio et al. (2010) for measured $PM_{2.5}$ concentration over a period of 22 months for both road-side and residential sites. This difference in estimated concentration between this study and Dionisio et al against Brauer et al may be down to the methodological approach of Brauer et al which used satellite-based estimates.

In the absence of any regulatory air quality (AQ) standards for all three countries, results here were also compared with the World Health Organisation (WHO) guideline annual mean value of 10 µg/m^3 for $PM_{2.5}$. Total $PM_{2.5}$ concentration for all three countries in 2010 exceed the guideline value of 10 µg/m^3 by a factor of more than 1 for cote d'Ivoire, 2 for Ghana and 3 for Nigeria. Although, natural background emissions are currently responsible for the majority of the ambient $PM_{2.5}$ in all 3 countries, the share of national anthropogenic emissions is projected to increase considerably, especially for Nigeria.

4.4.4. Uncertainties

Although, this work was done using the LEAP-IBC tool with input data that best represent the past, current and future estimates of activity data and emissions factors for each of the three countries studied, there are still some limitations in the form of uncertainties at various stages. These span the stages of inventory development, modelling of $PM_{2.5}$ concentration and subsequently the various impacts. These uncertainties are important but difficult to quantify. However, uncertainties associated with estimated emissions for each country was described and quantified in Chapter Two of this work.

In deriving $PM_{2.5}$ concentrations from national emissions, linear coefficients were used (see Section 4.2). Consequently, any change in emissions will either lead to an increase or decrease in $PM_{2.5}$ concentration. It does not account for non-linear change in chemical reaction in the atmosphere that results in the formation of secondary inorganic aerosol. An example is a reaction between NO_X, NH_3 and SO_2 to form ammonium nitrate and ammonium sulphate aerosol. The formation of secondary organic aerosol depends on the relative emissions of each of these primary pollutants. Therefore, while the GEOSCHEM Adjoint modelling captures the chemical environment in 2010 in which secondary organic aerosol takes place, it does not account for changes in the rate of secondary inorganic aerosol formation that would occur due to changes in the relative emissions of NO_X, NH_3 and SO_2 .

Furthermore, in estimating the health impacts, concentration-response functions were used. These functions are the same as those used in estimating the Global burden of Disease attributable to ambient air pollution. They were derived based on health research done in Europe and North America in the absence of concentration response functions derived from African epidemiological studies. Based on the limited information available, $PM_{2.5}$ concentrations are substantially lower in North America and Western Europe compared to West Africa. In addition, the underlying health status, mortality rates and health system and infrastructure is different between these regions (as well as being different within West Africa). Therefore, the application of these concentration response function assumes that the relationship between exposure and premature deaths is the same everywhere. Further studies to quantify (i) $PM_{2.5}$ levels, sources and composition, and (ii) the relationship between $PM_{2.5}$ exposure and negative impacts are required in order to evaluate the impacts of this assumption and to improve quantification of air pollution health burden in West Africa.

Despite the uncertainties associated with the quantification of the health impacts of air pollution in this study, there are reasons to suggest that the health burdens quantified here are an underestimate of the total air pollution health burden and the expected benefits from the implementation of the mitigation scenarios. Most importantly, this study did not quantify the health impacts associated with indoor air pollution exposure. The number of death in these countries associated with indoor air pollution exposure has been estimated to be approximately equal in magnitude to outdoor air pollution. The health benefits that could result from the clean cookstoves measures evaluated in the scenarios in particular may have substantially greater health benefits than estimated here. In addition, only the health impacts from ambient $PM_{2.5}$ were considered and not other pollutants associated with negative health impacts such as ozone and NO_2. The only health outcome evaluated was premature mortality and the effects of air pollution on morbidity outcomes such as hospital visits, asthma related effects etc were not quantified in the inclusion of these additional health aspects of air pollution could give a substantially higher estimate of the overall health burden but the quantification has the same or greater sources of uncertainty as outline above $PM_{2.5}$ associated deaths.

4.4.5. Recommendation

It is obvious from the health impact assessment (i.e. premature mortality due to exposure to air pollution) carried out in this study that there is potential for this adverse impact to be severe especially in the future for all three countries, and possibly the wider African continent. So, it is important that governments of all three countries prioritise, lead and implement actions to reduce the emission of air pollutants, particularly direct $PM_{2.5}$ (i.e. BC and OC) and $PM_{2.5}$ precursors (NO_x, NH_3 and SO_2). Global studies like Lelieveld et al (2015) show that developing countries with high population experience high premature mortality associated with air pollution exposure. This suggests that the African continent with the fastest growing population in the world will experience great adverse effect if nothing or significant actions are to taken to minimise air pollutants emission.

In addition, the metrics used to estimate health impacts of air pollution in global studies as well as this one are mostly based on long term studies done in other continents but Africa. This does not accurately represent the situation in these three countries and the whole of Africa, thereby, generating some uncertainties. As a result, government of African countries should partner with scholars, both local and international, to conduct national studies that will ultimately help achieve more accurate estimates of health impacts of air pollution.

Chapter 5

Conclusions and recommendations

5.1. Introduction

Air pollution affects everyone irrespective of the location, so, improving our understanding of the problem and its impacts especially in West Africa is important. It requires a comprehensive knowledge of the state of the atmospheric environment, i.e. the level of emissions of pollutants and the concentration of different sources, the concentrations of pollutants in the atmosphere, and the impacts of these pollutants on human health. Studies that have been carried out, mostly by independent scientists in the region, are limited in scope such that understanding all the components of air quality assessment and management on a national level is virtually impossible. So, this study set out to outline and apply a framework that could be used to assess the current air pollution problem in African countries and importantly, to identify and assess the most effective mitigation options to avoid even greater air pollution impacts in the future. In doing this, emission of air pollutants in 2010 were estimated for Cote d'Ivoire, Ghana and Nigeria and projected to 2050, and the associated impacts also quantified. The framework developed and applied how air pollution in West Africa can be assessed is presented in Section 5.1.1 below. This is followed by the key findings from the work in Section 5.1.2 and finally, recommendations based on the findings in Section 5.1.3.

5.1.1. Proposed framework

The framework presented here was developed based on the DPSIR model for assessing environmental problems. In this work, the model was adapted to assess and manage air quality in the countries included in this study. The framework was developed for Nigeria as an example of how a framework can help in assessing and managing the problem, so, it is applicable to both Ghana and Cote d'Ivoire, and indeed any other country within and beyond the region. Figure 5.1 below shows a schematic diagram of the framework with different parts or sections that tells us WHAT needs to be done, HOW they could be achieved, WHO are the relevant actors and finally, WHEN, that is, the time period the process could be achieved.

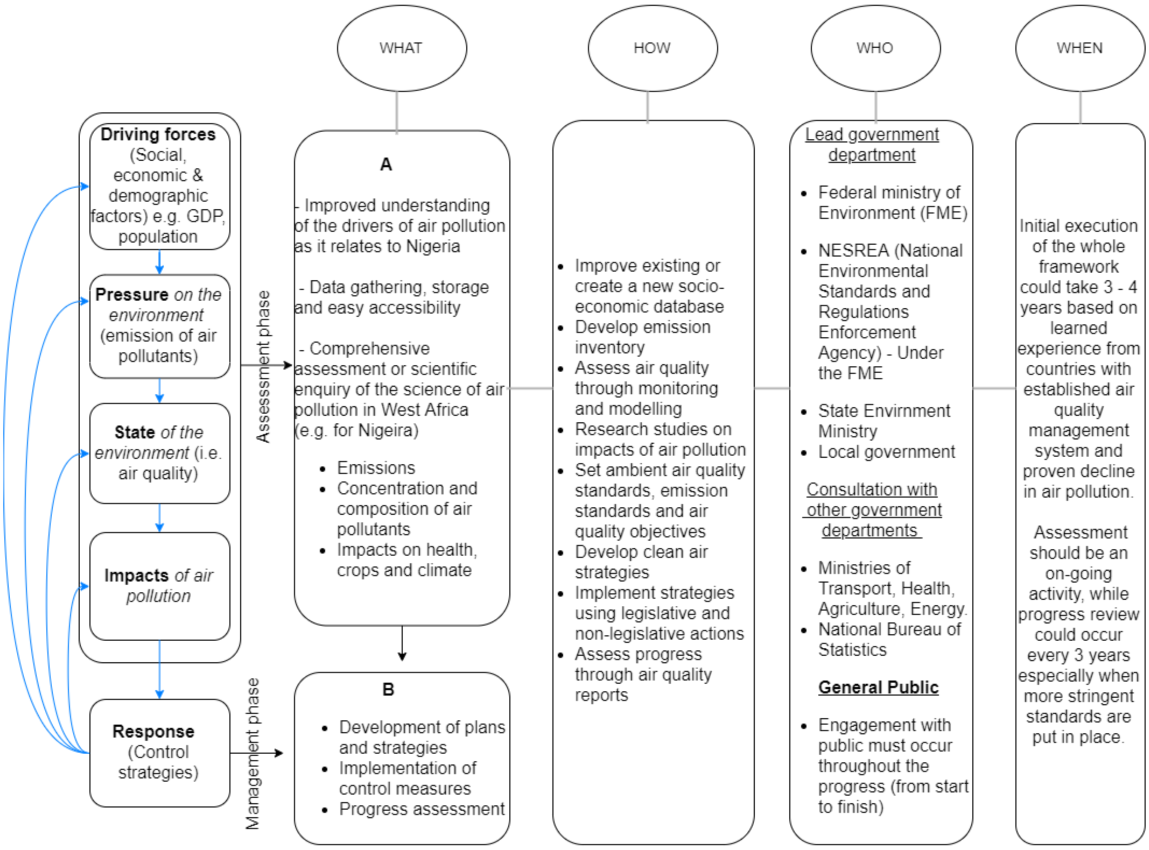


Figure 5.1: Schematic diagram of the proposed DPSIR-based framework for assessing air quality and management in Nigeria. **A** represents the assessment phase (i.e. DPSI of the DPSIR model) and **B** represents the management phase (i.e. R of the DPSIR model).

There are five elements or parameters within the DPSIR model i.e. driving forces, pressure, state, impacts and response. The first four deals with the assessment of the problem while the last one (i.e. response) deals with its management. So, in the DPSIR-based framework for air quality proposed here, the WHAT section is divided into two: A (i.e. assessment phase) and B (i.e. management phase).

The A part is the assessment phase for: (i) changes in socio-economic and demographic factors that cause lifestyle changes such as the need for energy, transport, food, shelter, etc, (ii) pollutants released into the atmosphere as a result of changes in human lifestyle (iii) concentrations and chemical constituents of atmospheric pollutants (iv) impacts of exposure to air pollution. The A phase is very important in order to have a robust scientific base which ultimately inform the design of appropriate management response. This assessment can be conducted by:

(a) Reviewing existing database(s) of socio-economic indicators in the country to ensure that they are fit for purpose, accurate, easily accessible to the public (e.g. available for free and via the internet) and user-friendly (e.g. in various formats for users). Otherwise, a new one might be required. This is important because these kinds of data are often required for research purposes. Government funded research into this topic area is also important to improve our understanding of the driving forces and air pollution in Nigeria context.

(b) Quantifying emissions of air pollutants by developing detailed emissions inventory will provide a systematic way of knowing which pollutants are released into the atmosphere, the amount and the sources of these pollutants. Ideally, doing this requires the use of country based emission factors which is not available. So, available ones from EMEP/EEA (2019) or IPCC (2006) or more applicable ones from the literature could be adopted. In the long run, a database of country specific emission factors should be developed. Also, the inventory should be developed to an international standard by meeting the five basic principles of inventory development – transparency, consistency, comparability, completeness and accuracy. It should include all relative unique emissions sources to the country e.g. use of backup generators, illegal refining of crude oil, etc.

(c) Establishing air quality monitoring networks to measure the concentration of pollutants especially those known to adversely impact human health. Both national and state air quality monitoring networks should be established. Concentration data from the national network could be used to set national ambient air quality standards as well as national goals and objectives while the networks coordinated by states could be used to identify priority areas within each state.

(d) Research to understand the various impacts of air pollution in the country. In this study, health impact of air pollution was estimated by relying on the concentration-response functions derived from outside of Africa to estimate air pollution health burdens. These concentration-response functions were derived at different levels of exposure and populations with very different health statuses. The development of Africa specific concentration-response functions through epidemiological analysis would increase the relevance and the accuracy of air pollution health burden estimates. So, government should lead by providing funds or grants for research, encouragement of international research collaborations, provision of research scholarships to students for local (i.e. within the country) and international studies, improving access to data from government and non-government sources e.g. hospital records.

(e) Develop the capacity of government personnel to undertake air quality assessment by ensuring adequate training is provided at both national and local levels.

The B part (of WHAT needs to be done) is the management phase. Management actions should be underpinned by scientific understanding and in this case, three management actions are required: (a) development of plans and strategies (b) Implementation of strategies and control measures (c) assessment of progress.

In the development of plans and strategies to address the poor air quality situation, national standards must first be established (i.e. air quality standards and emissions standard). The earlier assessments that would have been done in the assessment phase will help the government in setting these standards. The standards must also be backup with the appropriate legislative framework to ensure that it can be enforced. The executive arm will have to work with the legislative arm to make it a statutory requirement. Following the establishment of these standards, a national strategy aimed at improving air quality should then be developed in order to work towards attaining the standards. The national strategy should include the goals and objectives for better air quality with time allocations, details the obligations of other government levels (i.e. state and local governments) and also include control measures. The control measures could be emission reduction measures, changes in human attitudes and behaviour, among others.

Implementation of strategies and control measures could take different forms. However, based on the experience of countries with established framework for managing air quality like the United Kingdom, national objectives are usually implemented at the local level. Hence, the need for state air quality assessment network to identify priority areas where control measures must first be focused. Also, a combination of statutory and non-statutory measures could be used to achieve the desired air quality objectives.

Progress assessment is key to knowing if a plan of action is working or not. So, this is an important activity that must be done in managing air quality. A legal requirement for the production of air quality reports at various levels of government will help achieve this. Based on the review of these reports by experts or trained personnel, the appropriate steps can then be taken to address any element of the framework, whether in the assessment phase or the management phase.

This framework was developed using Nigeria as an example so that institutional structure could be identified for both phases of this framework. The assessment phase is predominantly the responsibility of the executive government, both national and local (i.e. state and local) governments, specifically, the respective Ministry of Environment. While the Federal Ministry of Environment (FME) establish national air quality network to screen air quality nationwide, State Ministry of Environment (SME) should also coordinate the establishment of state air quality monitoring network for more detailed assessing of air quality within each state. The management phase must be led by both FME and SME with support and contribution from other government ministries like Energy, Transport, Health, Agriculture, and so on. While the legislative arm of government (Senate and House of Representatives) have a part to play in making the right laws, the judiciary would help implement them by presiding over non-compliance cases. The general public must be engaged, consulted and informed every step of the way. This will allow input from the public in the making of decisions and improve the likelihood of success of the framework.

Lastly, based on experience from other countries, initial establishment of the framework (from assessment to implementation of management actions) could take 3 – 4 years. Thereafter, assessing should be a continuous activity while progress review could occur every 3 years. However, while air quality monitoring is being done, the government can temporarily adopt the WHO guideline limit as found in Table 1.1 (Chapter 1) of this work and put in place some emission control actions.

This thesis provides a framework for assessing the state of current air pollution problems and how they could be mitigated in the future. This work could be built upon by expanding the application of the framework to include more countries in West Africa and across the continent. The development of national scale inventories using a common methodology would allow countries within West Africa to compare the magnitude of the air pollution problem in each country. This includes the identification of major sources and likely progression into the future. Establishing a common framework for air pollution planning in the region would allow for regional mitigation strategies to be developed that could bring benefits to multiple countries. For example, this framework could be useful in quantifying the benefits of introducing low sulphur fuels across the region as has been agreed in (UNEP 2014) as well as for other mitigation actions.

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5.1.2. Key Findings

This study has shown that emissions from the 5 key sources (i.e. backup generators, illegal oil refining, two-stroke motorcycles, simple kerosene wick lamps and unpaved roads) could be significant to national emissions. This is certainly true for Nigeria where about 40% of total NO_X emissions and 17% of total SO_2 emissions come from these 5 key sources. These key sources are however not included or poorly characterized in available global inventories (i.e. EDGAR v4.3.1 and GAINS Eclipse V5a) suggesting that the global emissions for the three countries were underestimated. This was confirmed on comparison of estimates from this work with the global inventories where the estimates here were higher than the corresponding ones from EDGAR, and for GAINS, except CH_4 for all three countries and SO_2 and BC for Cote d'Ivoire and Ghana. In the process of developing the inventories, it was also discovered that there is the need for the development of local capacity to undertake air quality assessment through monitoring and modelling activities. This is because this study had to rely on international databases like IEA for some activity data and EMEP/EEA (2016) for most emission factors which may account for some of the uncertainties of the estimates calculated here. This study also shows that several gaps in knowledge still need to be filled to have a better understanding of air quality in West Africa as the only available inventories of national emissions for countries in the region are from EDGAR and GAINS. The inventory presented by Liousse et al (2014) focused on combustion sources which are important but mean more work is still required to estimate emissions from other sources like fugitive emissions, emission from manufacturing processes, among others. .

Future projections of emissions in this study also show that without any intervention, emission of air pollutants will continue to rise. This result is in line with Liousse et al (2014) which also projected continuous increase in emissions from combustion sources in African countries until 2030. Both studies also agree that domestic and transport sources are important emission sources in West Africa and emission reduction strategies will benefit from focusing on those sources. The projected emissions in this study also show that reducing emissions from the 5 key source only is not sufficient to bring about substantial reduction of national emissions. There needs to be well coordinated implementation of realistic control measures that can be demonstrated to achieve substantial emission reduction like those that constitute the MFR scenario. The MFR scenario was developed as a practical and achievable control measure and it achieved the maximum emission reduction in all three countries. Control measures here focused on three sources of emission – residential, road transport and energy generation. Therefore, coordinated actions by the three countries or across the region, where possible, might be more effective in reducing emissions from these sources.

By quantifying the impacts of these mitigation strategies on human health and global climate change, we show that these strategies are win-win strategies that have benefits for both air quality and climate. Therefore, their implementation would result in local benefits to the health of the populations in Ghana, Cote d'Ivoire and Nigeria while also reducing their contribution to global temperature increases.

The benefit of reducing both current and future emissions has been demonstrated in this study predominantly through the reduction in premature mortality associated with exposure to $PM_{2.5}$ as well as a reduction in the contribution to global temperature change by each country.

5.1.3. Recommendations

Addressing the poor air quality situation in West Africa as well as the accompanying impacts (especially on human health), requires actions that must be well coordinated, led by government at the national level of each country, and through international cooperation for the whole of West Africa. To undertake this process:

(1) Governments in all three countries must first acknowledge it as an environmental issue that must be prioritized just as economic development is a priority for them. Reducing emissions and minimizing exposure of residents in each country to air pollution must be a key policy agenda without which meaningful actions or progress cannot be achieved. Developed countries that can demonstrate substantial progress in improving air quality at one point in time realised that something must be done to clean the air. For instance, the was with the middle of the 20th century in the United Kingdom (Heal et al., 2012).

(2) Laws specifically designed to address air pollution issues in each country must be made. It was discovered in this study that the few policies which benefit air quality were not particularly made to deal with air pollution. Although, there might be a piece of legislation that mentions environmental protection in each country most times it is vague and does not allow appropriate interpretation and implementation. So, there is a need for proper detailed legislative framework which demands the management of air quality and serves as backup for the implementation or enforcement of actions that will help achieve desired air quality goals and objectives. The legislation could be an Act, policies or regulations.

(3) Government must set national ambient air quality standards as well as national goals and objectives in order to meet the standards. Emission standards for key stationary and mobile sources should also be established to help achieve cleaner air. This is lacking in the countries studied and indeed most of Africa. So, in the absence of country specific or region specific standards, adopting the World Health Organization AQ standard is a good starting point which can then be replaced when new standards are developed. Over time, countries in Europe and America continue to strive to achieve cleaner air by setting more stringent air quality standards.

(4) Policy actions should be designed to address pollution sources with the largest influence on emissions and impacts, achievable in a reasonable timeframe and at a cost effective way. This study has clearly identified large sources of emission in the three countries, namely: residential emissions, road transport and energy generation. These emission sources should be the focus of intervention in order to see substantial progress. The specific activities causing the problem must be examined. In this study,

a. Residential use of wood for cooking is a major activity causing air pollution in all three West African countries. The simple solution would be the immediate ban of the use of wood for cooking. However, that is not a practical or achievable solution now, especially with a greater share of poor people in these countries. So, a gradual shift from the use of wood to other cleaner fuel over a reasonable timeframe, as found in this study (Section 3.2.4), will help achieve a significant level of emission reduction. This is not a completely new measure for Nigeria as the shift to cleaner fuels for cooking was mentioned in the Sustainable Energy for All Action Agenda published in 2016. However, it cannot be achieved within the timeframe (see section 3.2.2) and without proper implementation.
b. Road transport is another big source of emissions – The use of 2-stroke motorcycles must be banned as well as the use of old vehicles (i.e. more than 10 years old) with high emissions. In Nigeria, the importation of cars older than 10 years is banned, however, lack of proper enforcement renders the policy quite ineffective due to smuggling from neighbouring countries. Furthermore, with the exception of Ghana, there is no system that ensures there are safe and clean vehicles on roads in these countries. The removal of catalytic converters from gasoline fueled cars is another problem that needs to be addressed. There is no form of vehicle maintenance check, less so vehicle emissions testing. This needs to be established together with a database of all vehicles in use in each country categorized based on the type of vehicle. This will help in enforcing the use of clean cars and prevent or minimize the smuggling of old vehicles.
c. Generation of energy is also an important emission source. Lack of regular supply of electricity results in the widespread use of backup generators in Nigeria and Ghana. These are highly inefficient compared to energy generation from the central or national power grid. Encouraging a rapid and widespread adoption of the use of solar panels to generate electricity in Ghana and Nigeria will greatly reduce emissions especially from the residential sector.

(5) Effective implementation of a policy action is key to the success of that policy. For the measures proposed in this work, this can take different forms. For instance, some measures must be enforced, some implemented through the provision of incentives, others through awareness or education, and so on. On implementing the shift to the use of cleaner fuels for cooking, government must raise awareness or educate the public on the health hazards, the

inefficiency and the wider environmental impacts associated with the practice of cooking using wood. Providing improved cook-stoves at a discounted price already occurs at a small scale in Nigeria, this should be continued and expanded throughout the country. The use of solar lanterns is a good alternative to simple kerosene wick lamps widely used in all three countries. Government should encourage the use of these solar lamps by providing a kind of incentive e.g. providing it at a discounted price. Clearing of land by burning for farming should be banned. The ban on the importation and use of old vehicles must be enforced. Vehicles over ten years imported into the country must be destroyed at the point of entry (usually at the port). Vehicle smuggling from neighbouring countries through road should also be prevented and the government should make it impossible to license or register old cars that managed to come in through this route. Government can provide incentive for the scrappage of highly emitting very old vehicles already in use or make it expensive to insure. Annual emissions test of vehicles as part of vehicle safety and roadworthiness test must be a requirement for the use of vehicle in all three countries. This already take place in Ghana, it must be done in Cote d'Ivoire and Nigeria.

(6) Based on some of the limitations of this study, a systematic collation and the development of a database of emission factors derived in Africa as well as an increase in the number of studies that derive emission factors in Africa will help improve it. The continuous updating of this databases when new studies are produced would provide an authoritative resource for the region to promote consistency in emission inventory development.

Appendices

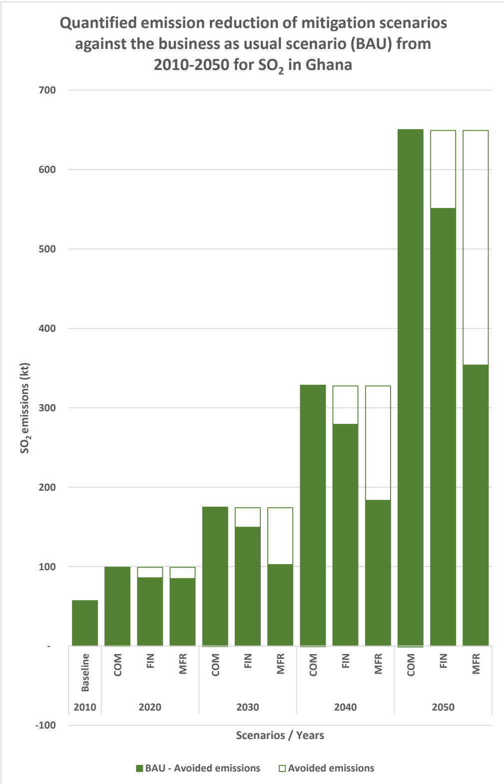
Appendix 1: Estimated $PM_{2.5}$ concentrations for Cote d'Ivoire, Ghana and Nigeria

Country	$PM_{2.5}$ (μg/m^3) Concentration	2010	2020	2030	2040	2050	2030 (percent change)	2050 (percent change)
Cote d'Ivoire	From National Emissions	5	6	7	8	9	32%	86%
	From Natural background	19	19	19	19	19		
	From the Rest of the World	3.6	3.8	4.0	4.3	4.7	9%	28%
	Total	28	29	30	31	33	7%	19%
Ghana	From National Emissions	8	8	9	12	15	25%	101%
	From Natural background	21	21	21	21	21		
	From the Rest of the World	4	4	4	5	5	3%	21%
	Total	33	34	35	38	42	6%	25%
Nigeria	From National Emissions	13	16	19	24	31	45%	135%
	From Natural background	31	31	31	31	31		
	From the Rest of the World	1.6	1.7	1.7	1.8	2.0	1%	21%
	Total	45	48	51	57	63	13%	40%

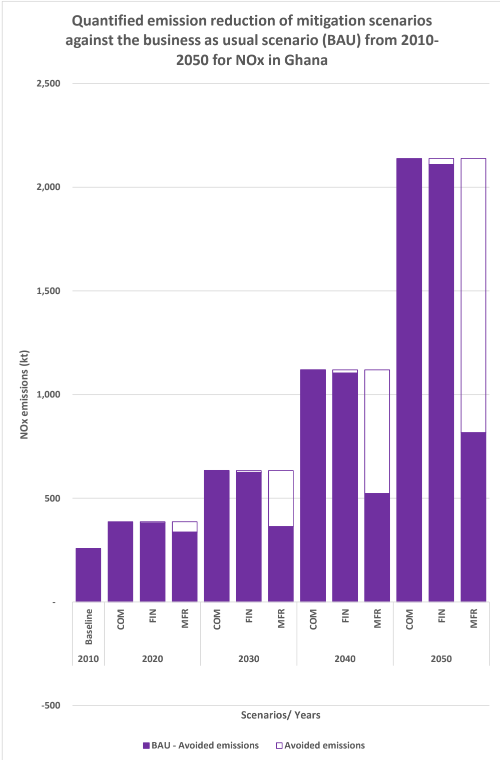
Appendix 2: Estimated mortality due to ambient $PM_{2.5}$ in Cote d'Ivoire Ghana and Nigeria (2010 – 2050)

	2010	**2020**	**2030**	**2040**	**2050**
Cote d'Ivoire					
From national emissions	1	2	2	3	4
From natural background emissions	4	5	5	6	8
From rest of the world emissions	1	1	1	1	2
Total mortality from $PM_{2.5}$ in Cote d'Ivoire	**6**	**7**	**8**	**11**	**14**
Ghana					
From national emissions	2	3	4	6	10
From natural background emissions	6	6	8	10	13
From rest of the world emissions	1	1	2	3	3
Total mortality from $PM_{2.5}$ in Ghana	**9**	**11**	**14**	**19**	**26**
Nigeria					
From national emissions	12	15	18	25	36
From natural background emissions	28	28	30	32	36
From rest of the world emissions	2	2	2	2	2
Total mortality from $PM_{2.5}$ in Nigeria	42	44	50	59	74

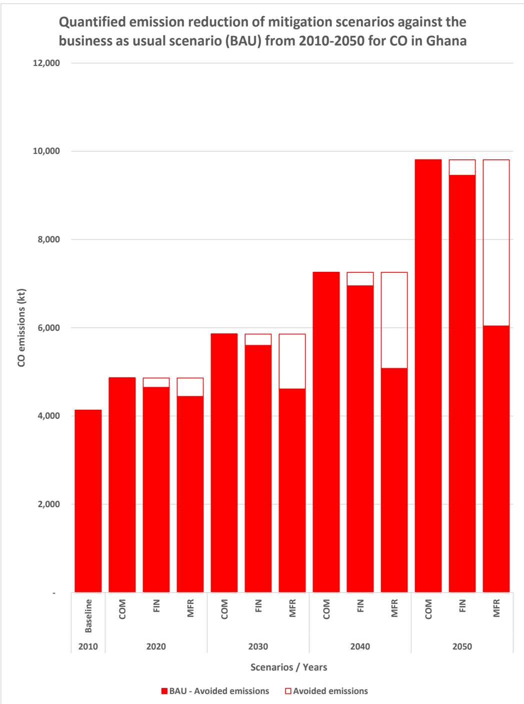
Appendix 3: Emission mitigation potential of mitigation scenarios in Ghana



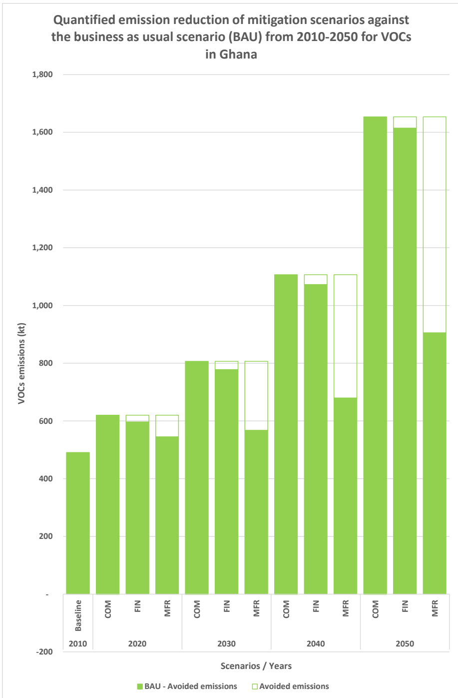
(i)



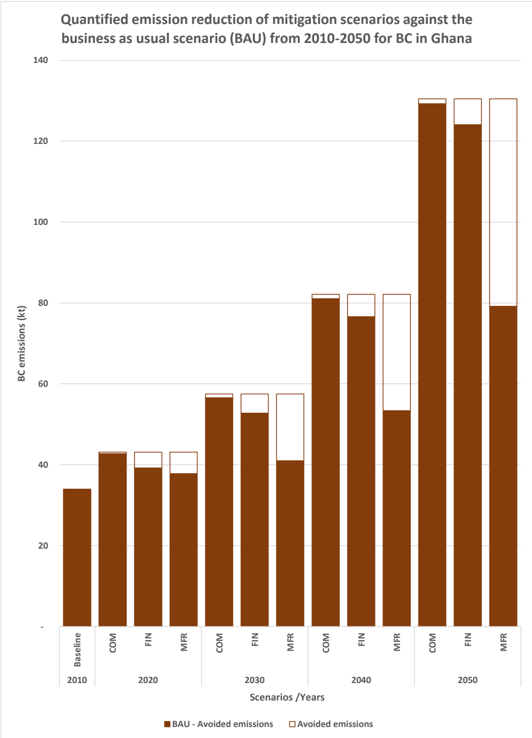
(ii)



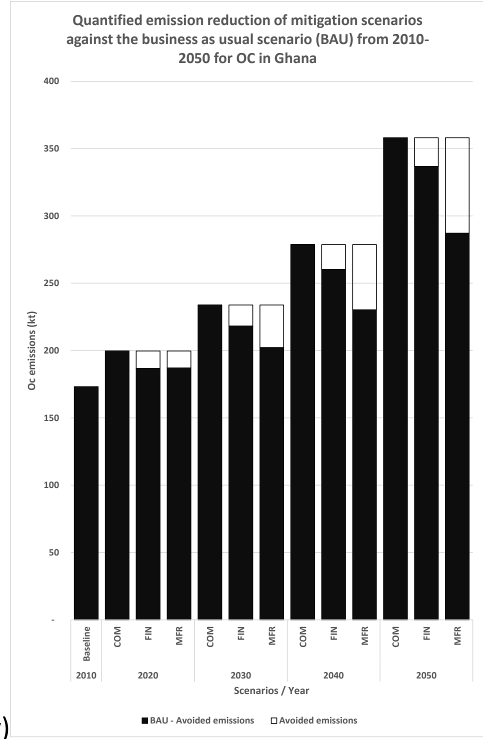
(iii)



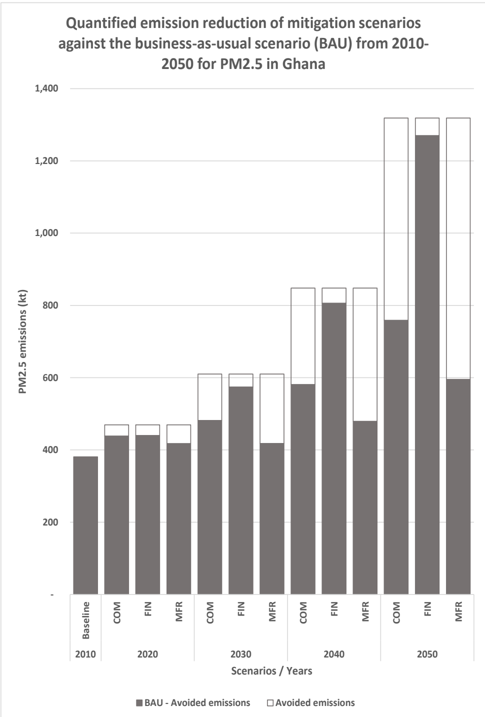
(iv)


Quantified emission reduction of mitigation scenarios against the business as usual scenario (BAU) from 2010-2050 for BC in Ghana
140
120
100
80
60
40
20
-
BC emissions (kt)
Baseline
COM
FIN
MFR
COM
FIN
MFR
COM
FIN
MFR
COM
FIN
MFR
2010
2020
2030
2040
2050
Scenarios /Years
BAU - Avoided emissions
Avoided emissions

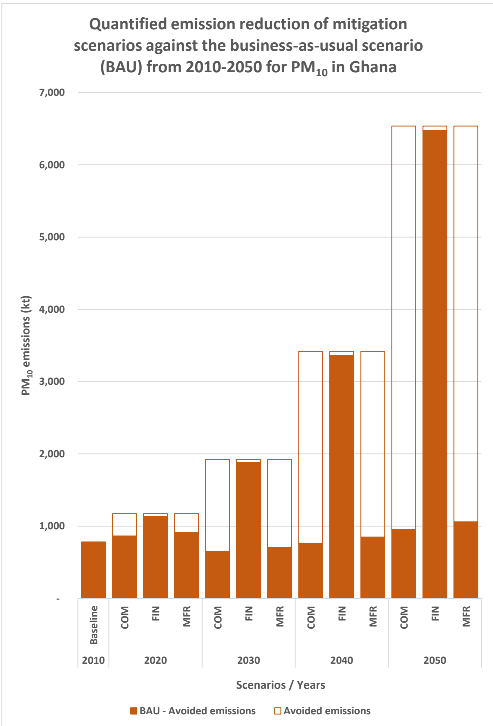
(v)


Quantified emission reduction of mitigation scenarios against the business as usual scenario (BAU) from 2010-2050 for OC in Ghana
400
350
300
250
200
150
100
50
-
Oc emissions (kt)
Baseline
COM
FIN
MFR
COM
FIN
MFR
COM
FIN
MFR
COM
FIN
MFR
2010
2020
2030
2040
2050
Scenarios / Year
BAU - Avoided emissions
Avoided emissions

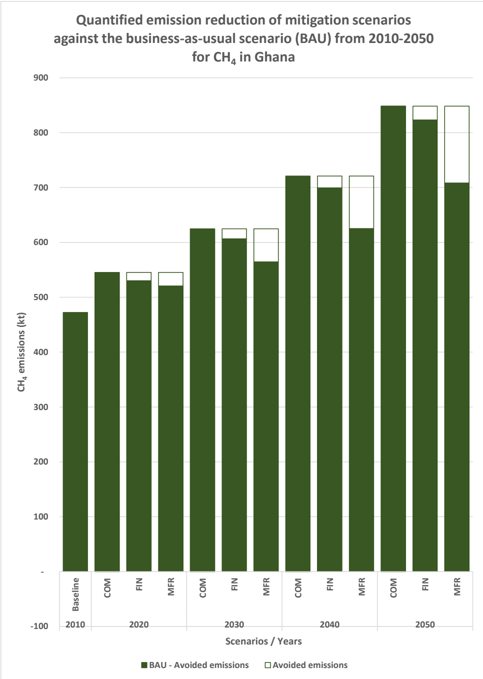
(vi)


Quantified emission reduction of mitigation scenarios against the business-as-usual scenario (BAU) from 2010-2050 for PM2.5 in Ghana
1,400
1,200
1,000
800
600
400
200
-
PM2.5 emissions (kt)
Baseline
COM
FIN
MFR
COM
FIN
MFR
COM
FIN
MFR
COM
FIN
MFR
2010
2020
2030
2040
2050
Scenarios / Years
BAU - Avoided emissions
Avoided emissions

(vii)


Quantified emission reduction of mitigation scenarios against the business-as-usual scenario (BAU) from 2010-2050 for PM_{10} in Ghana
7,000
6,000
5,000
4,000
3,000
2,000
1,000
-
PM_{10} emissions (kt)
Baseline
COM
FIN
MFR
COM
FIN
MFR
COM
FIN
MFR
COM
FIN
MFR
2010
2020
2030
2040
2050
Scenarios / Years
BAU - Avoided emissions
Avoided emissions

(viii)



Quantified emission reduction of mitigation scenarios
against the business-as-usual scenario (BAU) from 2010-2050
for CH4 in Ghana
900
800
700
600
500
400
300
200
100
-
-100
CH4 emissions (kt)
Baseline
COM
FIN
MFR
2010
2020
2030
2040
2050
Scenarios / Years
BAU - Avoided emissions
Avoided emissions

(ix)

Abbreviations

AQ – Air quality

AQM – Air quality management

BAU - Business as usual

BC - Black carbon

BUGs - Backup generators

CCAC – Climate and Clean Air Coalition

CIV - Cote d'Ivoire

CO – Carbon monoxide

COM – Combined 5 key sources

CH_4 – Methane

CO_2 – Carbon (IV) oxide

ECOWAS – Economic Community of West African States

EMEP/EEA – European Monitoring and evaluation Programme / European Economic Area

FIN – Fully implemented national policies scenario

FUR1 – Further cooking measures

FUR2 – Further road transport measures

FUR3 – Further electricity generating measures

GAPF – Global Atmospheric Pollution Forum

GDP – Gross domestic product

GHN – Ghana

IEA – International Energy Agency

ILL – Illegal oil refining

IPCC – Intergovernmental panel on Climate Change

LEAP-IBC – Long-range Energy Alternative Planning – Integrated Benefits Calculator

LPG – Liquified petroleum gas

MFR – Maximum feasible reduction scenario

NGR – Nigeria

NH_3 – Ammonia

NMVOC - Non-methane volatile organic compounds

O_3 – Ozone

OICA – International Organisation of Motor Vehicle Manufacturers

PCFV – Partnership for Clean Fuels and Vehicles

PM – Particulate matter

PWC – PricewaterhouseCoopers Ltd

REP – Renewable Energy Programme

SDG – Sustainable Development Goals

SIM – Simple kerosene wick lamps

SO_2 – Sulphur (IV) oxide

TWO – Two-stroke motorcycles

UN – United Nations

UNDESA – United Nations Department of Economic and Social Affiars

UNEP – United Nations Environment Programme

UNFCCC – United Nations Framework Convention on Climate Change

UNP – Unpaved roads

US – United States

WAF – West Africa

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